Gear Innovation:

Extending the Functionality of Outdoor Rock-Climbing Clothing through Ergonomic Design and the Integration of Smart Technologies

Aleksandra Novikova

A thesis submitted to
Auckland University of Technology in fulfilment of the requirement for the degree of Doctor of Philosophy (PhD)
2024 | School of Future Environment
Primary Supervisor: Professor Frances Joseph
Secondary Supervisor: Dr. Donna Cleveland

ABSTRACT

This research investigates the development of ergonomic and functional outdoor clothing tailored for rock-climbers, emphasizing improvements in fit, comfort, and safety. This involves a multidisciplinary investigation exploring the integration of smart technologies into garment design, focusing on incorporating wearable electronics into rock-climbing attire.

Rock-climbing presents both physiological and psychological challenges exacerbated by external environmental conditions. Given its inherent risks, mastery of climbing techniques, tactical manoeuvres, specialized equipment usage, and ergonomic clothing are crucial to safe route completion. Furthermore, appropriate rock-climbing apparel plays a critical role in preventing hypothermia, an independent risk factor contributing to mortality in trauma patients.

The study identifies the requirements and preferences of experienced rock-climbers concerning clothing, through data obtained from a survey of seasoned climbers. Current market offerings were evaluated, identifying shortcomings in existing clothing options for climbers. This review suggested areas in which improvements in design could produce more practical garments which would be responsive to the environmental challenges faced by climbers, while employing sustainable manufacturing technologies. This endeavour also leverages the researcher's expertise in patternmaking, material selection, and garment construction.

The research is underpinned by an epistemological foundation rooted in ergonomics, employing a methodological framework guided by a user-centred design approach throughout the project. Integrating principles from ergonomics underscores the interdisciplinary nature of the study, emphasizing user experience and user-centred design. This systematic user-centred design approach integrates qualitative and quantitative methods across project stages.

An outcome of the research is the development of an ergonomic outdoor jacket tailored specifically for rock-climbers, integrating climbers’ activities, needs, and preferences, alongside contemporary design innovations, technologies, and advanced textile materials. Additionally, a functional prototype of a smart heating system was developed with efforts directed towards future mass production through the creation of a customized PCB and assembly of a smart heating system. Furthermore, a conceptual proposal outlines the integration of this system into a jacket, considering the demands of rock-climbing activities and associated equipment.

The findings contribute to advancing the understanding of ergonomic design in outdoor rock-climbing apparel integrated with wearable technologies, proposing recommendations for contemporary solutions in garment design and material selection. Moreover, it contributes to knowledge about garment development and design methodology by applying information technologies such as the Xsens motion tracking system and virtual fashion design software, potentially benefiting manufacturers of outdoor sports clothing. Additionally, the research underscores the importance of an interdisciplinary methodological approach in leveraging e-textiles and creating prototypes of smart wearables. This approach could be extended to various other sports and activities such as multi-day hiking, trekking, polar expeditions, and search and rescue operations, highlighting the broader applicability of garment technology innovations.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ATTESTATION OF AUTHORSHIP

I hereby declare that this submission is my own work and that, to the best of my knowledge and belief, it contains no material previously published or written by another person (except where explicitly defined in the acknowledgements), nor material which to a substantial extent has been submitted for the award of any other degree or diploma of a university or other institution of higher learning

Aleksandra Novikova

October 2024

CO-AUTHORED PUBLICATIONS

Novikova, A., Joseph, F., & Cleveland, D. (2023). Rock-climbing apparel: an analysis of current clothing options and future strategies for the design of rock-climbing clothing. International Journal of Fashion Design, Technology and Education, 17(2), 193–201. https://doi.org/10.1080/17543266.2023.2261023

Novikova, A., Cleveland, D., & Joseph, F. (2023). Ergonomic Design of Rock-Climbing Clothing: Integrating Anthropometric Measurements and Movement Dynamics. [Manuscript submitted for publication]. International Journal of Fashion Design, Technology and Education.

ACKNOWLEDGEMENT

I would like to express my gratitude to my supervisory team, Professor Frances Joseph and Dr. Donna Cleveland, for their unfailing support, belief in this research project, trust me as a researcher, motivation and their expertise and substantial contribution. This study was guided by my supervisors throughout the challenges I experienced during some stages of this research project and my personal life. I am especially grateful to Professor Frances Joseph for her empathy, support, and for facilitating valuable connections within the exceptionally supportive AUT research community. I also would like to express my appreciation to Dr. Donna Cleveland, and her husband Peter Cleveland, for introducing me to e-textiles and sharing their expertise in the field of smart textiles.

I would also like to acknowledge the assistance of the AUT staff, colleagues, and students who supported me throughout this project, with particular thanks to Dr. Kelly Sheerin and Dr. Andrew Lawe for their invaluable help and support. Additionally, I am grateful to experienced climber Ilia Dushko for his involvement in all stages of the project as an end user of the final product, and other climbers participated in a survey. My thanks extend to Vladimir Kvasov, an electrician and friend, for his invaluable guidance and assistance with electronic connections. In additional, I would like to acknowledge my friend and an experienced pattern engineer Evgeniya Malaikova, who works in Vladivostok, Russia for her assistance with the 3D Fashion Design Software.

Moreover, I would like to acknowledge Dr. David Jones for his support towards the end of this research journey and for his meticulous proofreading of the final thesis document. Also my thanks expand to another proofreader, Agnes Terraschke, for her great work.

Finally, this thesis would not have been possible without the unwavering support of my husband, Evgenii Novikov, who encouraged me to move to New Zealand to pursue this study and believed in me throughout my research journey. The process was particularly challenging, as I relocated to New Zealand with my 7-year-old son just before the COVID-19 lockdown. Despite being in Russia, Evgenii's support and encouragement were crucial in helping me feel capable of achieving something significant and completing this project successfully. I am also grateful to my mother, other family members, and close friends for their understanding, continuous love and belief in me.

ETHICS APPROVAL

The Ethics application has been approved in stages by the Auckland University of Technology Ethics Committee (AUTEC), AUTEC Reference number 21/171.

ACRONYMS

ACCT	The Association for Challenge Course Technology
ANSI	The American National Standards Institute
AS/NZS	Australia and New Zealand Standards
AUT	Auckland University of Technology
BJT	Bipolar Junction Transistor
CAD	Automated Design Systems
CEN	European Committee for Standardization
CNT	Carbon Nanotubes
DC	Direct Current
DWR	Durable Water Repellence
e-textiles	Electrically driven smart textiles
ECG	Electrocardiogram
ECM	Electrically Conductive Material
EMG	Electromyography
ePE	Expanded Polyethylene
ESO	European Standards Organizations
EU	European Union
GPS	Global Positioning System
HM	Heart rate Monitoring
IC	Integrated Circuit
IEA	International Ergonomics Association
IMU	Inertial Measurement Unit
IO	Input/Output (Refers to the data processing pins on an MCU)
IT	Information Technology
LED	Light-Emitting Diode
MCU	Micro Controller Unit
MTw	Wireless Motion Trackers
NZAC	The New Zealand Alpine Club
PCB	Printed Circuit Board
PFC	Per and Polyfluorinated Compounds
PID	Proportional Integral Derivative
PPE	Personal Protective Equipment
PU	Polyurethane
PWM	Pulse Width Modulation
TA	Task Analysis
UIAA	The International Climbing and Mountaineering Federation
USB	Universal Serial Bus
UV	Ultraviolet

CHAPTER 1. INTRODUCTION

This chapter sets the scene for the study as the relevant issue is described. Based on this information, the rationale for the study is presented, including its aim, objectives, and research questions. It defines the scope of the investigation and introduces me as a researcher. Additionally, it presents the contribution and outcome of the project. An overview outlined the thesis structure is provided at the end of this chapter.

1.1. Research Background

While humans have always climbed, be it to find a safe cave for shelter or in search of a path across a mountain range, the sport of rock-climbing and mountaineering is only about 200 years old. The earliest documented examples of rock-climbing date back to the late 1800s, where mountaineers in China and Europe began to ascend steep and demanding rock faces in their effort to reach the peaks (Krug, 2023). New Zealand has an impressive track record in this area, as evidenced by Sir Edmund Hillary summitting Mount Everest with Tenzing Norgay in 1953 (NZ History, n.d.). Over the second half of the 20th century, adventure sports proliferated and became popular with a wider range of people rather than being reserved for the wealthy only. In recent years, rock-climbing has carved out a growing and significant niche within the realm of adventure activities. The popularity of rock-climbing has spread globally, diversifying to include new categories such as ice climbing and bouldering. Sport climbing was selected by the International Olympic Committee to be part of the Summer Olympic Games in Tokyo 2021 with three subdisciplines: lead climbing, speed climbing, and bouldering (Ginszt et al., 2023; International Federation of Sport Climbing, n.d.). Rock-climbing gyms can be found in most major cities and tourist destinations, often with walls designed for children and hosting birthday parties, further attesting to the growing popularity of what was once an extreme and exclusive sport.

Rock-climbing is a physiologically and psychologically demanding sport that is influenced by external environmental factors, at least in its original outdoor form. As climbing continues to gain popularity, there has been a corresponding increase in the number of accidents and visits to emergency departments due to climbing-related injuries, including hypothermia, which is an independent risk factor for mortality in trauma patients (Rauch et al., 2019). Climbing is a potentially hazardous activity, and expertise in proper climbing techniques, strategies, and the use of specialised equipment and ergonomic clothing is essential for safely completing climbing routes.

High quality climbing apparel is crucial to protecting climbers and mitigating exposure to hazardous conditions while supporting climbers' overall health condition. During rock climbing, the climber's body temperature can fluctuate considerably, particularly in high-altitude snowy environments where temperatures can vary widely along a climbing route. Climbers traditionally manage these fluctuations by employing a multi-layer approach to clothing, adjusting layers as needed to regulate their microclimate during ascent. However, this approach requires carrying multiple layers and introduces a significant risk factor due to the need to change clothing in potentially dangerous conditions, often while secured to safety ropes that must be adjusted. Additionally, given that climbing is physiologically unique in requiring specific dynamic movements, such as sustained and intermittent isometric forearm muscle contractions for upward propulsion (Sheel, 2004), it is important to consider body motion and body measurement changes while in dynamic positions when designing a functional and ergonomic garment for rock climbing. For example, jackets manufactured for horizontal outdoor activities are not designed for these movements, resulting in bunching of the fabric at the shoulders and exposure of the midriff to the elements when an arm is lifted. Similarly, walking trousers are not usually designed for extreme separation of the legs, and can become tight or split at the seams. This project is intended to address these shortcomings through the development of rock-climbing apparel that is ergonomic and functional while reducing the need for multiple layers or bulky jackets. Such innovations could significantly decrease weight and enhance safety and functionality, addressing key challenges in the current climbing gear market.

Historically, it has only been possible to use passive climate control in clothing, where the only source of heat is the climber's body, and heat regulation is managed through adding or removing layers, resulting in the dangers described earlier. With the development of new technologies, it is now possible to integrate smart technologies into garments, which allows for the integration of active or passive heating and cooling elements along with the necessary sensors to track and manage those systems. Smart clothing is an evolving interdisciplinary field that combines sensing and response technologies to deliver a variety of functionalities (Ismar et al., 2020; Research and Markets, 2021). While wearable electronics have been extensively introduced in many areas, including communication, information sciences, magnetic shielding, military sector, clothing, healthcare, and sport monitoring (Kubicek et al., 2022), there has been limited development of these technologies specifically for rock-climbing. It is a field with significant potential for the development of novel smart textiles and functional apparel, involving the integration of innovative sensing technologies into clothing to enhance safety, comfort, and performance of rock climbers, including technology that supports temperature regulation and establishing a stable microclimate.

The rationale and significance of this research are also underscored by the lack of published standards and requirements specifically addressing the apparel needs of rock climbers, coupled with limited research in this area. Current standards mainly focus on the safety and reliability of climbing equipment, such as ropes, carabiners and helmets, but there remains a gap in guidelines for climbing clothing. As a result, outdoor apparel manufacturers often establish their own design and fabric specifications which may not account for the specific needs and expectations of climbers. Climbers are therefore left to make clothing choices based on their personal needs and experiences with existing apparel. This gap highlights the potential for developing comprehensive requirements and practical recommendations for the design of ergonomic and functional rock-climbing clothing, as well as for integrating smart sensing technologies. As the number of rock climbers continues to rise, outdoor recreational clothing manufacturers and retailers should anticipate increasing consumer demand for rock climbing clothing that offer ergonomics and extended functionality in terms of fit, mobility, comfort, and protection. Given the scarcity of studies on outdoor recreational apparel, assessing the needs of this consumer segment has been challenging. This research aims to fill this gap by contributing to the limited scholarly work on outdoor sport apparel. It expands our current understanding of the functional needs of such apparel and explores the integration of smart wearable technologies into this clothing type.

1.2. Researcher and Context

I am originally from Vladivostok, Russia, and have an engineering background in apparel design and textile areas. With more than ten years of professional experience at the Research and Development Centre of Vladivostok State University of Economics (now Vladivostok State University), I attained a scientific degree in Russia, equivalent to a PhD in Science, specifically in the field of Engineering and Technology, conferred in 2009. My expertise lies in pattern making and innovative materials, coupled with hands-on experience with various laboratory equipment, testing protocols, and a profound understanding of textile properties and behaviour.

Realising my aspiration to broaden my expertise in wearable technologies, e-textiles, and smart clothing, I proposed the concept of developing smart clothing for rock climbers, aimed at enhancing safety and comfort during climbing activities. I made the decision to relocate to New Zealand, considering the substantial popularity of rock-climbing here, coupled with the conducive research environment.

New Zealand's climate is diverse, ranging from warm subtropical conditions in the far north to cool, temperate climates in the far south, with severe alpine conditions in the mountainous regions. Mountainous areas (see Figure 1.1) are subject to heavy snowfalls, high winds, and low temperatures. Semi-permanent snow and ice fields exist at about 1000 meters during winter. Anticyclones often bring settled weather in summer, but clear cold conditions in winter with severe frost (NIWA, n.d.).

I identified this country as an optimal location for pursuing this research endeavour. In New Zealand rock-climbing is a popular activity with over 19,997 climbing routes distributed across the country (The Crag. Aotearoa/New Zealand, n.d.). There are many rock-climbing clubs, including the New Zealand Alpine Club (NZAC), the oldest one in the world, which consists of 4300 plus members (New Zealand Alpine Club, n.d.). The availability of potential participants (experienced climbers) to gather information was one of the reasons this research was conducted in New Zealand.

Moreover, Auckland University of Technology (AUT) emerged as the best place for this multidisciplinary project due to its state-of-the-art facilities and the diverse range of researchers and resources available across various faculties. This project represents the convergence of diverse disciplines, including ergonomics, design, garment engineering, electronics engineering, programming, smart clothing, and e-textiles. I was enthusiastic about leveraging my expertise and background to contribute to the advancement of smart clothing and e-textiles within this interdisciplinary context.

Figure 1.1

Mt. Cook on the left, Roy's peak on the right

1.3. Research Aim and Questions

The **aim** of this research is to enhance the functionality and safety of outdoor rock-climbing apparel through ergonomic design and the integration of smart technologies, primarily by incorporating an autoregulatory temperature control system to replace the traditional layering approach.

The **primary question** guiding this research is:

How can the functionality of outdoor rock-climbing apparel be enhanced?

Secondary questions are:

1. How can the functionality, safety, fit, and comfort of climbing apparel be improved through employing an ergonomic approach to the design?

2. How can the functionality, safety and comfort of climbing apparel be enhanced by the incorporation of smart wearable technologies?

In order to answer these questions, the research process involved:

1. An examination of the current state of outdoor rock-climbing clothing through conducting a comprehensive review of relevant literature, published standards, and requirements specifically addressing the apparel needs of rock climbers. This includes investigating and assessing the rock-climbing clothing and smart clothing currently available on the market.
2. The identification of a methodological framework for this project.
3. A survey of the needs, preferences, expectations, and experience of experienced climbers and identification of current clothing options.
4. An investigation of the applications of new technologies into the clothing development process.
5. The development of a smart heating prototype and its integration into the clothing.
6. The development of a functional and ergonomic outdoor rock-climbing jacket integrated with wearable electronics.
7. An analysis of the results and the insights from the study, offering recommendations and discussion of considerations and contributions to this interdisciplinary design field.
8. A discussion of research limitations and potential future research directions that could be explored in order to create more advanced smart clothing solutions.

1.4. Contributions and outcomes of the project

The project offers both scientific innovation and practical implications. The scientific novelty of this project lies in the methodological approaches and techniques developed from a rock-climbing garment design perspective. These methods can be adapted and utilised by researchers in related fields. The project includes an evaluation of new technologies in the garment development process, such as the Xsens motion tracking system and virtual fashion design software. These technologies are applicable in both research contexts and the clothing design industry, offering novel insights and practical tools for advancing garment design.

The practical implications of these research findings include proposing recommendations for contemporary solutions in garment design and material selection grounded in a comprehensive understanding of ergonomic principles applied to outdoor rock-climbing apparel and integrated with wearable technologies. The study also offers a conceptual solution for incorporating a smart heating system into rock-climbing jackets, addressing the specific needs of climbing activities and associated equipment. Such innovations have the potential to benefit manufacturers of outdoor sports clothing, including those intended for other pursuits. Additionally, the future research directions proposed offer designers and researchers in pertinent fields clear suggestions for the exploration of new ways to enhance clothing functionality and improve user satisfaction.

1.5. Thesis structure

This thesis adheres to the traditional thesis structure. This thesis consists of eight chapters, namely an introduction, literature review, methodology, data analysis, practical realization, discussion, and a conclusion.

Chapter 1. This introductory chapter provides background information about the research context, including the research aim, objectives, and questions guiding this study. This chapter also presents an overview of the structure of the thesis.

Chapter 2. Chapter 2 provides a comprehensive literature and research review that encompasses an analysis of over one hundred scientific publications. The primary aim of this review is to identify pertinent information, key ideas, and existing gaps in knowledge. It also presents an overview of appropriate methodologies within the research field. This chapter addresses various aspects such as rock-climbing techniques, the functions of apparel, safety standards, and microclimate management. Additionally, it examines how cold and hypothermia affect rock climbers and concludes with a discussion of smart clothing, including market products, scientific research, and utility patents for heated apparel.

Chapter 3. This chapter outlines and justifies the methodological approaches employed in this research, emphasising its interdisciplinary nature. The research is epistemically grounded in ergonomics, with a methodological framework that adheres to a user-centred design approach throughout the project. The study integrates technical and functional design-led research with specific design methods and tools utilised in pattern engineering and the iterative development of prototypes. Both the qualitative and quantitative methods employed at various stages of the project are thoroughly described here.

Chapter 4. In chapter 4, the findings of primary data collection methods which informed the development of an outdoor smart jacket for rock climbers are presented. Information was gathered through surveys and observational techniques. The initial data was obtained through analysing the commercially available articles of outdoor rock-climbing clothing brands that were identified by experienced rock climbers gathered through the questionnaire.

Chapter 5 and Chapter 6. These chapters address the practical aspects of the project. The practical realisation of the development of a functional and ergonomic smart-outdoor jacket for the rock climbers consisted of two parts. Chapter 5 describes the process of developing and making a jacket, which parallels traditional garment development but incorporates additional functionality and ergonomics specific to rock-climbing activities. Chapter 6 illustrates the process of finding optimal solutions for the creation and integration of a sensing heating system prototype into a rock-climbing jacket.

Chapter 7. Chapter 7 presents a discussion on the primary considerations, challenges, and contributions of the project within the fields of outdoor rock-climbing apparel development and design of e-textiles and smart wearables. This chapter addresses the research limitations identified throughout the project and highlights relevant future directions.

Chapter 8. The final chapter provides the conclusion of the thesis. Here, the study's findings and reflecting on the research aim, objectives, and questions are summarised. It outlines the contributions of this thesis to knowledge across various fields and proposes future research opportunities that could help address the identified limitations and broader issues within the field.

1.6. Summary

The increasing popularity of rock climbing, coupled with issues associated with current climbing apparel options and the conventional multi-layer clothing approach, underscores the need for focused research in this area. Additionally, the existing gaps in standardisation in this field and the development of new technologies that could be integrated into climbing garment to enhance functionality and safety further justify the need for this research. This chapter provided a rationale for conducting this study in New Zealand, introduced the researcher, and outlined the background and significance of the research. It further delineated the aim and objectives of the study, along with the primary research questions and sub-questions that guide the investigation. Additionally, the chapter presented the structure of the thesis, including a brief description of each chapter.

CHAPTER 2. LITERATURE REVIEW

2.1. Introduction

The current chapter presents a thorough literature review of existing knowledge in areas relevant to the optimisation of outdoor rock-climbing gear based on the comprehensive analysis of more than one hundred scientific publications, including peer-reviewed journal articles, books, theses, conference proceedings, reports, standards, and online resources. The aim of this review is to provide a thorough account of the research area, define key concepts, explore prevalent methodological approaches, and identify gaps in the current knowledge.

The review consists of three sections. The first section discusses the classification of rock-climbing types and techniques, the main requirements and types of rock-climbing clothes, as well as safety standards and requirements for climbing and mountaineering. This is followed by an overview of the kinds tasks the different types of gear for different kinds of mountain- and rock-climbing styles must be able to perform and the kinds of conditions they must endure. The third section features a discussion on microclimate within the clothing layers and mechanisms of human heat transfer, including an examination of cold effects and hypothermia, while the next section provides an examination of the principles of thermoregulation for active sports clothing in relation of this study's goal to create functional and ergonomic rock-climbing clothing that do not require multiple layers. The final section focuses on smart clothing, both in terms of what is already available on the market or still in the prototyping stage. This review thus presents the context of the current research and highlights the gaps in the existing literature.

2.2. Classification of Rock-climbing Types and Techniques

In the sport of rock-climbing, there are several different classifications of styles, types, and techniques of rock-climbing based on a range of different factors, including the geology of an area (e.g. deep water soloing, big wall climbing, multi-pitch routes etc.), the season, the number of participants (one, often referred to as soloing, or involving more people), the type of rock face, the number of tools and pieces of equipment used, the skill level of the climber, and the type of risk involved. There are a few different types of risk associated with rock-climbing, including:

- Physical risks, related to falls, injures, rockfalls, hypothermia, sunburn and other physiological challenges encountered in extreme outdoor environments.
- Psychological risks, caused by overconfidence - often observed in experienced climbers - or from fear and panic, typically among the beginners. Mental and physical fatigue can impair decision-making, and restrictive or poorly designed clothing may further contribute to discomfort, distraction, and reduced mobility during climbs.
- Equipment and technical risks, including gear failure, improper use of equipment, clothing incompatible with rock-climbing gear (e.g., harnesses, carabiners) or belaying errors. Clothing that is not specifically designed for rock climbing may lack the necessary ergonomic features and

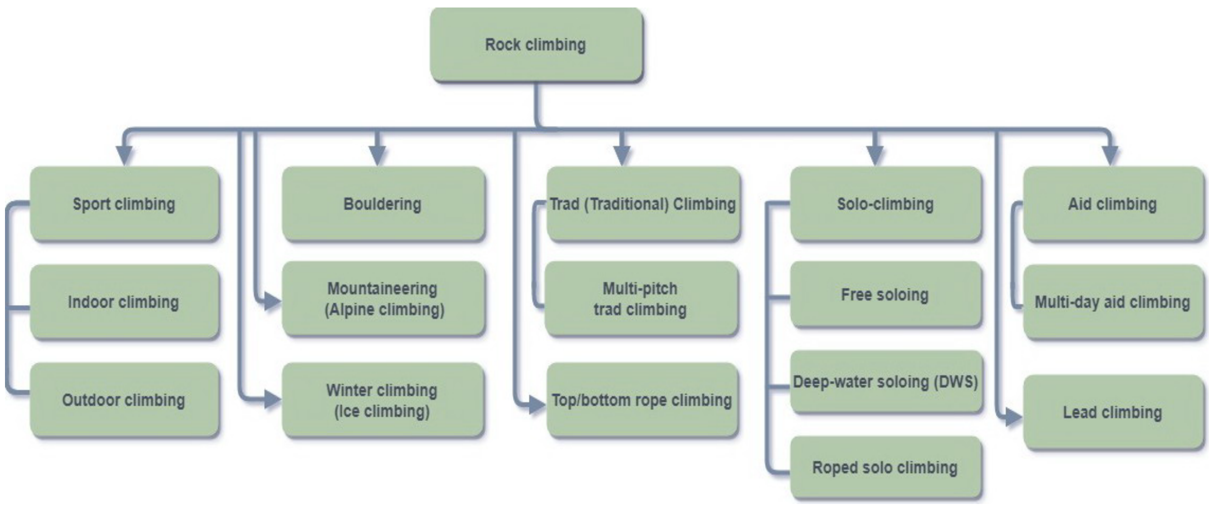
functional adaptability, potentially hindering performance and increasing the risk of technical failures.

- Environmental (climate) and situational risks. These include sudden weather changes, extreme temperatures, wet or unstable rock surfaces, and route-finding errors.
- Other types of risks, related to human error, for example communication errors during lead climbing, overcrowded climbing sites, and other interpersonal issues that can compromise safety.

Because information about rock climbing is scattered across different disciplinary areas and forms of publication, and there is no single acknowledged classification system for type and techniques of rock-climbing, it was difficult to determine which types of rock-climbing might warrant further research in terms of the focus of this project. In order to understand and structure this information, 22 sources were identified across the areas of sports science, mountaineering books, manuals and guides to rock-climbing, safety guides, and webpages for climbers. Based on these sources, information about the main types and techniques of rock-climbing were analysed and summarised by the researcher and the findings are presented in Figure 2.1 and Table 2.1 below.

Figure 2.1

The main types and techniques of rock-climbing



A brief description of the different types and techniques of rock-climbing identified from the data along with the equipment, gear, clothing, and the function of clothing required as well as the level of risks associated with each type are summarised below in Table 2.1.

Table 2.1

Summary of information about rock-climbing, gear and clothing

Style of rock-climbing	Description/main features/techniques	Equipment, gear, clothing	Function of clothes	Level of risk
Sport climbing	Sport climbing is a climbing style that involves ascending technical routes utilising fixed protection, a safety harness, and ropes. This form of climbing employs techniques similar to those used in bouldering, such as friction climbing, mantling, heel hooking, and stemming, to traverse extended routes on rock faces (Mountaineers, 2003).	Fixed protection: permanent anchors, bolts placed in rock, carabiners, harnesses, belay devices, helmets, quickdraws, ropes, shoes (Donahue & Luebben, 2014).	Indoor: Comfort Mobility (unrestricted movement). Outdoor: Comfort Mobility Protection (abrasion and bruising)	Low-risk
Bouldering	Bouldering is a rock-climbing style performed without the use of ropes or safety harnesses, typically involving very short climbs. Climbers use a crash pad, known as a bouldering mat, to mitigate the risk of injury from falls (Buckingham, 2008; Escalade Rock Climbing Gym, n.d.).	Bouldering mat, chalkbag, shoes (Buckingham, 2008).	Comfort Mobility (unrestricted movement). Protection (abrasion and bruising)	Low-risk
Top rope or bottom rope climbing (style and technique)	This is a style of climbing adopted by instructors where a short outcrop of rock is used to introduce beginners to the sport. It is a way to master the techniques of anchor placement and construction, and to practice belaying skills (Shepherd, 2014). Top roping involves a rigging setup where the rope is threaded from the belayer, ascends through an anchor point, and then descends back to the climber (DiAngelis, n.d.).	Anchors, ropes, harness, screw gate carabiners, belay devices, helmets	Mobility Fit Comfort	Low-risk
Solo-climbing (soloing)	This is a style of rock-climbing that involves the climber ascending independently, without the assistance of a belayer (Tyson & Loomis, 2006).	Rope and self-locking device (only for roped solo climbing). No rope or other forms of protection (other types of soloing).	Comfort	Higher level of risk

Trad (tradition-nal) climbing Multi-pitch trad climbing	Traditional climbing, commonly referred to as "trad climbing," involves the climber placing protective gear in cracks and fissures of the rock formation to safeguard against potential falls (Michaelson, 2015). A team for trad climbing is normally 2 or 3 climbers, but more than three will significantly slow down proceedings. The team arrives at the bottom of cliff and climb up using a recognised route (Shepherd, 2014). Multi-pitch trad climbing takes place on crags that are much longer than the length of a climbing rope and climbers ascend in stages, known as pitches (Shepherd, 2014).	Anchors, belay devices, carabiners, cord, ropes, safety harnesses, helmets, quickdraws, shoes, webbing sling, optional warm clothes (additional layer, depends on the route). The climbers will need to arrange their own protect-ion as they ascend, by placing wedge, hexagonal or camming devices into cracks in the rock face (Donahue & Luebben, 2014).	Protection. Trad climbing necessitates versatile clothing designed to protect the climber from harness chafing, jamming their body into cracks, and adverse weather conditions (Johnston & Koo, 2017)	Higher level of risk
Ice-climbing (Winter climbing)	Ice climbing is a style of rock-climbing which involves ascending frozen waterfalls or other ice formations. To be considered ice climbing, the formation typically needs to be reasonably vertical; traversing glaciers or climbing low-angled snow or ice slopes falls under the category of mountaineering. During an ice climb, climbers use ropes for safety and employ specialised crampons and ice axes for the ascent (Mountain Passions, n.d.).	Ropes, Placing gear: pitons, jam nuts, cams and slings, anchors. Helmet, harness, shoes (Wayatt, 2005). Ice axe and crampon front points.	Protection Comfort Mobility	High-risk
Aid climbing	Aid climbing is a climbing style in which progress is made by standing on or pulling oneself up using devices attached to fixed or placed protection (VDiff Climbing, 2020; Wittman, n.d.). This style of climbing relies on these aids to ascend, rather than solely on natural rock features or holds.	Anchors, belay devices, carabiners, cord, hooks, nuts, piton, hauling device, safety harness, helmets, quickdraws, ropes, shoes, fingerless gloves, haul bag, optional warm clothes (additional layer, depends on the route) (J. Chapman, 2022; VDiff Climbing, 2020; Wittman, n.d.).	Protection Comfort Mobility Fit	High-risk

Mountaineering (Alpine rock-climbing)	Mountaineering, also known as "mountain climbing" or "Alpinism" (particularly in Europe), is the sport of ascending mountains (Parra, 2018). A typical alpine climb might involve a steep six-mile hike to a glacier crossing, followed by six hours ascending steep technical rock and ice to a summit using rope protection and techniques common to many types of climbing (Smith, 2006).	Placing gear: pitons, jam nuts, cams and slings (Wayatt, 2005). Mountaineering rope, harness designed for mountaineering, mountaineering helmet, belay device, carabiners, crevasse rescue equipment, mountaineering boots. Camping items: backpack, four-season tent, sleeping bag (according to climate conditions). Ice axes, crampons, mountaineering gloves (Wayatt, 2005). Rock-climbing clothes consisted of few layers.	Protection Comfort Mobility Fit	High risk
Lead climbing (style and technique)	Lead climbing is a climbing style and technique, primary used in rock climbing (DiAngelis, n.d.; Kirby, n.d.). In a roped party, one climber assumes the lead role while the others follow (Coppolillo & Chauvin, 2022; Safety Academy. Lab Rock, n.d.). The lead climber is equipped with a harness connected to a climbing rope, which is linked to the climbers below. As the lead climber ascends the route, they periodically attach the rope to protection equipment to ensure safety in the event of a fall. Unlike some climbing styles, lead climbing does not utilize pre-threaded upper anchor points; instead, the climber must place protection as they progress (DiAngelis, n.d.).	Anchors, ropes, sling length, harness, carabiners, belay devices, quickdraws, helmets, shoes	Mobility Fit Comfort	High-risk

Risk emerged as a key factor in establishing groupings of climbing types. For example, in Table 2.1, the types of rock-climbing with a higher level of risk are classified as traditional climbing, including multi-pitch trad climbing, solo-climbing, mountaineering, ice-climbing, lead climbing, and aid climbing. All these types of rock-climbing are popular in New Zealand. A variety of factors determines the degree of danger associated with each rock-climbing type. For example, there is a higher level of risk for soloing without any forms of protection (Wayatt, 2005). The risk of severe weather, the cold temperatures, and nightfall intervening, and the increased risk of falling rock and ice, and physical injuries that can occur during lead falls are the reasons why some types of rock-climbing are so hazardous (Ascentionism, n.d.; Smith, 2006; Wayatt, 2005). According to Rauch et al. (2019), the number of climbing accidents and subsequent consultations in emergency departments due to climbing-related injuries has risen, reflecting the growing popularity of rock-climbing. Climbing can be a hazardous activity, and ensuring safety requires a thorough understanding of proper climbing techniques, effective tactics, the use of specialised climbing equipment, and the selection of functional and ergonomic apparel.

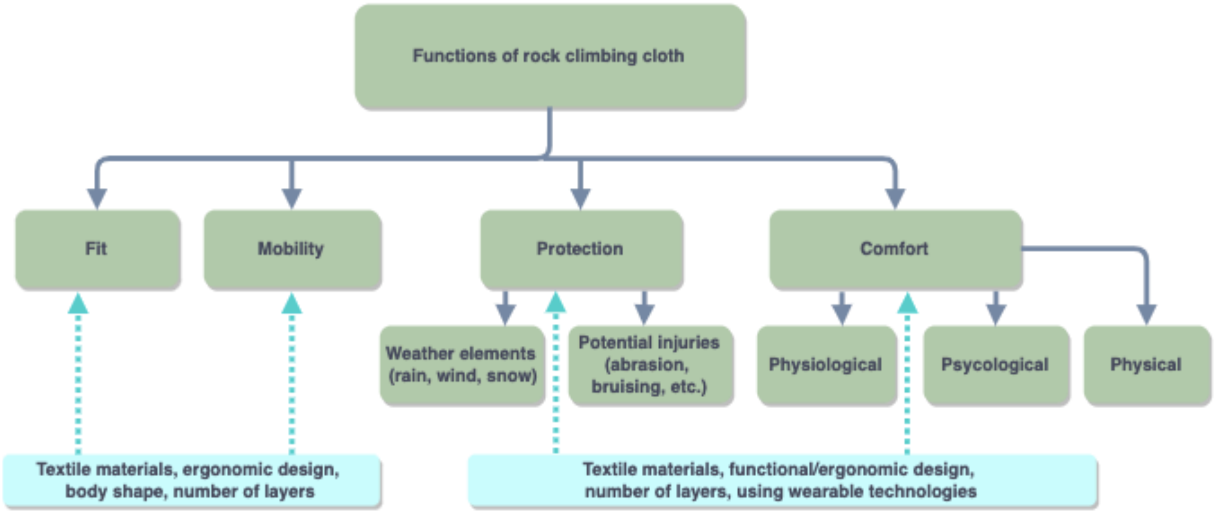
Ergonomics in clothing pertains to the design considerations focused on comfort and performance, tailored to specific user needs determined by the operational environment and the activities performed (Gupta, 2011; Jayasinghe & Seram, 2017). Bishop et al.'s (2013) review of the ergonomics of industrial, sport protective, and sports clothing examined the interactions between humans and their clothing to enhance comfort, well-being, safety, and performance. For rock-climbing, apparel must provide protection against diverse weather conditions and temperature variations as well as against abrasion and bruising (Johnston & Koo, 2017). Bishop et al. (2013) identified thermoregulation as an important aspect of clothing ergonomics, noting that the vapor and moisture permeability of clothing significantly impact the micro-environment and, consequently, are significant for wearer comfort. Additionally, in disciplines such as ice climbing and alpine climbing, appropriate clothing is essential to prevent hypothermia, a significant risk factor for mortality in trauma patients (Ainslie, 2003; Coalter et al., 2010). Hypothermia is frequently observed in severely injured climbers (Rauch et al., 2020). Therefore, the main functions of rock-climbing clothing are protection, comfort, fit, and mobility, with varying degrees of correlation to particular types of rock-climbing as presented in Table 2.1. A more detailed analysis of the functional aspects of rock-climbing clothing, drawn from the literature, is described below.

2.3. Functional Aspects of Rock-Climbing Clothing

The main functions of rock-climbing clothes identified are fit, mobility, protection, and comfort, as summarised in Table 2.1. Further details of these functions are presented in Figure 2.2. Some factors, such as the choice of different textile materials, are strongly influenced by functional requirements. However, factors such as fit and mobility are affected by ergonomic design. Ergonomic design refers to clothing design related to the topography of the body (Neves et al., 2015) and anthropometric characteristics in static and dynamic states to provide fit, mobility, comfort, enjoyment and satisfaction. Protection and comfort are mostly affected by functional design, which refers to clothing design that conforms to specifics needs of the user, e.g., protection, comfort, usability (Neves et al., 2015).

Figure 2.2

The essential functions of rock-climbing clothing



As the main focus of this project is the development of clothes with specific functionality for rock-climbing, the relevant factors are briefly defined and further considered here. This information informs the development process of rock-climbing clothing as functional garments by looking at fit, mobility, comfort, protection and climber expectations of rock-climbing clothing. Each aspect is a crucial and unique component of the overall performance of rock-climbing clothing (Michaelson et al., 2018).

Garment fit is not merely an objective measurebut a subjective characteristic influenced by various factors related to the wearer, including body shape, gender, size, age, lifestyle, ethnicity, and cultural influences (LaBat & DeLong, 1990; Michaelson, 2015). Perceived fit additionally depends on attributes such as range of motion and comfort (Das & Alagirusamy, 2010; Huck et al., 1997; Watkins & Dunne, 2015). A wearer's perception of fit is based on how well clothing conforms to the body. Ideally, the garment should hang smoothly, avoiding issues such as pulling, sagging, binding, twisting, or impeding the wearer's body while in motion (Boorady, 2011; LaBat & DeLong, 1990). Fit is particularly important in rock-climbing as excess fabric may bunch and snag on rocks or become entangled in ropes and harnesses, while a garment which is too tight will be uncomfortable in the extreme postures often employed in reaching hand and foot holds.

Mobility and body movement are intricately linked to fit in the evaluation of functional clothing. Functional clothing is engineered for a specific task or activity, as each type of functional clothing will have its own body movement requirements. Research has found that functional garments that are improperly designed or fitted can restrict movement, impair performance, negatively affect the level of wearer's protection, and potentially lead to bodily injury or/and pain (Michaelson, 2015). Horiba et al. (2020) investigated clothing mobility through the measurement of the motion-related deformation of garments to estimate the force applied to the human body based on the material properties of the clothing samples. The study employed a musculoskeletal simulator to predict clothing mobility. It highlights clothing mobility as an extremely important element in clothing design for rock climbing, where climbers will often contort their bodies into unusual postures in order to reach hand and foot holds.

In terms of **protection,** protective clothing encompasses various classifications and is constructed using diverse materials and technologies tailored to the specific type of protection required, such as for occupational, recreational, or everyday use (Gupta, 2011). The durability of such apparel must be assessed to ensure it provides sustained protection and meets consumer expectations. Key protection factors include abrasion resistance, seam and fabric strength, the impact of dyeing and finishing on fabric fibres, and the stretch effects on fabric integrity (Michaelson, 2015). To some extent, all apparel provides some degree of protection from the environment, however, functional clothing is designed to provide for the wearer a specific, often crucial, protective function for the wearer (Gupta, 2011). Protective apparel is intended to address occupational hazards, mitigate potential injuries, and reduce the risk of fatalities in both the workplace and sports contexts (Gupta, 2011). Rock climbing is a particularly dangerous sport, requiring high levels of protection to ensure safety. Clothing designed for rock-climbing should provide protection from the environment, weather, sharp rocks, sun burnt, and other hazards.

Comfort encompasses psychological, physiological, and physical sensations that arise from an individual's interaction with their external environment. This sense of comfort, or its absence, is influenced by subjective perceptions of the thermal environment as well as nonthermal factors, such as humidity, air movement, ease of movement, and both tactile and visual sensations (Tabor et al., 2020). Measuring comfort can be challenging due to its relative and subjective nature, meaning that it varies according to individual preferences and comfort levels. Participants may find it easier to explain discomfort than to evaluate comfort (Markee & Pedersen, 1991). A microclimate forms between the body and the garment, impacting overall wearer's comfort; however, it can also lead to discomfort if skin moisture becomes trapped between the skin and the clothing, particularly during intense physical activities (Michaelson, 2015). When comfort is optimized, the wearer is less distracted by their clothing and can perform tasks effectively without interference (Michaelson, 2015).

The physical comfort of a garment is influenced by factors such as the textile used, the fit of the garment, and the pressure it exerts on the body. Descriptions of physical comfort may include terms such as snug, light, loose, heavy, stiff, or soft (Das & Alagirusamy, 2010; Kamalha et al., 2013). The thickness of the textile and the surface roughness of the yarn, fibre, fabric, or finish can significantly impact the wearer's perception of comfort. Physical comfort is closely linked with physiological and psychological comfort, collectively shaping an individual's overall comfort experience (Das & Alagirusamy, 2010).

The psychological aspects of clothing comfort encompass tactile, sensory, and thermoregulatory responses (Das & Alagirusamy, 2010; Kamalha et al., 2013). Tactile sensation refers to the somatic experiences encountered when the skin contacts a fabric or garment, which is influenced by the specific and measurable characteristics of the fabric's surface and mechanical properties. These properties are largely determined by yarn type, fabric texture and construction, and chemical finishes (Tabor et al., 2020). Wearers may describe tactile sensations using terms such as smooth, prickly, stiff, itchy, scratchy or rough, reflecting how the fabric feels against their body (Kamalha et al., 2013). Thermoregulatory responses are characterised by sensations such as hot, chilly, damp, clingy, sticky, or wet, which relate to the body's thermal comfort (Das & Alagirusamy, 2010; Kamalha et al., 2013). These thermo-regulatory responses are frequently experienced by athletes and individuals engaged in intense physical activities, where trapped moisture between the skin and clothing can lead to discomfort (Das & Alagirusamy, 2010). Additionally, researchers studying sailing and military apparel also found that climate and exercise impact thermal balance and may lead to a threat for hypothermia, dehydration, and heat exhaustion (Michaelson, 2015).

Physiological comfort is closely related to the body's thermoregulation processes, which either generate or dissipate body heat (Das & Alagirusamy, 2010; Kamalha et al., 2013). The perception of physiological comfort is affected by various individual factors, including health, gender, age, and activity level. Outdoor apparel users have notable thermophysiological regulation requirements due to their physical exertion across diverse climatic conditions (Das & Alagirusamy, 2010). Thermophysiology is a field of research concerned with how the thermal environment impacts the functioning of the human body (Tabor et al., 2020). A thorough understanding of thermophysiology can facilitate the development of advanced technologies for environmental control, which are essential for human health and comfort (Tabor et al., 2020). The mechanism of heat transfer that is related to thermophysiological comfort and microclimate within the clothing layers is discussed in detail in section 2.4.

The information presented above in Table 2.1 and the subsequent analysis of functionality has been further considered across different stages of the research and has informed the ongoing development of the project in several areas. It informed the development of a questionnaire for rock climbers providing an understanding of the most dangerous types of rock-climbing which helped with establishing criteria to identify potential participants with experience in higher-risk climbing techniques. In addition, this analysis assisted in pattern making in terms of understanding and solving the problematic parts of clothes affected by equipment such as ropes and harnesses. For example, rock-climbing clothing should be based on optimal ergonomic and functional design, so decisions regarding the placement of pockets or additional protection from abrasion were in part informed by the findings of this review. The information gained by the current review also helped with garment design decision making in terms of the specification of textile materials that would provide additional functionality such as optimal durability and protection from external environmental factors.

2.4. Microclimate within the Clothing Layers

2.4.1. Indicators of Microclimate within Clothing Layers

To ensure the normal functioning of the thermoregulation mechanism and the associated sensations of thermophysiological comfort, a certain and stable microclimate within the clothing layers is required. Indicators of the microclimate inside clothing include air humidity, air temperature, air mobility, and carbon dioxide levels (Dell' et al., 1991). These microclimate indicators are used for the hygienic assessment of clothing, especially for the comparative assessment of clothing for various purposes, as well as for their design and composition, including protective clothing, winter wear, sports apparel, and others. The review relied extensively on research into the hygienic assessment of clothing which was originally published in Russian and subsequently had little influence outside Russia.

2.4.2. Humidity within Clothing Layers

In conditions of thermal comfort, the relative humidity of the air between the surface of the human body and the lower layer of clothing is typically 35–60%. Materials and clothing design should be combined to maintain this indicated humidity level within the clothing layers, regardless of environmental temperature and humidity levels, and the degree of skin sweating. During a hygienic assessment of different clothing options, the dynamics of humid air between the body's surface and the lower layer of clothing are characterised by the ability of the textile materials used within the clothing layers to remove moisture from this space (Ermakova, 2006).

In hot conditions, inadequate moisture removal can result in overheating of the body, while the accumulation of moisture within the clothing and on the skin (particularly in dusty environments) can lead to the mechanical irritation of the skin. In cold conditions, increased humidity between clothing and skin may suggest a mismatch between the heat-retaining properties of the clothing and its operating conditions or insufficient moisture conductivity of the clothing (Ermakova, 2006). In either scenario, the clothing becomes moistened, consequently diminishing its heat-retaining capabilities.

2.4.3. Carbon Dioxide within the Subclothing Space

A necessary condition for the normal functioning of the human body is the maintenance of normal levels of skin respiration whereby the metabolic products of human activity, including carbon dioxide, are continuously released into the subclothing space. Skin respiration significantly increases under conditions of high ambient air temperature (38–40°C) and during intense physical activity. The amount of carbon dioxide in the subclothing space is the most important criterion for the degree of contamination with products of skin respiration and the degree of ventilation of the subclothing space (Ermakova, 2006).

Within multi-layered clothing, which generally has lower total air permeability than each individual layer, the amount of carbon dioxide is higher than within single-layer clothing. Refer to Korotkova (2012), the amount of carbon dioxide released through the skin varies from 2 grams to 32 grams per day. With an increase in air temperature from 20°C to 38.4°C, the amount of carbon dioxide increases. Adults, while at work-rest regimens, emit 255 milligrams of carbon dioxide per hour on average in an air temperature of around 25°C. The amount of emitted carbon dioxide increases up to 365 milligrams per hour during routine low-energy work, and up to 945 milligrams per hour during higher levels of physical activity (Korotkova, 2012).

When the carbon dioxide amount in the air and inside clothing exceeds 0.7–0.8%, a person may experience discomfort. This is attributed to the fact that, at low concentrations, gaseous carbon dioxide exhibits minimal toxicological effects, whereas at higher concentrations, it can lead to an increased respiratory rate, cardiac arrhythmias, tachycardia, and impaired consciousness (Langford, 2005). Managing the potential toxicological effects caused by carbon dioxide requires designing and selecting materials for clothing that can effectively promote adequate ventilation within the subclothing space.

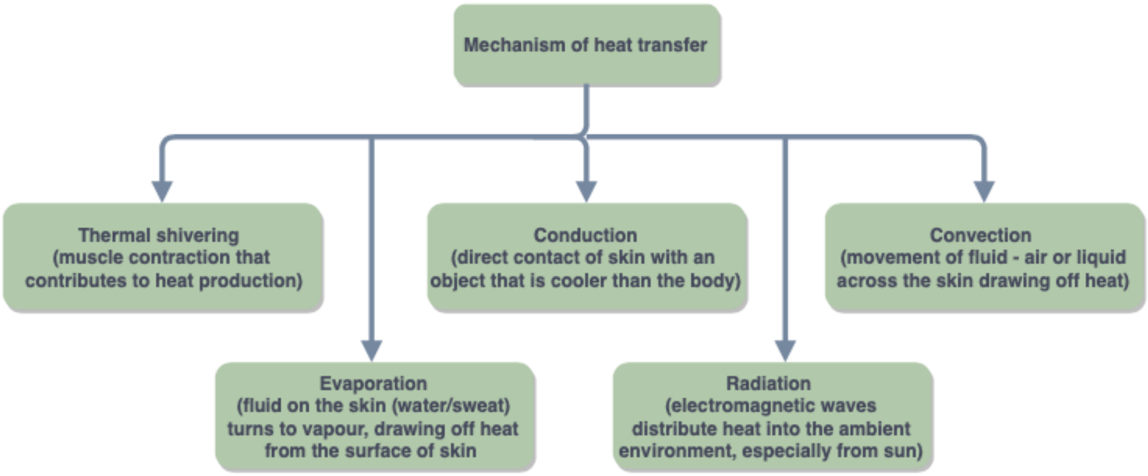
2.4.4. Temperature within the Clothing Layers and Mechanism of Heat Transfer

Humans are homeothermic organisms which needs to maintain a core temperature around 98,6°F (37,0°C) for optimal cellular metabolism (Seifert et al., 2017), although this value can fluctuate by 0.5 to 1 °C throughout the day due to circadian rhythms. Conversely, skin temperature should generally be maintained within the range of 33 to 34 °C to ensure comfort, although this temperature tends to decrease with increased physical activity (Tabor et al., 2020). For example, the average skin temperature decreased during cycling and running tests, with greater variability observed during running (Igarashi et al., 2022). In extremely cold environments, there is a persistent risk of hypothermia, a condition characterised by a dangerous reduction in core body temperature to below normal levels. Hypothermia occurs when the body's temperature drops below 98.6°F (35°C) (Anderson & Price, 1991; Axelrod & Diringer, 2008; Better health channel, n.d.; Brown et al., 2012).

The physiological system responsible for core temperature regulation comprises sensors, control centres, and effectors (Seifert et al., 2017). Thermoreceptors, primarily located in the skin and brain, detect temperature changes. The control centres, situated in the hypothalamus, process this information and regulate the response through effectors distributed across the extrapyramidal and autonomic nervous systems. Under steady-state conditions, the heat produced by cellular metabolism is balanced by heat loss through the skin and pulmonary ventilation, maintaining a core temperature of approximately 37 °C. As noted by Seifert et al. (2017), heat transfer is primarily influenced by the temperature gradient between the skin and the external environment. The exchange of heat between the skin, the core (internal organs), and the surrounding environment is closely related to the intensity of skin blood flow, which is regulated by vasodilation or vasoconstriction of the skin's blood circulation (Seifert et al., 2017). This process is controlled by the sympathetic nervous system. Figure 2.3 below summarises information on the mechanism of heat transfer from the skin based on the analysis of various sources (Anderson & Price, 1991; Better health channel, n.d.; Seifert et al., 2017).

Figure 2.3

Mechanism of heat transfer from the skin



In mountainous environments, exposure to extreme cold can significantly increase heat loss, exacerbated by direct contact with snow (conduction) and the influence of wind (convection) (Seifert et al., 2017). In response to such conditions, behavioural adaptations are crucial. These include employing specially designed clothing to enhance insulation by increasing the thickness of the outer layer and minimising exposure to strong winds (Seifert et al., 2017). Physiologically, the body responds to cold through skin vasoconstriction and shivering; however, these mechanisms alone may be insufficient for adequate protection against severe cold (Seifert et al., 2017). Additionally, thermoregulatory responses, such as shivering or sweating, are frequently observed during sports or other intensive physical activities. These responses can lead to moisture becoming trapped between the skin and clothing, resulting in discomfort for the wearer (Das & Alagirusamy, 2010; Ho et al., 2011).

When temperature control mechanisms are overwhelmed, two pathological conditions may arise: frostbite, which affects localised areas of the skin, and hypothermia, which impacts the body as a whole (Seifert et al., 2017). According to Seifert et al. (2017), preventing frostbite is critical and relies on adequate clothing and protection from wind and cold**.** When selecting appropriate clothing for rock-climbing, various factors, including the type of climbing, weather conditions, and the quantity and types of equipment used, would have to be considered**.** Clothing should be multi-layered as the air trapped between layers serves as an effective insulator. An internal layer facilitates sweat evaporation with minimal absorption, a middle layer provides insulation, and a removable external layer, which should be wind and water-resistant, allows for moisture evaporation. Protection for extremities such as toes, fingers, and ears is also essential (Seifert et al., 2017). Thus, a climbing clothing system basically consists of at least three layers: a base layer that contacts the skin directly, an insulating middle layer, and an outer shell layer (Mountaineers, 2003). The base layer is crucial for wicking moisture away from the skin to keep the wearer dry, the primary function of the insulating layer is to retain warm air close to the body, and the outermost layer shields against wind, rain, and sun (Mountaineers, 2003).

According to Wayatt (2005), layering is the key to suitable clothing for New Zealand's diverse weather. The author gives some recommendation in terms of type of clothing and layers suggesting that multiple thin items with zippers provide versatility. The outer layers of clothing should include a parka, pants, jersey or pullover, hats, glacier shirt, scarves and bandanas, gloves and mittens, gaiters, and climbing boots, while the inner layer may include thermal tops (polyester or fine wool tops with zips, turtlenecks, and long sleeve), thermal pants (long johns) for winter climbing (100-weight fleece for pants, tracksuit pants, and polypropylene or light wool pants) and socks (Wayatt, 2005).

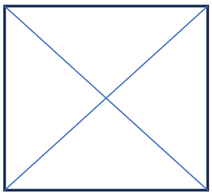
Each layer of clothing is characterised by thermal properties. These properties are largely determined by the thickness of the layers, including both the thickness of materials and of air layers. Thermal properties are primarily influenced by the presence of entrapped air within fibres and yarns or by the air contained in woven and knitted fabrics. The presence of air gaps or air layers in clothing composites, as well as larger gaps and air layers within the clothing itself, can have a significant impact on thermal properties (Rogale et al., 2023). The optimal thickness of all layers of the clothing can be ascertained according to a method which calculates the required thermal resistance of clothing by taking into account a human's energy consumption, the time of their stay in given meteorological conditions, ambient temperature, wind speed, and breathability of clothing (Afanas'eva et al., 2006; Dell' et al., 1991). This method is based on the equation of the body's heat balance, which is achieved by coordinating processes aimed at the formation of heat in the body (heat production) and its release (heat transfer). According to this method the combined thickness of all layers of materials forming the jacket (the main fabric, lining, and insulation) should be from 0.0033 to 0.005 meters depending on the temperature, which varies from 0 °C to -15 °C. This ensures that the jacket provides the necessary thermal properties and wind resistance (see Appendix B). This combination of materials is ideal to maintain optimal body temperature levels during ascent, offering a lightweight, comfortable, and unrestricted movement experience for climbers.

Thermoregulation is a critical consideration in the development of active sports clothing. Thus, Di Domenico et al. (2022) have evaluated the impact of sports clothing on comfort, thermoregulation, and performance during exercise through prolonged protocols characterised by short-to-moderate durations, light-to-moderate intensities, and mild environmental conditions. Based on their findings, they provided recommendations for exercise testing protocols to accurately examine the effects of sports clothing on athletic populations during physical activity in hot conditions (Di Domenico et al., 2022).

During rock-climbing, the climber's body temperature can fluctuate considerably, particularly in high mountainous environments characterised by snowy climates. Furthermore, temperatures along a climbing route can vary markedly. Variations in activity levels during climbing may result in periods of warmth during climbing and cold during rest or belaying. However, wearing multiple layers to maintain warmth proves inconvenient in a sport that demands precise movements. Although layering is recommended to adapt to varying weather conditions, it can introduce bulk and potentially impede movement (Cloud et al., 2013). Additionally, the multitude of layers do not regulate temperature in themselves, only in combination with each other. Climbers have taken a multi-layer approach to clothing in order to regulate the microclimate inside clothing layers by putting on or removing additional layers of clothing and stowing them while rock-climbing. This process is not always convenient and can impact safety (see Figure 2.4).

Click or tap here to enter text.**Figure 2.4**

The process of putting on the rain jacket while climbing



Note. From "GORE-TEX. The new Ladakh GTX Waterproof Jacket" (https://www.facebook.com/rab.equipment/videos/670960866725914/). Copyright 2019 by GORE-TEX®.

Some manufacturers address this issue by using armpit zip vents to avoid overheating, because the waterproof synthetic (nylon) fabrics, that are usually used as an outer layer in jacket, cannot provide enough breathability (see section 4.2. "Clothing Analysis"). However, this issue can also be addressed by the use of new generation textile materials and new technologies. Recent developments in advanced textiles for personal thermal management and their implications for energy efficiency were studied by Peng and Cui (2020). The authors provided a comprehensive review of recent research on these advanced textiles, classifying them according to their operational mechanisms. By analysing the pathways of human body heat dissipation, they demonstrated how passive textiles regulate thermal radiation and conduction properties to facilitate both warming and cooling (Peng & Cui, 2020). Advanced textiles offer promising solutions for enhancing thermal comfort and offer new perspectives into ways of achieving energy savings.

Additional functionalities may be provided by new developments in more traditional textile materials. For example, Armadillo Merino® is used to produce an advanced protective next-to-skin garment for tactical operators and professionals operating in high-risk environments (Armadillo, n.d.). This clothing provides superior thermoregulation, moisture management, natural UV protection against the sun's harmful rays, absorption of sweat, and natural flame resistance (Hamish, 2017). Textile materials with such characteristics could be used in the inner layer of rock-climbing clothes to provide additional comfort. Creating and implementing clothing made of such materials might mitigate the potential negative social and environmental impacts, enhancing the sustainability of the garment.

Another example of a new generation material that enhances comfort in extreme weather conditions is waterproof breathable fabrics, such as membrane fabrics. The membrane fabric would be suitable to be used for an outer layer of rock-climbing clothes to protect the wearer from wind and water, be it rain or snow, while also being breathable. Membrane fabrics consist of thin polymer films. In general, there are two types of membranes: hydrophilic membranes and microporous membranes, which are hydrophobic (Camotrek, 2020). The key feature of these materials is their one-way transfer capability as they prevent moisture from penetrating the lower layers of clothing while allowing sweat to escape and ensuring the skin remains dry. This functionality supports microcirculation and maintains appropriate moisture levels and temperature, all while being nearly impervious to atmospheric moisture. Furthermore, the integration of advanced insulating materials can ensure consistent warmth and optimal breathability during physical activity. For instance, the Alpha® insulation system, developed for the U.S. Special Forces, addresses the need for advanced thermal regulation in uniforms during dynamic combat scenarios (Polartec®, n.d.). By incorporating patented low-density fibres between air-permeable woven layers, Polartec created a fabric that enhances warmth regulation and moisture transfer. This innovation improves thermal adaptability across varying conditions and activity phases, enabling sustained comfort without the need to shed layers.

Moreover, GOREWEAR has also developed a new GORE-TEX fabric free from per- and polyfluorinated compounds (PFCs) by utilising an expanded polyethylene (ePE) membrane instead. This innovative fabric features a reduced carbon footprint, lower environmental and human toxicity impact, and improved performance tailored for endurance activities (Henkel, 2023). A three-layer jacket, designed for runners seeking unrestricted movement along with effective waterproofing and windproofing, the ePE membrane fabric is not only durably waterproof, windproof, and breathable but also boasts an improved strength-to-weight ratio. This enhancement reduces the material required, positively impacting resource efficiency and the jacket's overall weight, while maintaining durability comparable to other available options (Henkel, 2023).

PFCs, also known as PFAS (perfluoroalkyl and polyfluoroalkyl substances), constitute a broad category of thousands human-made synthetic chemical pollutants that can persist in both the human body and the environment (eBioMedicine, 2023; National Institute of Environmental Health Sciences, n.d.). These substances are renowned for their water and oil repellent properties, which render them valuable for industrial applications, for example, firefighting foams and consumer products (e.g., water-resistant clothing, food containers, and non-stick cooking utensils) (eBioMedicine, 2023). However, PFAS have been identified as persistent, bio-accumulative and toxic (NIKWAX Outdoor Innovation, n.d.). Increasing concerns about the health and environmental impacts of PFCs have led governments globally to regulate or ban these chemicals. For instance, the European Union (EU) is advancing toward restricting specific PFCs in consumer products, including textiles, under the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation (Takanori, 2024). The exploration of environmentally friendly alternatives to PFCs has driven substantial innovations in textile technology, reflecting a broader movement towards sustainability.

To summarise, for types of climbing that are influenced by environmental factors and cold, wet, and windy weather conditions (for example, alpine climbing, ice climbing, mountaineering, etc.) suitable clothing is a fundamental factor to protect climbers and to provide both psychological and physiological comfort. The development of protective rock-climbing clothing that is functional, ergonomic, and smart in terms of thermoregulation is the main target of this project. A significant issue identified in this review and to be addressed in this research project is the design of rock-climbing clothing that does not involve multiple layers or bulky garments. This study was motivated by the necessity to address this issue to developing a conceptual solution for temperature regulation within a rock-climbing jacket. During the specification of materials for such a garment (discussed in Chapter 5, section 5.4.) and the integration of smart components (addressed in Chapter 6), it was recognised there should be a focus on combining traditional textile materials and smart textiles, with their characterisation determined by the provision of performance and functionality. The review of literature pertaining to microclimate within clothing layers and human heat transfer mechanisms presented in this section provided insights into optimal body temperature levels and other parameters critical for the normal functioning of the thermoregulation mechanism and the associated sensations of thermophysiological comfort.

2.5. Standards and Requirements in Rock-climbing

Another focus of the literature review has been to identify existing standards and requirements associated with rock-climbing. The main purpose in doing this was to find information about clothing and textiles' regulation for rock-climbing apparel, available information about requirements for pattern making parameters, and specifications of textile materials. An analysis of standards and requirements in rock-climbing identified a lack of published standards and requirements for the apparel needs of rock climbers. Currently, only standards for climbing equipment safety and reliability are available. The development of standards for smart wearable technologies were also reviewed to inform the design of smart, ergonomic/functional climbing clothing. Information about existing standards, particularly regarding smart textiles and heating in smart textiles is described in chapter 7 (section 7.7). It was also important to identify standards that regulate the size and measurements of rock-climbing equipment such as a helmet, in order to design a hood, a harness to design the pockets, and rope positions to assess the optimal places for the positioning and integration of sensors.

European Standards (EN) are implemented by one of three European Standards Organizations (ESOs)—CEN, CENELEC, or ETSI (Bright, 2014). The database of the European Committee for Standardization (CEN) involves 45 standards and all of them relate to equipment and safety. All standards from CEN and the International Climbing and Mountaineering Federation are based on research of the human body and subsequent survivable loading magnitudes for equipment.

Most climbing hardware is regulated under the European Personal Protective Equipment Directive (PPE), which applies to equipment designed to protect individuals from falls from heights. To market a PPE item in Europe, manufacturers must have their equipment tested and quality control processes verified by an independent “Approved Body” (Worksafe, 2020). Upon successful testing and verification, the equipment receives the CE mark, allowing it to be sold.

Another set of safety standards includes the Mountaineering Equipment Standards established by the International Climbing and Mountaineering Federation (UIAA), which are recognised as the leading international standards for climbing and mountaineering. These standards encompass over 25 types of safety equipment, such as harnesses, helmets, and crampons (UIAA, 2024). The UIAA works in collaboration with the CEN to harmonise these standards. In certain instances, the UIAA may require additional tests, thereby imposing stricter criteria than those set by CEN. Consequently, UIAA standards may exhibit slight differences from CEN standards. The UIAA recommends that climbers and mountaineers worldwide utilise equipment that meets these standards. Equipment that successfully conforms to UIAA standards is awarded a UIAA safety label, a distinguished symbol indicating adherence to the highest international safety standards for mountaineering and climbing equipment (UIAA, 2024).

The Association for Challenge Course Technology (ACCT) is an international trade association and an accredited standards developer under the American National Standards Institute (ANSI) for the global challenge course, canopy tour, aerial adventure park, and zip line sectors. The main standard issued by the ACCT is the ANSI/ACCT 03-2019, which addresses challenge courses and canopy tours (ACCT. Association for Challenge Course Technology, n.d.).

This standard encompasses guidelines for the design, inspection, and performance as well as training and operational standards.

Despite extensive online searches, no standards or requirements associated with clothing and textiles for rock-climbing apparel, requirements for pattern making parameters of such clothing, nor any standards for smart wearable technologies to inform the design of smart, ergonomic and functional climbing clothing could be identified. Instead, the focus shifted to collating the standards that have been established for rock-climbing equipment.

The first task was to identify standards that regulate the size and measurements of a helmet for the development design and pattern making of a hood for a rock-climbing jacket. Wearing helmets is one of several risk mitigation strategies utilized by rock climbers. Helmets are employed to safeguard the skull from falling debris, such as rocks encountered in alpine climbing or dropped equipment, as well as to absorb impact forces to the head during a fall while climbing. This protection is particularly crucial in scenarios where the lead climber may be flipped over during a fall and therefore is likely to hit the ground head-first (Linxweiler & Maude, 2017; Soleil, 2012). Helmets are utilised inconsistently across many styles of rock-climbing such as sport lead, top-rope, traditional lead and belay, etc. (Soleil, 2012). The typical safety helmet with some climbing-style features may include a short brim, chin strap, and lower profile (HexArmor, 2022). In order to design and make a pattern involving a hood, it is necessary to know the size of helmet in order to develop a hood. Analysis of current standards shows that there are currently no U.S. standards that talk about climbing style or at-height helmets. There is, however, a European mountaineering helmet standard, EN12492:2012 (CEN, 2012), which accounts for the risk of swinging and repeated all-round impact and requires safety helmets to meet several rigorous tests. This standard, as well as UIAA 106 (UIAA, 2018), which is based on EN12492:2012, does not include any information regarding the size or style characteristics of helmet for rock-climbing.

The next set of standards considered were related to harnesses. Standard EN 12277: 2016 + A1: 2019 (CEN, 2019) proposes that "a harness is an assembly of narrow textile fabric(s) (hereafter referred to as a tape), adjusting device(s) and/or other elements which fit around the body to support it in a hanging position after a fall" (p.5). Two distinct categories of standards for harnesses cover climbing harnesses and those specifically made for height safety (Aspiring Safety, n.d.). Globally, there are only two recognised standards for climbing harnesses: the European standard (EN 12277) and the UIAA standard. The UIAA standard is derived from the European standard but includes certain variations. It applies to a range of harness types, including full-body harnesses, sit harnesses, small-body harnesses, and chest harnesses. According to EN 12277, all harnesses must adhere to the following requirements:

- Load transmitting parts must have a minimum width requirement depending on type and body location: from 28 mm for sit harnesses, and 23 mm for the shoulder straps.

- All have to have contrasting colours or surface appearance to tape.
- No burrs or sharp edges are to be on components or textiles.

The other harness standards cover mostly focus on height safety. There is a joint standard between Australia and New Zealand, AS/NZS 1891.1 in the height safety field (AS/NZS, 2020; Aspiring Safety, n.d.). Additionally, there are four European standards, EN 354 (Lanyards), EN 361 (Fall-arrest), EN 358 (Work-positioning), and EN 364 (Testing), which are collectively equivalent to the Australian and New Zealand standard AS/NZS 1891.1. As a result, harnesses constructed according to the AS/NZS 1891.1 standard are considered to meet a significantly higher level of quality than those adhering to European standards (Aspiring Safety, n.d.). It is important to note that all these standards do not address considerations related to the type of clothing worn during rock-climbing.

Overall, standards related to rock-climbing cover issues such as the safety and reliability of climbing-specific gear, design, definitions of terminology, performance and inspection standards, and training standards. There are no standards or requirements for the apparel needs of rock climbers, including smart wearable technology for climbing. Due to these gaps, there is potential for the development of requirements and practical recommendations in terms of the design of ergonomic and functional rock-climbing clothing with the integration of smart sensing technologies into textiles. In its quest to design a functional ergonomic rock-climbing apparel, this project explores a variety of aspects such as climbers' perspectives on their needs, preferences, and expectations of their clothing as well as assessments of the designed garments' sports specificity, the performance of the new textile materials used, and the innovative technologies used as part of the production process. Outdoor apparel manufacturers could improve their clothing designs for climbing by integrating this research's results.

2.6. Smart Clothing and E-textiles

Smart clothing is an emergent interdisciplinary field (Ismar et al., 2020) that unites experts from design, information technology, microsystems, materials science, and textiles. This field integrates research in textile materials, wireless sensor technology, and actuator networks to monitor the human body, combining these technologies with statistical methods for data analysis and interpretation to offer diverse functionalities (Borges et al., 2008). Currently, smart clothing and electronic textiles are among the most rapidly evolving and heavily invested areas in modern clothing technology (Lepak-Kuc et al., 2019).

There is a growing trend towards smart wearable fabrics in the healthcare, sports, and fitness industries, driven by the comfort of these types of textile materials and the potential for integrating smart functionality into such garments (Yang et al., 2024). Electrically driven smart textiles (e-textiles) have garnered significant attention for their potential applications in rehabilitation, health monitoring, and training assessment. Interactive textiles, which incorporate electronic devices and algorithms, can collect, process, and digitise data on human body movement in real-time (Meena et al., 2023). Moreover, smart textiles are increasingly being applied in protective applications within military and defence sectors, as well as for personal protection use (Chapman, 2013; Zaman et al., 2021). Naturally, e-textiles have also found applications in the fashion industry. The global smart clothing market was valued at USD 1,143.09 million in 2019 and is projected to reach USD 6,418.08 million by 2027, with an estimated compound annual growth rate (CAGR) of 24.4% from 2020 to 2027 (Research and Markets, 2021). The following review explores e-textiles used in sports and other garments, along with an analysis of smart heated clothing.

2.6.1. E-textiles for Sport and Other Applications

Smart textiles refer to textile that can interact with their environment by receiving input and providing output based on their specific applications (Asadi, 2022). A broad range of wearable technologies has been created for (or utilised) in sports and consumer fitness applications, applicable to both recreational and elite levels (Yang et al., 2024). Wearable sensors offer valuable data on vital bio-signals and key performance metrics, such as speed, acceleration, and distance, which can enhance training effectiveness and reduce injury risks. According to Yang et al. (2024), e-textiles serve as an ideal platform for the ubiquitous integration of wearable technologies due to their soft and comfortable nature, as well as the suitability of the textiles for everyday wear. Different techniques and applications exhibit varying levels of integration. Thus, some smart textiles involve the addition of modular sensors or electronic units (e.g., IMUs, GPS) directly into pockets of the garment to embedding sensing materials within the textile itself, thereby creating sensing textiles (e.g., ECG/EMG electrodes, force or pressure sensing fabrics). Such textiles are typically connected to detachable electronic units (Yang et al., 2024).

Electrically driven smart textiles are produced using a range of methods and materials incorporated with textiles substances (Asadi, 2022). An example includes the manufacturing techniques employed in e-textiles using electrically conductive materials (ECMs) for integrating electronics into textiles. Three primary ECM types are frequently utilised in e-textiles:

- Electrically conductive yarns or threads: These are integrated into textiles in place of passive yarns during knitting, weaving, sewing, or embroidery processes (Komolafe et al., 2021).
- Electrically conductive films: Produced through printing and weaving methods, these films are used for creating large-area planar circuits (> 100 cm^2) or for concealing and localizing circuits within small fabric spaces (< 10 cm^2) (Komolafe, 2016).
- Narrow electronic filaments: These filaments, with widths of less than 5 mm, are at the forefront of technology for integrating electronic functionality into textile yarns and garments, achieved through conventional knitting and weaving processes (Komolafe et al., 2021).

Coating non-conductive yarns with galvanic substances, metals, or metallic salts is another method for creating electrically conductive yarns from pure textile threads, thus facilitating the production of e-textiles (Gonçalves et al., 2018). Alternatively, conductive lines can be embedded into textiles through the stamping of conductive inks. Various technologies are available for printing conductive materials onto textile substrates; all of these techniques utilise conductive inks containing high-conductivity metals such as copper (Cu), silver (Ag), and gold (Au) (Gonçalves et al., 2018).

Carbon-based conductive materials, such as graphene, graphite powder, carbon black and carbon nanotubes, are generally attached to the surface of ordinary fibres in the form of nanoparticles to form conductive fibres, which has a wide range of sources (Fang et al., 2022). The invention of graphene and carbon nanotubes (CNTs) in particular has effectively improved their conductive properties (Fang et al., 2022). The primary distinction between graphene and carbon fibre lies in their thicknesses: graphene consists of a single layer of carbon atoms, while carbon fibre has a thickness on the micrometer scale (Madhu, 2018).

Graphene. Graphene is a two-dimensional carbon nanomaterial characterized by a hexagonal honeycomb lattice of carbon atoms arranged in sp^2 hybridized orbitals (Fang et al., 2022). This material can be incorporated into polymers or textile materials as fibres, allowing for a range of applications. Consequently, additional elements can be immobilised or doped onto graphene nanosheets to enhance its functionality for various applications, including electrocatalytic and catalytic systems (Asadi, 2022). Graphene exhibits exceptional electrical, optical, and mechanical properties, making it a highly conductive material (Fang et al., 2022). Additionally, it is highly efficient in conducting heat and electricity and is nearly transparent. Finally, graphene displays diamagnetic properties and features a two-dimensional structure characterized by strong covalent bonds and a planar arrangement (Fang et al., 2022; Madhu, 2018), which significantly enhances the mechanical strength of fibres (Fang et al., 2022).

Graphene-integrated textile materials have been applied in different studies (Asadi, 2022; Fang et al., 2022; Kim et al., 2019; Shathi et al., 2020; Tian et al., 2019; Wang et al., 2017; Yang et al., 2024). For instance, graphene-based textile electrodes that are highly conductive, washable, flexible, and breathable have been manufactured using a pad-dry-cure method to develop a sports bra designed for human health monitoring (Shathi et al., 2020). The results indicate a significant improvement in the electrical conductivity of the graphene-coated textile electrodes, with resistance reduced from 3.5 MΩ to 400 ± 5.0 kΩ after 12 padding passes. These wearable textile electrodes have proven effective for measuring electrocardiograms, pulse rate, and pressure responses under various conditions (Shathi et al., 2020).

One example of the effectiveness of graphene's electronic conductivity was provided by Tian et al. (2019), who applied graphene/polyurethane (PU) composite ink to spray cotton woven fabric in order to develop graphene-based fabric Joule heaters. The resulting fabrics exhibited a bilayer structure, consisting of an inner graphene/polyurethane layer and an outer graphene oxide layer. The fabric sprayed with five layers of graphene oxide/PU had the most significant Joule heating performance. At the applied voltage of 12V, the maximum equilibrium temperature could be up to 162.6°C with the highest heating rate of 8.4°C/s (Tian et al., 2019).

Carbon fibre. Carbon fibre is a high-strength and high-modulus fibre consisting of more than 90% carbon content that has mostly carbon atoms arranged in a hexagonal pattern (Fang et al., 2022; Madhu, 2018). These fibres typically have diameters ranging from 5 to 10 micrometers. Carbon nanotubes (CNTs), on the other hand, are one-dimensional nanomaterials known for their lightweight nature and strong, hexagonally structured carbon connections, as well as excellent mechanical, electrical, and chemical properties (Fang et al., 2022). Currently, carbon fibre is utilised as a raw material in commercial electro-heated garments such as heated underwear or jackets. For instance, Ilanchezhiyan et al. (2015) developed a highly efficient, flexible electrothermal heater using cotton fabrics functionalised with highly conductive carbon nanotubes. The conductive cotton fabric was prepared by dip-coating it with CNTs, using single-walled carbon nanotubes as dispersants to integrate CNTs with the cotton fabric. This integration increased the number of conductive paths on the fabric surface, thereby improving its conductivity. The fabric could achieve a temperature of 96°C when an applied voltage of 40V was used (Ilanchezhiyan et al., 2015).

The development of Organic Nanocarbon ink by blending organic materials with CNTs was also explored (Arbab et al., 2019). This ink was used to create printable composites using woven and nonwoven fabrics, serving as flexible and wearable heating systems and cathodes for dye-sensitised solar cells, respectively. The proposed ink was found to facilitate electron transport pathways, resulting in enhanced heat dissipation due to its high conductivity and electrocatalytic activity. This innovation paves the way for the development of solution-printable, high-performance thermoelectric and conductive materials, both woven and nonwoven, for use in wearable electronics. Sadi et al. (2019) developed the CNT ink which could be printed directly on the cotton fabric. They achieved a straightforward yet effective method of producing multifunctional wearable cotton fabrics through screen printing of CNT ink on one side of weft-knitted cotton fabrics. Such CNT/Cotton Composite fabric exhibited excellent electrothermal performance with the potential to be used as an electric heater (Sadi et al., 2019).

While carbon-based conductive materials can be part of a heating element system, certain factors prevent the use of materials containing carbon nanotubes (CNTs) in research projects like this one. The primary reason is their high cost, attributed to the advanced manufacturing techniques and specialised equipment required for their production and integration into textile materials (Kubley et al., 2021). Moreover, accessibility to such materials remains a challenge. Additionally, there are significant sustainability concerns surround the manufacturing processes of CNTs, which typically involve energy-intensive methods and the use of hazardous chemicals

(Fang et al., 2022). These processes contribute to carbon emissions and environmental pollution, highlighting sustainability challenges. However, there are alternative textile-based heating systems. These can be classified into two main categories: polymer-based and metal-based textile heaters (Bahadir & Sahin, 2018). Metal-based textile heaters incorporate metals to generate heat, whereas polymer-based textile heaters utilise polymer materials as heating elements. The primary objective of these textile-based heating systems is to deliver requested warmth to the user in cooler environments. Integrating wearable electronics into such heating systems enhances the functionality of the end product, aligning with the primary goal of this project. The findings from this review are relevant to the design of a heating element system for the garment developed as part of this project. The final design for the heating elements to be incorporated into the smart heating system is detailed in Chapter 6.

2.6.2. Smart Heated Clothing

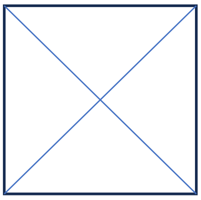
While there are growing numbers of smart wearable applications in the healthcare and high-performance sport sectors (Lee & Baek, 2021), there has been limited development in the area of rock-climbing. To date, most wearables for climbing have primarily been developed as activity trackers, focusing on tracking movements and evaluating climbers' performance during indoor gym workouts, with data visualisation provided after the ascent (Mencarini et al., 2019). For example, Ladha et al. (2013) provided a detail account of the development and assessment of ClimbAX, a wristband designed to measure a climber's power, stability, control, and speed, and Mencarini et al. (2019) created and tested a vibrotactile wearable device intended to enhance communication between instructors and trainees. This device was evaluated for its usability, usefulness, and comfort during indoor climbing observation sessions. The prototype aimed to support climbers in learning proper climbing techniques while providing reassurance through the instructor's attentive presence. The device consisted of eight vibrating devices that were placed on the climber and controlled via a tablet by the instructor.

While several heated clothing products have come on the market over the past five years as commercial products, access to more detailed technical information and user testing responses is limited. For the purposes of this review, existing commercial products with related characteristics were identified and available documentation was reviewed, along with an analysis of their construction. Among the most interesting projects in terms of regulating temperature are the Mercury Jacket (Hitti, 2018; Priday, 2018), the Gamma Jacket (Gamma Jacket, 2023), Ororo Men's Heated Jacket (Becker, 2018; ORORO Heated Apparel, n.d.), the Gobi Heat Shift Snowboard Jacket (Becker, 2018; GOBI Heat, n.d.) and the Milwaukee model of a heated jacket (Milwaukee, n.d.). The following sections describe these jackets in terms of the materials used, their thermoregulation functionality, and the production processes involved in their manufacture.

The Mercury Jacket. The Boston-based start-up Ministry of Supply developed the Mercury, a self-heating smart jacket designed to adapt to temperature changes and create a personalised "microclimate" for its wearer (see Figure 2.5). Addressing the challenge of dressing for transitional weather conditions, this technologically advanced jacket utilises three thin carbon fibre heating pads to provide warmth automatically through a resistive heating process (Hitti, 2018)**.** The jacket is equipped with sensors to monitor the external temperature, and the wearer's body temperature. It also features an accelerometer to track movement. A microcontroller processes the information collected by both sensors to determine the optimal garment temperature and regulate the power supplied to the heating pads (Hitti, 2018; Priday, 2018).

Figure 2.5 (Image removed due to copyright restrictions)

The Mercury jacket



Note. From "Self-heating jacket responds to changes in temperature", (https://www.dezeen.com/2018/02/28/ministry-of-supply-self-heating-smart-jacket-responds-temperature-changes-technology/) (left) and from "The Alexa-powered Mercury jacket can heat itself and listens to your voice commands", (https://www.wired.com/story/ministry-of-supply-kickstarter-mercury-jacket-self-heating/) (right). Copyright 2018 by N. Hitti and by 2018 R. Priday relatively.

The jacket reaches temperatures of up to 57 degrees Celsius within approximately 90 seconds. Additionally, it features two zipped hand-warming pockets and an integrated wireless charging phone sleeve, enabling users to charge their devices while on the move. The outer shell of the jacket is made from fabric with waterproof feature and includes a detachable hood**.** A gilet (west) version is also offered. Notably, the Mercury jacket incorporates voice-control functionality through Amazon's Alexa, enabling users to preheat the garment before wearing it (Hitti, 2018). Furthermore, users can customise their preferences via a dedicated application, which employs artificial intelligence to learn and predict their preferences over time. According to the manufacturer, Mercury's design represents a novel approach as it uses data to continually adjust and improve its performance. However, a limitation for backers outside the US, such as those in the UK, is that they will not receive the 10,000mAh battery that is provided by default to American customers due to shipping constraints (Priday, 2018). This case underscores the challenges associated with the development, commercialisation, and standardisation of smart clothing. Issues related to the supply chain and the availability of suitable components for smart textiles will be discussed further in Chapter 7.

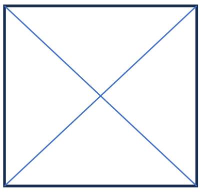
GAMMA: The All-Season 100% Graphene Infused Heated Jacket. The second innovative jacket relevant for this study is the Gamma Jacket – a 100% graphene-infused, thermoregulating, waterproof and UV blocking high-tech jacket with a multifunctional 10-

pockets system for everyday use (see Figure 2.6) that was developed by Gamma Jacket, a Hong Kong-based team (Gamma Jacket, 2023; Gamma Jacket: Wear Graphene, n.d.).

This jacket is lightweight, waterproof, breathable, and durable. It has a smart customisable built-in-heating, uniform heat distribution as well as a antimicrobial and anti-odor graphene powered layer. While this jacket is developed for men and women, there are only difference in the size chart and fit, and no differences in the design and pattern construction or other important features such as the weight of the jacket.

Figure 2.6 (Image removed due to copyright restrictions)

The Gamma jacket

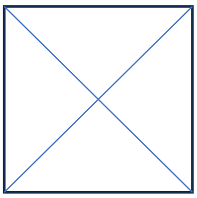


Note. From "Gamma jacket: The first Jacket for year-round, all-climate control," (https://www.kickstarter.com/projects/weargraphene/gamma-all-season-graphene-infused-heated-jacket). Copyright 2021by Gamma Jacket.

Graphene is a nanomaterial with a lattice structure that is only one atom thick, making it the strongest and most flexible material known (see Figure 2.7). By incorporating a graphene layer into the Gamma Jacket, developers have created a versatile outerwear solution. The Gamma Jacket serves multiple functions: it operates as a winter jacket, a windbreaker, a cool-weather jacket, a rain jacket, and activewear simultaneously. According to product publicity, the Gamma Jacket represents a significant advancement in modern sustainability and style for graphene-integrated apparel (Gamma Jacket, 2023).

Figure 2.7 (Image removed due to copyright restrictions)

Comparison traditional synthetic insulation with Gamma Graphene insulation



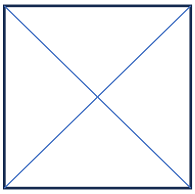
Note. From "Gamma jacket: The first Jacket for year-round, all-climate control," (https://www.kickstarter.com/projects/weargraphene/gamma-all-season-graphene-infused-heated-jacket). Copyright 2021by Gamma Jacket.

Graphene's thermal properties are considered revolutionary functioning almost like a second skin as it adapts to the human body. Its lattice structure enables efficient heat transfer, distributing warmth uniformly across the body (see section 2.6.1. for a more detailed description). In warm conditions, graphene expels heat and wicks away moisture to keep the wearer cool.

Conversely, in colder environments, graphene helps retain and evenly distribute heat across the upper body. The Gamma Jacket leverages this property by incorporating built-in heaters that channel heat through the jacket as illustrated in Figure 2.8. It features three carbon fibre heating elements with adjustable temperature settings which can be easily cycled with the press of a button to combat various levels of cold. Additionally, the Gamma Jacket's heaters are powered by any standard power bank (Gamma Jacket, 2023).

Figure 2.8 (Image removed due to copyright restrictions)

Positions of the heating elements throughout Gamma jacket



Note. From "Gamma jacket: The first Jacket for year-round, all-climate control," (https://www.kickstarter.com/projects/weargraphene/gamma-all-season-graphene-infused-heated-jacket). Copyright 2021 by Gamma Jacket.

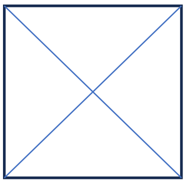
The Ororo Men's Heated Jacket. One jacket that was designed for outdoor enthusiasts, featuring a wind and water-resistant outer shell (93.5% Polyester, 6.5% Spandex), soft fleece lining (100% Polyester), and a sporty look is Ororo men's heated jacket, depictured in Figure 2.9 (Becker, 2018; ORORO Heated Apparel, n.d.). On the ORORO Heated Apparel website (n.d.), the description of the jackets mentions that it has a raglan sleeve design for unrestricted movement and a flattering shoulder line as well as a detachable hood for extra protection on windy days. The jacket is equipped with heating elements, which feature three adjustable temperature settings, strategically positioned in the chest and back areas to deliver optimal warmth to the wearer's core (see Figure 2.9). The heating system includes:

- Three carbon fibre heating elements: These elements generate heat across core body areas, including the upper back and the left and right chest.
- Three adjustable heating settings: Users can easily switch between high, medium, and low settings with a single button press.
- Up to 10 hours of operational time: The jacket provides approximately 3 hours on high, 6 hours on medium, and up to 10 hours on the low heating setting.
- Rapid heating: Equipped with a 4800 mAh, 7.4V UL/CE-certified battery, the jacket heats up quickly within seconds.
- USB port: Includes a USB port for charging smartphones and other mobile devices.

The manufacturer states that this heating system is machine washable and gives 3-year limited warranty on heating elements.

Figure 2.9 (Image removed due to copyright restrictions)

The ORORO Heated Jacket

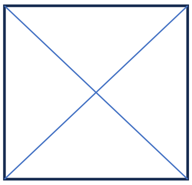


Note. From "Men's Heated Jacket in Black & Gold", (https://www.ororowear.com/products/ororo-sports-heated-jacket-black-gold?variant=41759098044598). Copyright 2023 by ORORO Heated Apparel.

The Gobi Heat Shift Snowboard Jacket. Another heated jacket that was designed for outdoor activities is the Shift Mens Heated Snowboard Jacket (see Figure 2.10). This jacket was built specifically with snowboarders in mind by Gobi Heat (formerly Dragon Heatwear) (Becker, 2018; GOBI Heat, n.d.). As a result, the jacket offers several distinctive features not commonly found in other heated jackets. These include pit zips for venting excess warmth, a hood designed to be compatible with helmets, and an integrated snow skirt to prevent snow from entering the interior. Additionally, the Shift jacket incorporates five independent heat zones—one on the back and four on the front—to provide enhanced coverage. The included battery pack is reported to provide up to nine hours of usage on a single charge and features adjustable temperature settings of low, medium (up to 6.5 hours), and high (up to 5 hours).

Figure 2.10 (Image removed due to copyright restrictions)

The Gobi Heat Shift Snowboard Jacket



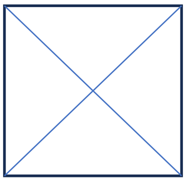
Note. From "Shift Mens Heated Snowboard Jacket", (https://gobiheat.com/products/shift-mens-5-zone-heated-snowboard-jacket). Copyright (n.d.) by GOBI Heat.

The M12™ TOUGHSHELL™ Heated Jacket. This heated jacket model, made by Milwaukee, features heating elements strategically placed across the chest, back, and front pockets (see Figure 2.11). It utilises an advanced system of heat technology that integrates durable and lightweight carbon fibre heating elements, enhanced fabric construction, and optimised interior liners. This system allows the jacket to provide heat for up to 8 hours of runtime when paired with the M12™ REDLITHIUM™ 3.0Ah Battery Pack (Milwaukee, n.d.). A notable aspect of the jacket is its compatibility with an adapter for Milwaukee batteries, which are typically used for powering tools such as drills, facilitating easy integration for existing Milwaukee users.

The jacket includes a button with an embedded LED controller, located below the Milwaukee logo. This button allows users to adjust the heating settings for each zone (High, Medium, Low), with the LED light indicating the selected setting. Additionally, the jacket features a unique battery pocket pass-through design, accommodating battery placement in either the front or back pockets. The product also comes with an M12™ Compact Charger & Power Source [M12TC-0]. The design constructive features that a manufacturer developed are FREEFLEX mobility gussets that allow for enhanced movement, adjustable cuffs and waist with drop tail extended back, dropped shoulder seam and under arm gussets for improved flexibility. The jacket is washer and dryer safe (Milwaukee, n.d.).

Figure 2.11 (Image removed due to copyright restrictions)

The Milwaukee Heated Jacket

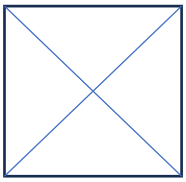


Note. From "The M12™ TOUGHSHELL™ Heated Jacket", (https://www.milwaukeetool.co.nz/job-site-apparel/heated-gear/heated-jackets/M12HJBLACKX0.html). Copyright (n.d.) by Milwaukee.

The Life Tech Jacket. Design Studio Seymourpowell has developed an advanced smart jacket named Life Tech for the outdoor sportswear brand Kolon Sport, specifically engineered for extreme environments (Blessthisstuff, n.d.). As depicted in Figure 2.12, this jacket is tailored for survival in harsh conditions such as severe weather and high-altitude environments like the Himalayas. It incorporates several critical technological features, including a tri-layered system that provides both waterproof and windproof protection, and a wearable first-aid and survival kit.

Figure 2.12 (Image removed due to copyright restrictions)

The Life Tech Jacket



Note. From "Life Tech Jacket/By Kolon Sport", (https://www.blessthisstuff.com/stuff/wear/coats-jackets/life-tech-jacket-by-kolon-sport/). Copyright (n.d.) by Blessthisstuff.

The jacket is equipped with oversized zip pulls designed for use with gloves,. It features back straps and easy-access shoulder straps to assist in rescue. It also includes a built-in GPS for emergency geolocation and a wearable wind turbine generator that can power the GPS and other mobile devices. Additionally, the Life Tech jacket boasts a Heatex system that offers up to seven hours of heat, with adjustable temperatures of 40-50ºC (high 50°C, medium 45°C, and low 40°C) (Blessthisstuff, n.d.; Lee & Baek, 2021; Sports Techie, n.d.).

Other Heating Clothing. Scientific publications and utility patents for different types of electrically heated clothing were also analysed. This included account of a jacket with an automated system of thermoregulation (Brink et al., 2019), a jacket with an automated electronic internal temperature control system (Khaluta, 2015), and an electrically heated clothing/pants combination with controller (Chen & Huang, 2015). The jacket with an automated system of thermoregulation (Brink et al.,2019) consists of a removable insulation lining with an automatic heating system including heating elements, a controller, heart rate sensors located on the inner surfaces of the sleeve cuffs and collar, and an external temperature sensor. The heating elements are made of soft heat-conducting polymer fibres with partial metallisation and with built-in temperature microsensors located at 5.0 mm from each other along the tracks of the conducting thread that transmit information about the temperature in all areas under the clothes to the controller. Power supply depends on differences in the local comfort temperature of the human body's parts and is provided by removable batteries with an on/off button in an inner lining pocket.

The jacket with the automated electronic internal temperature control system (Khaluta, 2015) consists of heating elements in the inner layers and an automated electronic internal temperature control system with a computer. The heating elements are rectangular with a mesh structure inside the perimeter, made of flexible fibrous carbon material. Each heating element comes with electrically insulated temperature sensors that connect to an automated electronic internal temperature control system with a computer. There is a touch screen on the left forearm for choosing the heating zones, the heating temperature, and heating intensity. The on/off button is positioned in the lower right corner of the jacket.

The electrically heated clothing/pants with a controller (Chen & Huang, 2015) uses removable heating devices instead of inbuilt ones. Thus, the garment includes a silicone rubber heater as a heating device, battery, and control element. The silicone rubber heaters are placed separately in the pockets. Removable elements such as heaters and batteries simplify the washing of clothing, but also makes clothes heavier, bulkier and reduces mobility.

Lee and Baek (2021) described the development of a smart outdoor jacket prototype that monitors the user's health and outdoor activities. This study focused on developing a multifunctional wearable system that can be connected with a smartphone to enhance the capabilities of existing smart outdoor apparel. The objective was to address the limitations of current smart outdoor wear by incorporating a system that offers six key functions: (1) Bluetooth hands-free calling, (2) heart rate monitoring (HM), (3) emergency calls, (4) temperature-reactive heating, (5) fall detection with automatic emergency calls, and (6) ultraviolet (UV) monitoring.

While the prototype was not specifically designed for climbers, its wearability and the usability of the system, as well as the associated smartphone application, were evaluated during climbing activities (Lee & Baek, 2021). The evaluation identified no major issues, though two minor improvements were noted: enhancing the font size for the UV value display on the UV module's built-in screen and reducing the processing time for the heart rate data. Overall, the prototype—including the garment platform, wearable system, and smartphone application—functioned as intended (Lee & Baek, 2021).

Overall, these examples show that heated smart outdoor clothing consistently focuses on technical functionality despite the differences in using new textile fibres, materials, design, and enabling technologies. Besides the main body heat function, some projects include extra purposes such as heart rate monitoring, GPS-based geolocation, emergency calls, mobile device charging, etc. However, most examples provide a single key body heat function with different types of heating systems. This analysis investigated various methods of heating clothing within the e-textiles space. Heating elements that consist of heat-conductive carbon fibres are used in about half of the presented jackets. The Gamma Jacket (Gamma Jacket: Wear Graphene, n.d.) features a heating layer made of graphene. Conductive polymer fibres were used as a heating element in such projects as the Life Tech jacket (Blessthisstuff, n.d.) and the jacket with an automated system of thermoregulation (Brink et al.,2019). Lee and Baek (2021) used the pre-made heating sheets in their smart outdoor jacket prototype. This type of heating element facilitates easy integration during the initial prototyping phase, particularly for assessing thermoregulatory responses and establishing a microclimate within clothing layers.

All featured jackets share a common characteristic of placing heating pads on both the back and front. This would be the areas most critical for maintaining warmth in harsh climates as this covers the body core (see section 2.4 above). However, some manufacturers incorporate additional heating systems in pockets, exemplified by the Milwaukee Heated Jacket (Milwaukee, n.d.). The placement of heating elements can therefore be considered a key issue to bear in mind for the design of a heating jacket for rock-climbing developed in this study. Other considerations include the strategic placement of rock-climbing equipment such as ropes, harnesses, and backpacks, minimising wearer discomfort, ensuring safe distances between components, and addressing wiring connection issues.

While thermoregulation is the main function of all presented examples, these clothes were not developed specifically as clothing for rock-climbing. Rock-climbing is different to other sports as it involves dynamic movements, requires the use of special equipment, and takes place in harsh environments under extreme climate conditions that can change quickly. Because the described garments were not developed specifically for rock-climbing, the position of heating pads, batteries, on/off buttons, pockets, textile specification, do not correspond with the specific demands of the sport. Also, it is widely recognised that the use of e-textiles can lead to potential issues of efficiency associated with durability, washability, abrasion, resistance to heat, and other performance issues (Iftekhar Shuvo et al., 2021). The presented jackets were designed mostly as streetwear (Gamma Jacket: Wear Graphene, n.d.; Khaluta, 2015; Milwaukee, n.d.; ORORO Heated Apparel, n.d.; Priday, 2018) or as protective wear (Blessthisstuff, n.d.; Brink et al., 2019), and only the Shift Men's Heated Snowboard Jacket was designed specifically as a sportwear with snowboarders in mind (GOBI Heat, n.d.). However, some of the projects discussed consist of sports related constructive features in design. For example, the Milwaukee heated jacket was developed with FREEFLEX mobility gussets that allow for enhanced movement, adjustable cuffs and waist with drop tail extended back, dropped shoulder seam and under arm gussets for improved flexibility. Thus, by including these features in the design, the manufacturer extended the use of the jacket from streetwear to the area of sport in general (Milwaukee, n.d.).

Regarding the activation of the heating function, most jackets currently on the market require wearer intervention to activate the function by pressing an on/off button. A notable feature absent from these products is an "Auto" function. Furthermore, many existing products lack temperature sensors essential for enabling effective operation of an auto function. Such an Auto feature would be particularly crucial in clothing designed for rock climbers, where manual input during climbing activities is inconvenient if not impossible. This project aims to address this issue by incorporating a smart heating system, including temperature sensors. When the jacket is powered on (i.e., connected to a power bank), it will utilise temperature sensor data along with heating element output to automatically regulate a comfortable temperature for the wearer. However, it is essential to determine the optimal type of temperature sensor for an effective smart heating system (see the chapter on Development of Heating System for further details).

2.7. Conclusion

The literature review presented in this chapter has drawn on a range of different source material to provide a comprehensive overview of the primary types and techniques of rock-climbing, encompassing brief descriptions of the activities involved and the associated risks as well as accounts of the types of equipment, gear, and clothing needed to perform these activities. This information allowed the current project to be anchored in a context of the needs of the rock-climbing community, what products were already commercially available, and what gaps remain. From the review it emerged that there is currently no smart clothing on the market that have been specifically designed for out-door rock climbers. One significant challenge identified is the absence of a universally accepted classification system for styles, types, and techniques of rock-climbing, with existing information dispersed across various sources and publication formats. The absence of any such system meant that it was necessary to design a climbing jacket based on the needs and comments of end users, without the ability to rely on existing design standards. At the same time, this gap also offered the opportunity to develop the product without being constrained by such standards.

This review explored various rock-climbing types characterised by higher risk levels, including traditional climbing (such as multi-pitch trad climbing), solo climbing, mountaineering, ice climbing, lead climbing, and aid climbing - all of which enjoy popularity in New Zealand. An understanding of the different needs and contexts of these types of climbing was useful in informing the design of the jacket, but the limited resources on this topic area underscores the need for further research aligned with the focus of this project. As a result, this study had to expand its intended methodology to collect first hand data that would be relevant for the development of the proposed design (see Chapter 3 for a discussion of the study's methodology). Different types of climbing also create different challenges for clothing, affected by equipment, ropes, harnesses, and other gear, suggesting that this is an important consideration for pattern development. Extending this point, the review identified the key functions of rock-climbing apparel: protection, comfort, fit, and mobility. This information guided the design of a functional rock-climbing garment that encapsulates considerations of ergonomic design, mobility, comfort, protection, and climber expectations, specifically with regard to range of motion, abrasion protection, optimal sensor integration, and pocket placement.

Appropriate clothing plays a crucial role in protecting climbers and ensuring both psychological and physiological comfort, especially in types of climbing influenced by severe and highly variable external environmental factors. During rock-climbing, the climber's body temperature can fluctuate considerably, particularly in high-altitude and snowy environments where temperatures can vary widely along the climbing route. Climbers, like most outdoor enthusiasts, traditionally manage these fluctuations by employing a multi-layer approach to clothing, adjusting layers as needed to regulate their microclimate during ascent. However, while effective, climbers do not have the luxury of sitting down safely to do this, there are added risk for them in carrying multiple layers, and changing clothing introduces a significant element of personal risk to the climber as they may be tethered to safety ropes that would have to be removed or repositioned. There would be substantial benefits in terms of weight reduction and safety inherent in the design of rock-climbing apparel that minimises the necessity for wearing multiple layers or bulky jackets, and this is one of the primary drivers of this thesis project.

The literature review highlighted insights into microclimate within clothing layers, including cold effects, hypothermia, and human heat transfer mechanisms. These insights informed my understanding of optimal body temperature levels and other critical parameters for the normal functioning of the thermoregulation mechanism and the associated sensations of thermophysiological comfort. The review relied extensively on research into the hygienic assessment of clothing which was originally published in Russian and subsequently had little influence outside Russia. This research was translated for this project and was used to determine a jacket's optimal layer thickness using a method that calculates required thermal resistance of clothing based on factors such as human energy consumption, duration in given meteorological conditions, ambient temperature, wind speed, and clothing breathability (Afanas'eva et al., 2006;

Dell' et al., 1991). The detailed calculation of optimal thickness of combined layers of the jacket are presented in Appendix B.

The literature review also discussed the analysis of new generation textile materials and new technologies which offer potential solutions to the problem of overheating during climbing. Advanced textiles offer promising solutions for enhancing human body thermal comfort and provide new insights into ways of achieving energy savings. These insights informed the selection of materials for the current project.

The literature review revealed a significant gap concerning published standards and requirements specifically tailored to the apparel needs of rock climbers. An exhaustive analysis of existing standards and requirements associated with rock-climbing intended to identify information regarding regulations for rock-climbing apparel, requirements for pattern-making parameters, specifications of textile materials, and regulations pertaining to smart wearable technology for climbing determined that no such standards exist. Existing standards related to rock-climbing primarily focus on the safety and reliability of climbing gear, definitions of terminology, design, performance and inspection standards, as well as training standards. However, standards that specify the size and measurements of rock-climbing equipment, such as helmets for hood design and harnesses for optimal pocket placement, were analysed. These identified gaps highlight the potential for developing requirements and practical recommendations for the design of ergonomic and functional rock-climbing clothing, particularly in terms of the integration of smart sensing technologies. Addressing these gaps could enhance the safety, comfort, and performance of climbers by providing guidelines tailored specifically to the apparel needs of rock-climbing activities.

The final section of the review focused on examining smart clothing available on the market, scientific publications, and utility patents related to various types of heated clothing. This exploration aimed to gain insights into the functions and components of heating systems used in smart clothing currently available or in initial prototypes. Additionally, the section covered the review of e-textiles for sport and other application areas, encompassing an assessment of both conventional electrically conductive materials in e-textiles and emerging carbon-based conductive materials. Limitations associated with the use of textiles incorporating carbon nanotubes (CNTs) in research projects were identified in this evaluation, including their elevated costs, accessibility challenges, and sustainability considerations linked to CNTs. Furthermore, alternative textile-based heating systems, categorised into polymer-based and metal-based textile heaters, were described. The integration of wearable electronics into these heating systems enhances their functionality, aligning with the primary objective of this project. This review of e-textiles provided valuable insights into potential solutions for the heating element system envisioned for this project.

Overall, the literature review revealed a surprisingly limited number of innovations in the development of smart wearable applications specific to rock-climbing, with existing efforts predominantly focusing on activity trackers and performance evaluation tools for climbers. Notably, there was a lack of identified outdoor rock-climbing clothing integrated with smart technology. To address this gap, the study examined commercially available heated clothing products intended for urban settings, drawing primarily from online information provided by manufacturers or sellers. However, comprehensive technical details and user testing feedback were limited, necessitating a review of available documentation alongside an analysis of the design and key features of these apparel items, which is described in a subsequent stage of the research. This initial investigation of available information underscored the potential for innovation in the development of smart heating clothing for outdoor rock-climbing, offering insights into their functionalities, operational mechanisms, and constituent heating systems utilised in contemporary smart clothing designs.

In essence, smart clothing represents a technological and functional innovation that prioritises the needs and expectations of the wearer, integrating insights from diverse fields such as garment design, e-textiles, information technology, and electronics engineering. This underscores the interdisciplinary nature of such endeavours. By placing human needs and expectations at the core of the design process, a methodological framework emerged that incorporates principles from ergonomics, human factors, human-centred design, and user experience. The primary objective of this project is the development of protective rock-climbing apparel that is functional, ergonomic, and integrates smart thermoregulation features. My research project adopted a User-Centred Design approach to develop ergonomic, functional, and smart rock-climbing apparel, grounded in a thorough understanding of climbers' needs, expectations, and the contexts in which they are used. The subsequent chapter will detail the methodology applied in this study.

CHAPTER 3. RESEARCH METHODOLOGY

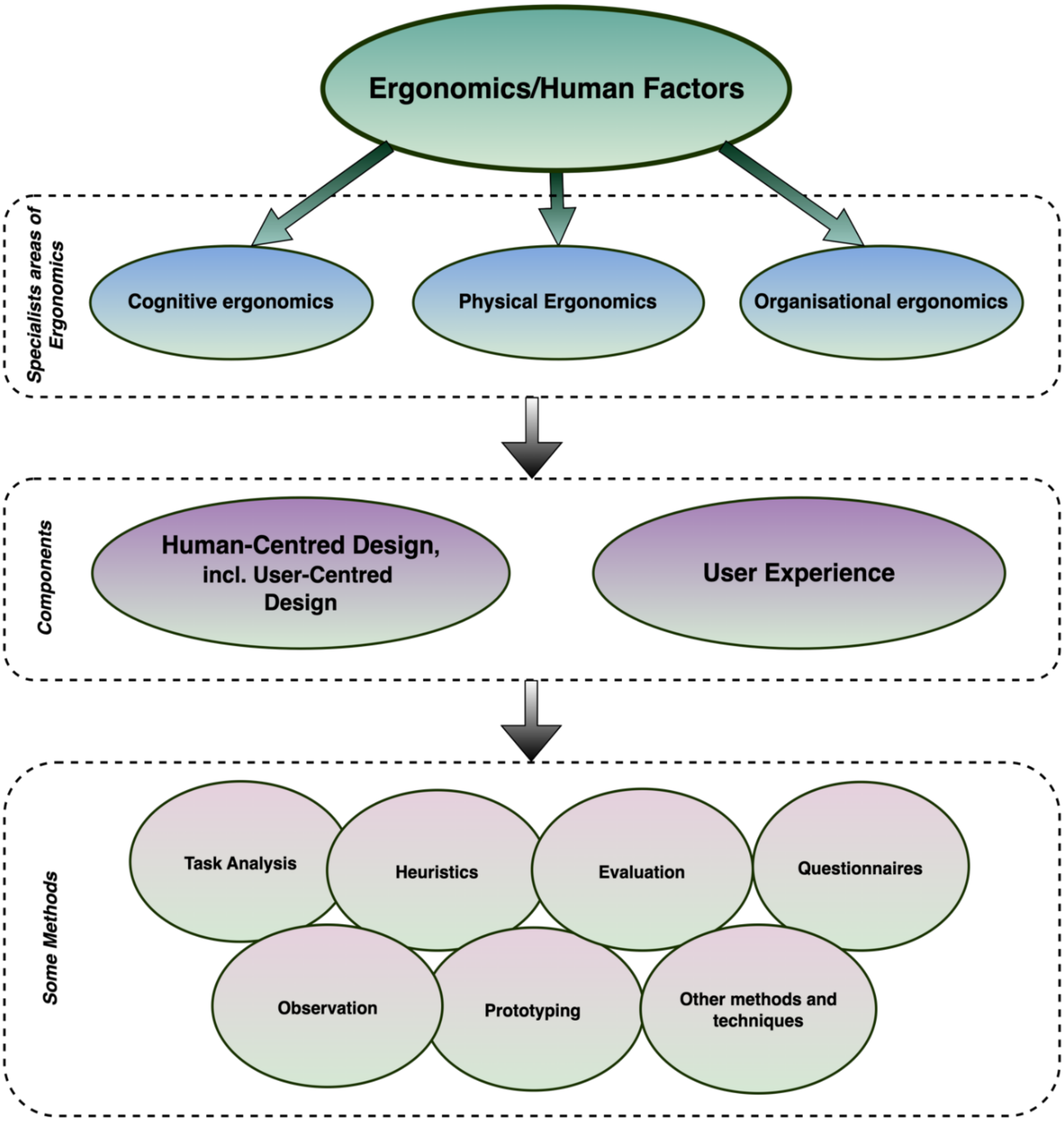
This chapter describes and discusses the methodology employed in this research, highlighting its interdisciplinary nature. The chapter consists of two sections. The first section discusses the theoretical research framework to understand the context and user needs. The second section describes the practical application of this framework and the development of working prototypes. Drawing from different fields such as ergonomics, design, garment engineering, electronics engineering, programming, smart clothing, and e-textiles the methodological framework adopts principles from ergonomics incorporating human factors, human-centred design, and user experience (IEA, n.d.; Tosi, 2020b). A systematic user-centred design (UCD) approach (Cherrington et al., 2020; IEA, n.d.; Naesgaard et al., 2017; Putnam et al., 2016; Tosi, 2020b) underpins the research, employing both qualitative and quantitative methods throughout the project's stages. Insights gathered from data analysis informed the human-centred design process, facilitating the development of smart rock-climbing apparel tailored to climbers' needs and the context of their use. Consequently, the project integrated technical and functional aspects of design research alongside specific design methods and tools employed in pattern engineering and the iterative development of prototypes.

3.1. Research Framework

The research's epistemic foundation is grounded in ergonomics (IEA, n.d.; Tosi, 2020a), with the methodological framework guided by a user-centred design approach throughout of the project. The International Ergonomics Association (IEA) defined ergonomics as "the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimize human well-being and overall system performance" (IEA, n.d., para. 1). Ergonomics, encompassing human factors, human-centred design (including user-centred design), and user experience, represents an interdisciplinary amalgamation of knowledge from psychology, engineering, social sciences, medicine, and design. It includes methods and procedures focused on assessing people's needs and expectations in their interactions with products, services, environments, and systems, whether in a work setting or daily routines (Tosi, 2020a). Ergonomics aims to enhance both people's well-being and the system's overall performance through design and evaluation activities. These activities aim to align systems and environments with individuals' needs, capabilities, and limitations (Tosi, 2020a). Ergonomic methods aim to advance products by understanding or anticipating human interaction with them (Stanton et al., 2014). The principles of ergonomics are applicable across various industrial sectors, with apparel being one of them (Mukhopadhyay, 2023). Figure 3.1 presents the methodological framework adopted for this research.

Figure 3.1

The methodological framework for the research



The diagram in Figure 3.1 outlines three specialist areas, identified by the IEA: Cognitive Ergonomics, Physical Ergonomics, and Organisational Ergonomics. These specialist areas collaborate closely with various application and intervention sectors (IEA, n.d.; Tosi, 2020a). These three areas are described in Table 3.1 below. The principles of Physical Ergonomics predominantly dictate the development process of functional clothing, providing tools that, when applied during clothing conception stages, may allow for precise tailoring of product characteristics to enhance safety, efficiency, and comfort. To comprehend the complexity of integrating the body with clothing, studies in anatomy and body movement are essential (Neves et al., 2015; Raji et al., 2021).

Table 3.1

The specialist areas of Ergonomics

Physical Ergonomics
focuses on human anatomical, physiological, anthropometric, and bio-mechanical characteristics as they pertain to physical activity. Relevant topics in this field encompass working postures, repetitive movements, materials handling, work-related musculoskeletal disorders, workplace layout, as well as health and safety considerations.
Cognitive Ergonomics
focuses on mental processes, such as memory, perception, reasoning, and motor responses, and their influence on interactions between individuals and various system elements. Key areas of interest include mental workload, skilled performance, decision-making, human-computer interaction, work stress, human reliability, and training, all of which are integral to designing effective human-systems.
Organisational Ergonomics
focuses on optimising sociotechnical systems by improving their organisational structures, processes, and policies. This includes topics such as work design, communication, scheduling, crew resource management, teamwork, community ergonomics, participatory design, collaborative work, virtual organisations, new work models, and quality management.

Note. From "Ergonomics and Design", (https://doi.org/10.1007/978-3-030-33562-5_1). Copyright 2020 by Tosi.

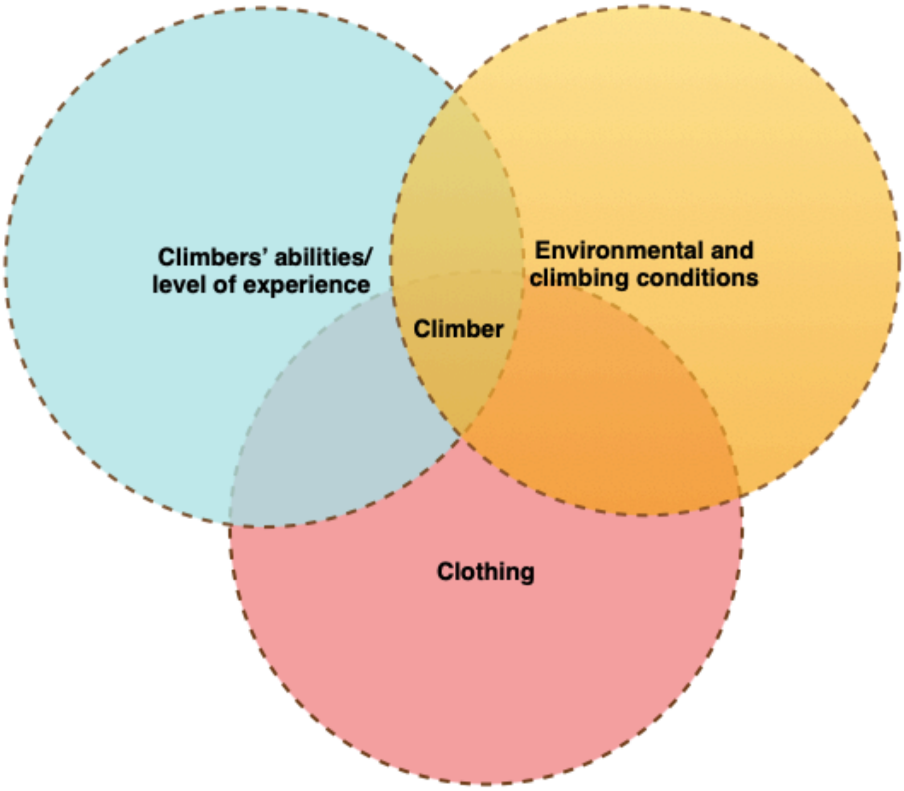
Following the depiction of these areas, the engagement of ergonomics in design adopts a transformative perspective that shifts focus in two keyways:

- transitions from evaluating and designing products, systems and environments to assessing and designing the interactions between people and these products, systems or environments;
- transitions from evaluating the current objective reality with people to envisioning future possibilities and designing optimal solutions to meet anticipated needs and desires (Tosi, 2020a).

The methods and tools developed through ergonomic research, which are based on a philosophy centred on human needs and expectations, play a vital role in advancing both research and design practices. This ergonomic approach is a critical factor in the innovation and development of products and systems (Tosi, 2020b). In the fashion industry context, ergonomics mediates the interaction between garment, the wearer, and the environment forming a simplified system that enhances functionality (Mukhopadhyay, 2023). Firstly, it is essential to identify all relevant user and stakeholder groups, as products, services, and systems should be designed with consideration for those who will use them, as well as other stakeholders who may be directly or indirectly affected by their use (ISO, 2010, 2016). In this research, the climber has been identified as the central user whose needs and experiences guide the development and design of rock-climbing clothing. The simplified system consists of three main components: the clothing, climbers' abilities or level of experience, and the environmental and climbing conditions (see Figure 3.2). These components were chosen as they were considered to be the most salient factors impacting on the interactions between clothing and rock climbing. These components interact continuously, affecting the climber's performance and safety.

Figure 3.2

Basic model of the climbing apparel design system



The basic model of the climbing apparel design system (figure 3.2) was further conceptualized into a Figure 3.3 that illustrates dynamic nature of the relationship between these elements and various factors related to the Physical Ergonomics approach. The model thus captures various sub-elements inherent in the system, encompassing dynamic postures and movements of climbers, dynamic parameters of the climbing conditions, and the dynamic ease required for optimal performance. Dynamic components were incorporated based on an analysis of their influence on the system's elements. Accordingly, dynamic postures and movements have a direct effect on dynamic parameters and are influenced by the climber's abilities, including the type of climbing and their level of experience.

These dynamic components hold considerable importance for the development of patten engineering solutions for specific parts of the clothing, given the need for clothing to both accommodate and amplify the climber's movements and functionality. Such solutions may include the strategic placement of constructive lines, the degree of elongation in certain parts of the garment, and allowances for dynamic ease. This comprehensive approach ensures that the clothing not only provides comfort and protection but also augments the climber's range of motion and facilitates optimal performance throughout dynamic climbing activities.

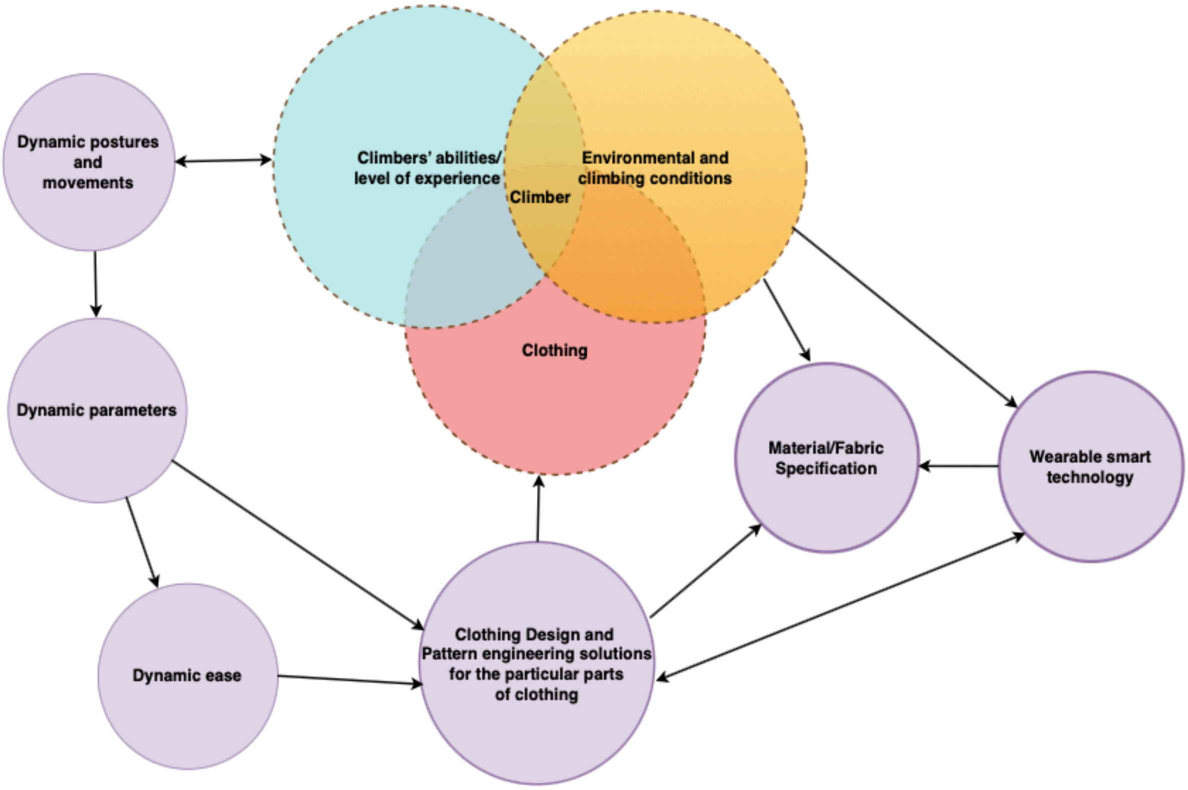
Figure 3.3

Model of the climbing apparel design system featuring the Physical Ergonomic components

The model presented in Figure 3.3 can be further expanded to incorporate wearable smart technology, as illustrated in Figure 3.4 below. Figure 3.4 depicts the holistic model of a system, encompassing elements such as material and fabric selection and the integration of wearable smart technology. These elements were selected based on the typical stages of clothing development, with consideration given to the integration of smart technology. In the context of proposing a smart heating system, the interactions between the system's components were identified. During the stage of textile materials selection, it is imperative to consider various factors that serve as sub-elements within the system, including clothing design, environmental and climbing conditions, and the incorporation of wearable technologies. All these factors are essential in deriving an optimal solution for material specification. Moreover, solutions pertaining to the integration of wearable smart technology are intricately influenced by environmental and climbing conditions, clothing design and pattern solutions, and the specification of textile materials. This holistic model for the design of rock-climbing clothing thus captures the interplay between the climber, the clothing, and the unique challenges posed by the climbing conditions.

Figure 3.4

Model of the final climbing apparel design system, extending with material selection and the integration of wearable smart technology



Following the User-Centred Design (UCD) approach, these models present a system in which the climber, as the central point, interacts with other elements of the system. They highlight the sub-system components that need to be considered in relation to the main system. The system presented in figure 3.4 served as a blueprint for the research design. Thus, the system informed the order in which different aspect of the study were conducted and ensured that all relevant factors were considered in the final design.

3.2. User-Centred Design Approach

A UCD approach (Cherrington et al., 2020; IEA, n.d.; Naesgaard et al., 2017; Putnam et al., 2016) is based on ergonomics and usability knowledge with the aim of identification of the user's needs (Chammas et al., 2015). UCD enables designers to incorporate Human Factors/Ergonomics (HF/E) considerations from the initial design phase. Through UCD, potential HF/E issues can be proactively addressed across cognitive, physical, and organisational ergonomics perspectives (Sun et al., 2018b). Through the UCD approach, addressing the end user's needs involves considering the broadly understood requirements of users, analysed outside the specific context of use and evaluated according to the physical and psycho-perceptual characteristics of the typical user (Tosi, 2020a). A UCD approach means that "users should be involved throughout the project development process" (ISO 9241-210, 2010, p. 6). By engaging individuals who use the product or services from the earliest stages of design development, the study seeks to gain insights into their existing experiences and requirements. This approach enables designers to devise solutions closely aligned with user needs, thereby enhancing the overall effectiveness and usability of the final service or product (McCann & Bryson, 2009).

UCD is a design approach which originated in the IT sector and was later adopted across the broader field of design. Its primary goal has always been to direct the development process of products or services to achieve a high level of usability (Tosi, 2020b). Initially, UCD methodologies focused on improving the usability of interactive system interfaces within the Human-Computer Interaction sector during the 1970s, 1980s, and 1990s. As daily-use products and technological innovations grew more complex, the UCD approach evolved to address the changing nature of user-product-systems or service interactions (Tosi, 2020a). While the original aim of UCD was to evaluate usability, it has since progressed to encompass design activities that address the entire user experience from the beginning, with the user playing a pivotal role at every stage of the design process (Tosi, 2020a). UCD, sometimes referred to as Human (People)-Centred Design, considers the user—referred to as the human or individual—the central focus of the design process (Watkins & Dunne, 2015). It is important for the designer to avoid assumption and to establish what it is that the user needs and wants for optimum performance in a new clothing product (Ledbury, 2018). It is then the designer's responsibility to define problems based on gathered information; the development of design concepts, along with the evaluation of manufacturing techniques, materials, and cost implications, which follow are likely to be more effective in reaching a solution, when founded upon rigorous research (Ledbury, 2018). In the field of smart garments, designers develop wearable technologies or wearable computers (Ferraro & Ugur, 2011) through the UCD approach. Engaging users throughout the entire design process of smart garments, as advocated by UCD, enables the design team to address concerns related to both physical and cognitive interactions between the wearer and the garment (Imbesi & Scataglini, 2021). Users are considered the foremost experts as they are in the best position to effectively evaluate design prototypes, suggest modifications, and ultimately incorporate the final products into their daily routines (Ferraro & Ugur, 2011).

There are a number of examples of functional clothing research and development projects that have successfully adopted an UCD approach. For instance, this approach was employed for the development of cold-protective clothing designed for offshore petroleum workers who operate in the Barents Sea (Naesgaard et al, 2017). Another example of the adoption of an UCD approach and combined with co-design methods is found in the development of wearable technology for sport climbing (Mencarini et al., 2019). This wearable technology enabled instructors to transmit real-time information to beginner climbers by activating vibration sensors on parts of their body they should be using, which helped focus attention on their climbing technique and provide reassurance. The system was valued for its effectiveness in delivering timely information and its adaptability to various trainees' needs. Additionally, a UCD methodology was utilised in designing smart garments to monitor physical and physiological functions in older adults (Imbesi & Scataglini, 2021). This approach was aimed at understanding user needs, developing strategies to meet those needs, fostering a positive perception among elderly users, and reducing design complexity by providing a framework for comparing significant solutions.

This research adopted an UCD approach to develop ergonomic, functional, and smart rock-climbing clothing that are grounded in a comprehensive understanding of climbers' (users') needs, expectations, and contexts of use. One of the features of UCD is the use of structured and verifiable methods of investigation and evaluation to examine the interactions between climbers and the system (Tosi, 2020a). Therefore, input and feedback from climbers was gathered at every stage of the research, development, and testing phases.

Multiple investigative methods and techniques (Table 3.2) fall under the umbrella of an UCD approach (Tosi, 2020b). Each method possesses unique characteristics, advantages, and limitations that determine its suitability for evaluating or designing a particular product and for a specific phase of the evaluation or design process (Tosi, 2020b).

Table 3.2

Human-centred design methods

Planning HCD	Context of use	Requirements	Design	Evaluation
• Usability planning and scoping • Usability cost benefit analysis	• Identify stakeholders • Context of use analysis • Survey of existing users • Field study/user observation • Task analysis	• Stakeholder analysis • User cost-benefit analysis • User requirements interview • Focus groups • Scenarios of use • Personas • Existing system/ competitor analysis • Task/function mapping • Allocation of function • User, usability and organizational requirements	• Brainstorming • Parallel design • Design guidelines and standards • Storyboarding • Affinity diagram • Paper prototyping • Prototyping	• Participatory evaluation • Assisted evaluation • Heuristic or expert evaluation • Controlled user testing • Satisfaction • questionnaires • Assessing cognitive workload • Critical incidents

Note. Reworked from Maguire (2001) (Maguire, 2001), from "Ergonomics and Design", (https://doi.org/10.1007/978-3-030-33562-5_1). Copyright 2020 by Tosi.

Some of the methods employed in this research are illustrated in Figure 3.1 and discussed further in the next section of this chapter. These methods include questionnaire, observation, and prototyping. The surveys and observation method are categorised as primary data collection methods. The results obtained from these data collection methods are presented in Chapter 4, "Data Analisys and Finding Interpretations".

3.2.1. Questionnaire

Questionnaires, as a survey method, are an efficient way to collect data on users' opinions, insights, and feedback regarding a particular product (Tosi, 2020b). Information received from users is a crucial element in the HCD approach. Assessing designs with users and refining them according to their feedback is an effective strategy for reducing the risk that a system will fail to meet user or organisational needs, including those requirements that may be implicit or challenging to articulate explicitly (ISO, 2010).

In the context of the development of a new product, surveys can assist designers by (1) identifying the potential user population, (2) determining users' actual needs and desires, and (3) understanding how users are currently addressing their issues or reaching their goals (Sun et al., 2018b). For the development of a new version of an existing product, surveys can help designers by (1) identifying users' dissatisfactions and desired improvements regarding the current product and (2) gaining insights into how users interact with the existing product (Sun et al., 2018b).

The survey component of the study utilised qualitative methods in the form of a questionnaire to obtain a deeper understanding of climbers' experiences, issues, and preferences related to clothing (Novikova et al., 2023). A survey was selected as the primary data collection method instead of interviews, as the study aimed to involve a large number of participants from various countries. While interviews can offer the potential benefits of capturing richer qualitative insights, they are more suitable for smaller, localized participant groups. In this context, an online questionnaire was considered a more practical and accessible tool for both participants and the researcher. The questionnaire, titled "Rock climber's clothes - satisfaction, preferences, requests and needs of rock-climbers" was conducted online using the Qualtrics platform (https://www.qualtrics.com/). Since this stage of the project involved collecting information from participants an ethics application had to be submitted. Ethical approval was obtained from the Auckland University of Technology Ethics Committee (21/171) (see Appendix A for a copy of the approval letter).

The participants, all experienced climbers, were selected using a non-probability sampling method, namely a purposive sampling method (Campbell et al., 2020; Etikan, 2017). This method is employed when a researcher identifies and selects participants who fulfil predetermined criteria, thereby determining the composition of the sample in alignment with the objectives of the study (Eshenaur Spolarich, 2023). This approach was deemed most suitable for the current context as ensures the quality, qualifications, and experiential insights of participants' responses, which are deemed more critical for obtaining meaningful design insights than the sheer number of respondents. Initially, emails were dispatched to coordinators of various rock-climbing clubs and experts, including those from the New Zealand Alpine Club, to solicit potential participants. The few responses received included contact details for potential participants. Subsequently, the primary researcher sent an information sheet via email to these potential

respondents. The rock climbers who expressed interest were asked to complete a Consent Form before any data was collected. Following consent, an invitation letter containing the survey link was emailed to them. Additionally, the potential participants were required to confirm their level of climbing expertise; those who did not meet the necessary criteria were thanked for their interest and excluded from the survey. According to the International Rock-climbing Classification Systems (*International Grade Comparison Chart*, 1999) climbers' abilities are classified as:
Beginner (Yosemite Decimal System (YDS) 5.2-5.9, AUS 10-17);
Intermediate (YDS 5.10a-5.11d, AUS 18-23);
Advanced (YDS 5.12a-5.13d, AUS 24-31);
Professional (YDS 5.14a-5.15c, AUS 32-38).

The survey targeted only climbers at intermediate or higher levels of experience, specifically those proficient in at least one specialised outdoor rock-climbing style, such as mountaineering, traditional climbing (including multi-pitch traditional climbing), or winter (ice) climbing. Beginners and less experienced climbers were excluded from the study. The criteria for inclusion and exclusion were clearly outlined in the participant information sheet. Additionally, the questionnaire included queries regarding participants' prior climbing experience (questions 3-5), and any climbers identified as novices during this phase were excluded from the study.

There were no conflicts of interest between the researcher and the participants. If the participants had any questions, concerns, or inquiries about the research project, both the researcher and the supervising team were available to address these issues. The survey did not include any sensitive questions, and participants retained the right to abstain from answering any questions or participating in any discussions that made them uncomfortable.

Seven participants, categorised as either advanced or intermediate climbers, were selected and took part in the survey. They were queried about their preferred types, styles, and designs of outdoor rock-climbing apparel, as well as the brands of the clothes they prefer to wear while rock-climbing. Open-ended responses were analysed using a content analysis approach to gain insights into participants' perceptions and experiences with their current climbing attire.

The questionnaire comprised between thirty and thirty-eight questions, depending on the participants' responses (see Appendix C for a paper copy of the survey report). The qualitative questions focused on describing and evaluating individual climbing experiences, experience with existing rock-climbing clothes, and identifying potential opportunities for integrating smart technology into climbing gear. The survey included four questions on climbers' preferred types of clothing and brands for outdoor climbing, and their preferences in terms of aesthetic, colour, fibre, and fabric. Two questions related to the factors that the respondents deemed most important by climbers when they purchase rock-climbing clothes. A set of four questions explored the typical number of clothing layers worn by climbers and their experiences while removing or putting on clothing during climbing activities. Additionally, three questions were concerned with microclimate regulation within clothing layers. Lastly, six questions examined the intersection of clothing and smart technology.

A qualitative heuristic approach was employed in the data analysis, which included content analysis of open-ended responses. A heuristic analysis is an inspection method that takes an experience-based approach to problem-solving (Moustakas, 1990; Nielsen, 1994). The heuristic method is often considered the most straightforward evaluation technique for experienced designers as it involves the evaluator (researcher) assessing a product's usability, error potential, safety, and overall design based on their expertise, skill, and experience (Tosi, 2020b). The outcomes of the questionnaire were synthesised into tables, models, and diagrams (refer to Appendix C for a paper copy of the survey report). Substantial findings are presented and discussed in depth in Chapter 4 "Data Analysis and Finding Interpretations".

Due to the dearth of published literature concerning rock-climbing clothing, this primary research proved indispensable for comprehending the challenges and identifying potential areas for design intervention. The findings from the questionnaire thus make a relevant contribution to the advancement of functional clothing design within the field.

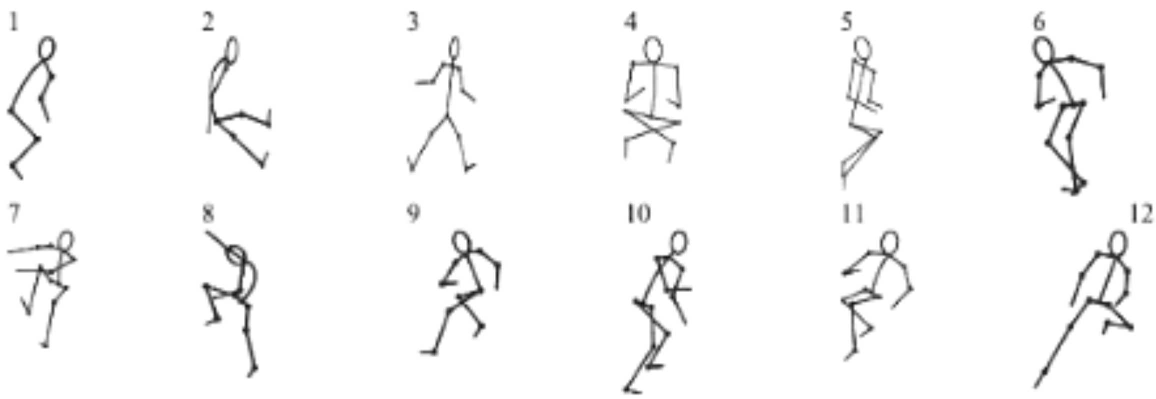
3.2.2. Observation

Observation is a research method wherein the researcher gathers information by the direct monitoring of subjects' responses or activities. This method involves a range of techniques and approaches that can be combined in various ways (Ciesielska et al., 2018). It is particularly valuable for assessing physical tasks and usability since users may struggle to provide detailed explanations about their use of a product, for instance, whether it is familiar or new to them. Furthermore, users might not accurately perceive their own behaviour in different real-world scenarios. Different observation techniques currently available include direct observation, indirect observation, and participant observation (Tosi, 2020b). The research involved direct observation focused on the anthropometric measurements of climbers in static and dynamic postures. When functional clothing is designed, there are different elements involved in the process, for instance, the anthropometry, which refers to the dimensions of the human body, is particularly crucial (Mukhopadhyay, 2023). The data provided by anthropometry pertains to both structural (or static) dimensions, which refer to the measurements of the human body in various stationary positions, and functional (or dynamic) dimensions which describe the measurements of the body during movement (Tosi, 2020b). According to Mukhopadhyay (2023), this data should inform the allowances required in the clothing as well as the fabric and the number of stitches in the areas needed that are likely to experience the greatest force and pressure from bony joints and tissues.

Insights gained from the literature review and questionnaire provided the relevant background information for this stage of the project. For instance, the identification of rock-climbing postures and techniques that informed observation was based on the information shared by the respondents. Rock climbers employ a variety of techniques, movements, and dynamic postures during climbing. Examples of some dynamic postures featuring notable angles are illustrated in Figure 3.5, which features schematic representations of the main dynamic postures. These schematics were incorporated into the questionnaire for further analysis (see question 3 of the questionnaire report in Appendix C).

Figure 3.5

Schematic view of the main dynamic postures while climbing



For the observation phase of the research, two experienced climbers were recruited to participate. The observation sessions occurred on an indoor climbing wall at the Sports Performance Research Institute New Zealand (SPRINZ), situated within Auckland University of Technology's Millennium gym. The climbers worked as a pair, with one engaged in climbing while the other served as the belayer, simulating real rock-climbing scenarios. During the session, one climber was equipped with an Xsens motion tracking system, specifically the MVN Awinda Straps System (Xsens Technologies B.V., 2020). This system comprised 18 Wireless Motion Trackers (MTw), an Awinda Station, two Awinda Chargers, MTw full-body Velcro straps (including shirts, headbands, footpads, and gloves), a Segmometer, and a Quick Setup sheet. Each MTw unit was equipped with 3D linear accelerometers, 3D rate gyroscopes, 3D magnetometers, a barometer, and an internal battery. Figure 3.6. shows the MTws used during observation before they were attached to the climber. These trackers were strategically placed on the various body segments and secured with straps, as illustrated in Figure 3.7, to record the movement of each segment.

The proper placement of the motion trackers is important to ensure accurate motion capturing. Each tracker is assigned a specific ID, which is utilised throughout the motion capturing process (Xsens Technologies B.V., 2020). The MVN Straps provided sufficient fastening for most movements. It is essential to tightly secure and tape the straps over the placements of these motion trackers on the body segments to minimize skin motion artefacts.

Figure 3.6

Identifying the Wireless Motion Trackers of the MVN Awinda system, prior to placement on the body

Figure 3.7

The placement of Shoulder Motion Trackers on the Scapula (shoulder blades)

The MVN system is controlled by the MVN Analyze/Animate software application that was specifically designed for Windows 10, providing real-time viewing and recording capabilities (Xsens Technologies B.V., 2020). The setup workflow stage encompasses three key components:

subject body dimensions, sensor-to-segment calibration, and data fusion. Prior to sensor-to-segment calibration, the individual's body height and foot length (footwear length at the time of the measurement) need to be inputted into MVN Analyze/Animate. These measurements enable the software to compute additional segment lengths using an anthropometric model. To streamline data collection, body dimensions can be recorded in advance and inputted into MVN Analyze/Animate without the need to connect an MVN suit in the session configuration. This functionality enables users to save an individual's body dimensions as an MVNA file before instrumenting a subject. Subsequently, when the system is connected, the file can be retrieved and loaded from the Body Dimensions panel. Segment calibration is a crucial step that synchronises the motion trackers with the corresponding segments of the subject. Once the calibration data has been processed, the system provides an indication of the accuracy of projected calibration parameters and displays warnings if any issues are detected (Xsens Technologies B.V., 2020). The subsequent stages involved the preview and recording sessions.

During the recording session, data was collected according to an observation protocol. The climber's dynamic parameters were measured and their movements were observed and analysed during a range of rock-climbing postures and techniques defined by the experienced climbers who participated in the survey (Novikova et al., 2023). The recording sessions consisted of three parts:

1. The climber performed commonly used climbing movements at a low altitude or while remaining on the ground.
2. The climber demonstrated a range of movements, postures, and techniques while climbing upwards, including high stepping and mantle technique, lieback, stemming technique, and others (see Figure 3.8).
3. The climber performed a chimney climb.

The MVN Fusion Engine performs calculations to determine the orientation, position, and other kinematic data of each body segment relative to an earth-fixed reference coordinate system. Initially, the body frames are synchronised with the global reference system when the subject adopts a T-pose. To calculate joint angles, an additional reference frame, originated from a standard anatomical posture, is used to identify the body frames. The anatomical frame determines the origins of the joints, which are centred on the functional axes, with the X, Y, and Z directions corresponding to functional movements (Schepers et al., 2018; Xsens Technologies B.V., 2020). Once the recording is completed, the data can be imported to the computer by connecting the Body Pack. The final stage of the workflow involves analysing the collected data, which involves evaluating the data and interpreting the results.

Figure 3.8

Example of some commonly used postures in climbing

During the observation session, multiple sources of data were collected, including the primary data obtained using the Xsens system technology, as well as photographic and video recordings, and manual measurements. The manual body dimensions were taken using tape measurements according to ISO 8559:1989 “Garment construction and anthropometric surveys - Body dimensions” (ISO, 1989) and ISO 7250 - 1:2017 “Basic human body measurements for technological design” (ISO, 2017). In addition, the placement and interaction of equipment such as harnesses and ropes with the clothing were assessed and recorded during the observation session. These measurements and assessments were taken into consideration during the pattern making stage to inform the ergonomic design of rock-climbing clothing.

Based on the analysis of survey data, observational insights, and information gathered from a comprehensive literature review and clothing analysis, an informed decision was reached regarding the specific type of clothing and its smart features to be explored and developed towards a working prototype stage. Notably, the input of participants influenced the direction of the research, ensuring its alignment with the preferences and requirements of the intended user base.

The insights gained and findings derived during these preliminary stages provided valuable data for subsequent phases of the research, such as the design and development of rock-climbing clothing as well as the process of integrating smart technologies into this clothing, including prototyping.

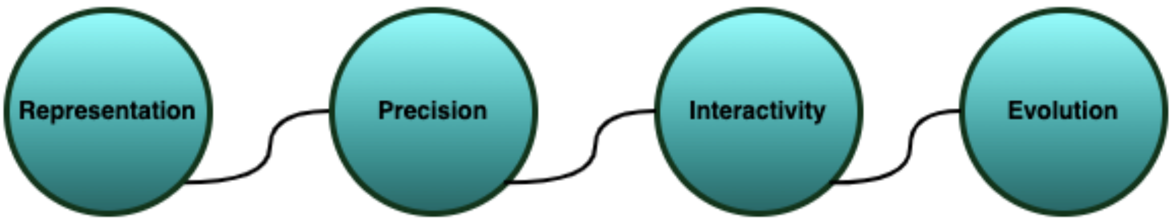
3.2.3. Prototyping

Prototyping is integral to nearly all product, service, and system development initiatives (Camburn et al., 2017). A prototype serves as a pre-production representation of a particular element of a concept or final design. According to Camburn et al. (2017), the process of prototyping frequently dictates a significant portion of resource allocation during development and plays a crucial role in determining the success of a design project. Jacko (2012) noted that “a prototype is a tangible artifact, not an abstract description that requires interpretation” (p. 1082). As such, a prototype facilitates communication and discussion among all stakeholders engaged in the process of development (Budde et al., 1990). Designers, developers, managers, customers/clients, and end users can utilise these artifacts to visualise and critically assess the final system (Jacko, 2012).

There are different types of prototypes depending on the field. For example, designers in the fashion industry produce a full-scale, one-of-a-kind model, such as a sample of a handcrafted dress (Jacko, 2012). While this prototype may serve as the final product in haute couture, the ready-to-wear market necessitates additional design stages to develop a design suitable for mass production in various sizes. Figure 3.9 below presents the four dimensions that are commonly used to analyse prototypes and prototyping techniques These four dimensions are described in detail below.

Figure 3.9

Four dimensions of prototyping



Note. Reworked from “The Human–Computer Interaction Handbook” by Jacko J., (2012).

Representation. Prototypes serve various purposes and therefore manifest in different forms. Representation pertains to the form that prototypes take. For instance, both a series of quick sketches on paper and a detailed computer simulation can be classified as prototypes (Jacko, 2012). Representation of prototypes occurs in two fundamental forms: online and offline. Online prototypes, also referred to as "software prototypes," operate on a computer, whereas offline prototypes, also known as "paper prototypes", do not require a computer. In this research project, both types of prototypes were used. For example, for the first stage of prototyping- clothing design, offline prototypes involved the use of initial sketches (both creative and technical), paper patterns and a toile. At a later stage, online prototypes were employed for computer visualisation, evaluation and movement simulation using 3D fashion design software such as CLO3D and 3DStyle. This stage of clothing development is described in detail in Chapter 5, “Development of an Ergonomic and Functional Rock-Climbing Jacket”.

Prototyping is an iterative process where each prototype provides insights into specific aspects while ignoring or excluding others. At each phase of the design process, the designer must consider the purpose of the prototype (Houde & Hill, 1997) and select the representation that best addresses the current design question (Jacko, 2012).

The prototyping stage of this project is described in more detail in Chapter 6 “Development and Integration of a Heating System Prototypes”. This stage was guided by the secondary research questions which pertained to the identification of the most suitable technologies and components for the smart sensing integrative module and the optimal design for the positioning and integration of the smart heating system components in terms of fit, ergonomics, and comfort. This prototyping stage culminated in the creation of two final prototypes of the heating system: the conceptual and functional. The prototype also featured the conceptual solution for the integration of this system into clothing. A conceptual prototype presents a novel idea. Thus, in this project, the conceptual prototype was used to understand the optimal placement of the components of the wearable smart system. Rock climbers use a range of techniques, movements, and dynamic postures while climbing and they need to carry rock-climbing equipment and personal items, for instance a backpack. Consequently, the integrated smart system needs to provide comfort without impeding on the climber’s freedom of movement or interfering with any equipment. To solve this issue the conceptual prototype of the system was created and implemented into the jacket with consideration of the garment constructive lines. Scenario development and refinement for a conceptual prototype can be a lengthy process because it is coinciding with the process of defining the product (Adkisson, 2022).

A functional prototype is the closest representation of the final product that simulates its real-world functionality (*What Is a Functional Prototype?*, 2023). For this project, a functional prototype was created to demonstrate the operation of the heating system, encompassing both its hardware and software components. The development process was iterative, in which each successive prototype was informed by the evaluation of the previous one, addressing issues that emerged during the assessment phase. Software prototypes are typically more efficient in the later phases of design, once the fundamental design strategy has been established (Jacko, 2012). These prototypes create an intermediary step between the concept and its implementation, which can slow down the design cycle (Jacko, 2012).

Precision refers to the level of detail used to assess a prototype, ranging from informal and rough to highly refined and reliable (Jacko, 2012). It pertains to the relevance of details with regard to the prototype's purpose, focusing on the content of the prototype itself rather than its relation to the final system as this has not yet been defined (Jacko, 2012). The precision level typically escalates as prototypes are created successively, incorporating more detailed elements with each iteration. The level of prototype precision is often reflected by the prototype form; thus, sketches in general tend not to be detailed, while computer simulations typically present high level of precision. Precision defines the tension between what the prototype states (relevant details) and the aspects it leaves unspecified (irrelevant details). In my project, precision was important at various stages, including garment design, pattern making, and the selection of materials (specification).

Interactivity refers to the degree to which users can engage with the prototype, ranging from "watch only" to fully interactive experiences. An interactive system prototype plays a crucial role in elucidating the user-system interaction dynamics. Although online prototypes may seem naturally suited for this purpose, offline prototypes often facilitate the exploration of different interaction strategies more effectively (Jacko, 2012). Prototypes can exhibit varying degrees of interactivity. Fixed prototypes, for instance, are non-interactive: users cannot engage with them or simulate interaction. They are typically employed to demonstrate or test scenarios and are particularly suited for task-based and horizontal prototypes, which demonstrate a design from the user's perspective and/or the system's range of functionalities. This category of prototypes was utilised during the computer visualisation stage of clothing design, employing a digital model that included the simulation of some movements for the evaluation of fabric tension across different body segments.

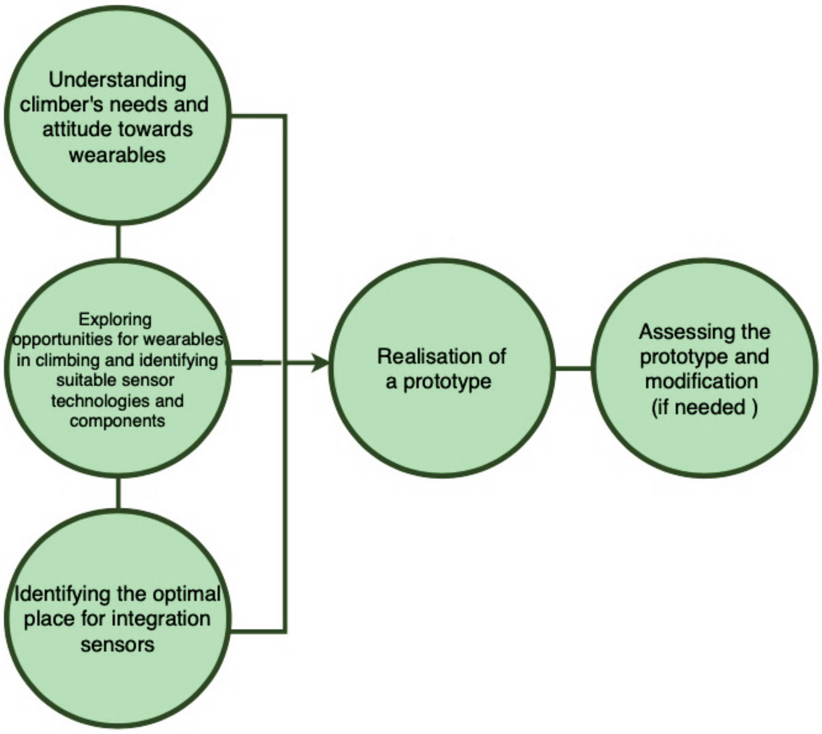
Open prototypes provide users and designers the flexibility to explore a broad range of potential interactions with the system. While these prototypes emulate the real system to some extent, they are subject to certain limitations. Typically, they address only a part of the system and may have limited error handling or reduced performance compared to the final system (Jacko, 2012). As a result, open prototypes can demonstrate or test various levels of interactivity. This type of prototype was utilised during the integration phase of the smart system into rock-climbing clothing.

Evolution refers to the anticipated lifecycle of a prototype, such as whether it is intended to be throwaway or iterative. This dimension of prototyping also involves considerations of sustainability (Motlogelwa, 2018; Niinimäki & Armstrong, 2013). Rock-climbing clothing must ensure proper fit, practical design, and durability of material as this type of garment should have a longer lifespan (Klepp et al., 2020). This means that climbers wear and use these garments for a longer period and this helps extend their lifecycle, thus making them more sustainable. Extending the lifespan of clothing is one of the most effective strategies for reducing the environmental impact of a garment as it decreases the frequency of its replacement, thereby minimising waste and reducing production and transportation needs (Laitala & Klepp, 2020). Given that rock-climbing clothing is not regular clothing, the service lifespan of such clothing can be described and measured in years (Klepp et al., 2020).

Prototyping is one of the key processes used in UCD, serving as a means to both learn from and guide the design process. Through prototyping, design assumptions derived from user insights are embodied in a tangible model that users can test. This iterative process allows for the refinement of the design based on user feedback about which aspects are practical and which are not (Naesgaard et al., 2017). A simplified model of the design process of a prototype related to the development of rock-climbing clothing or parts of garments is presented in Figure 3.10.

Figure 3.10

A simplified model of the design process of a prototype



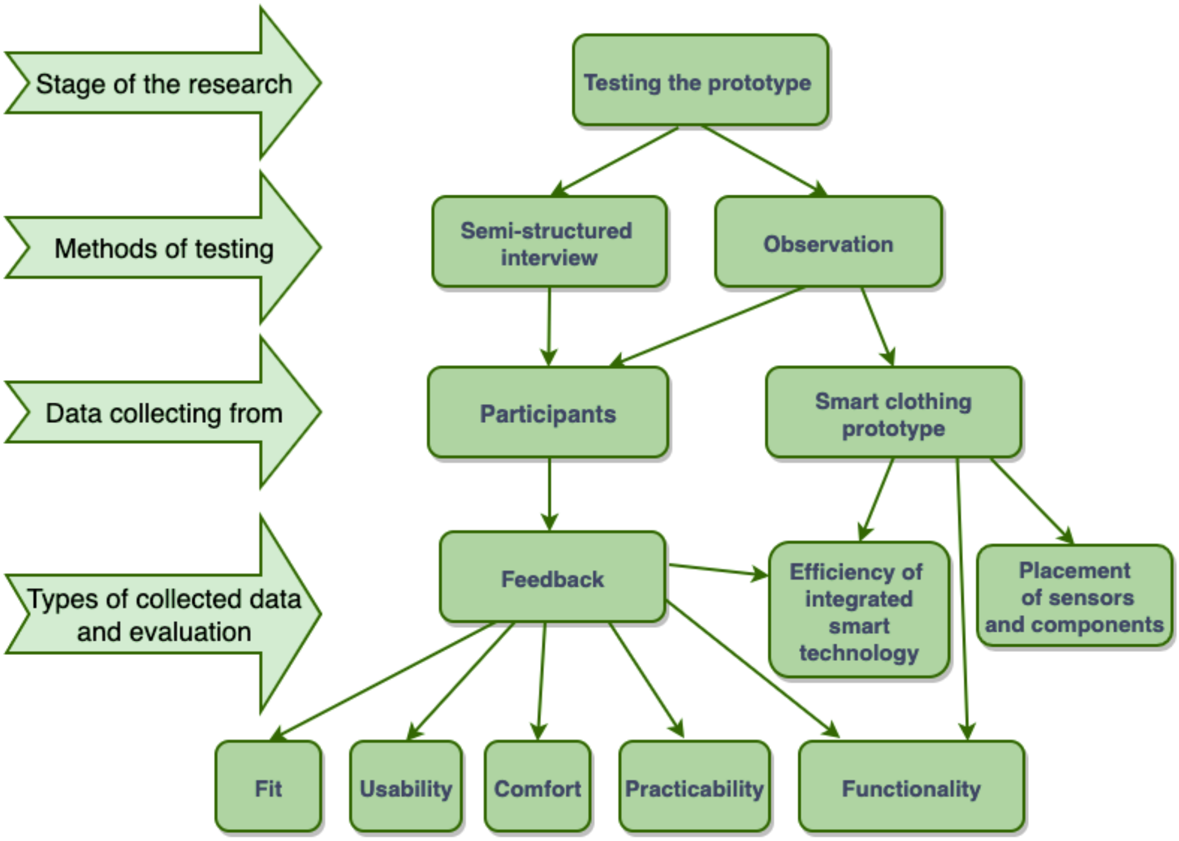
Note. This diagram was modified from "Co-Designing Wearable Devices for Sports: The Case Study of Sport Climbing". Copyright 2019 by Mencarini et al. (p. 30).

The development, testing, and refinement of prototypes is depended on the involvement and feedback of participants. In HCD and UCD, user feedback is a pivotal source of information. Involving users in the designs assessment and improvement designs based on user feedback is an effective strategy for reducing the risk that a system will fail to meet user needs, including those that may be latent or difficult to articulate explicitly (ISO, 2010). This assessment allows preliminary design solutions to be tested against real-world scenarios, with insights gained being used to progressively improve the design. Evaluation according to the UCD approach should also be a key component in the final acceptance of the product, ensuring that all requirements have been adequately addressed. Moreover, collecting feedback on operational use helps identify long-term issues and provides valuable input for future design improvements (ISO, 2010). In the primary testing phase of the prototype, a climber was involved in wearing and evaluating the prototype during climbing activities to assess its ergonomics and functionality, identify potential issues, and provide feedback that was then used to guide subsequent product modifications.

Feedback on the wearability, ergonomics, and functionality of the prototypes was gained through the evaluation by both the researcher, who has a garment engineering background, and an experienced climber (user) during an observation session, through a semi-structured interview. The interview questions were related to the fit, usability, comfort, and practicability of the selected clothing item and its functionalities. The evaluation of the clothing item integrated with wearable electronics involved assessing the correct placement of components within the garment. To achieve this, the climber was interviewed regarding their perception of each component while wearing the clothing in both static and dynamic postures. The diagram in Figure 3.11 illustrates the process of testing and evaluating the prototype.

Figure 3.11

The process of testing and evaluating the prototype



3.3. Development of a Functional and Ergonomic Smart Outdoor Jacket

The process of design and development of a smart rock-climbing jacket is structured and include the creation of both online and offline prototypes. For creating these prototypes, pattern-engineering methods and techniques as well as 3D fashion design software such as 3DStyle and CLO3D were utilised alongside various other programming tools. Electronics engineering methods, testing, and programming were also employed in this process. The smart outdoor rock-climbing jacket was developed in two separated processes: the jacket and the smart system were developed separately before being combined for the final design. These two processes, depictured in Figure 3.12, are:

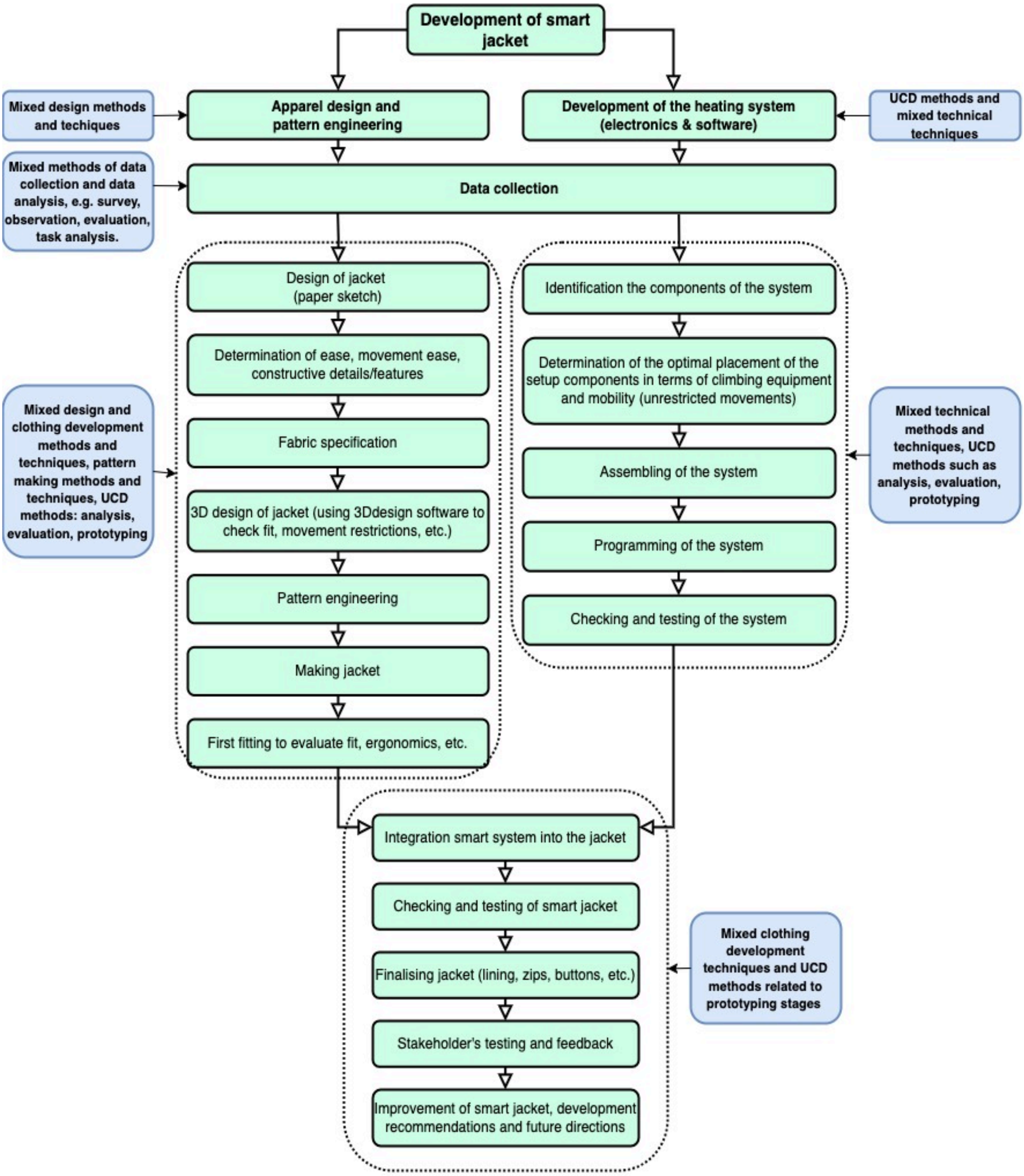
- the traditional process of development and fabrication of the jacket, incorporating considerations for its functionality in rock-climbing;
- the construction of an electronic heating system that provides warming functionality through the use of sensors.

This flowchart also indicated where UCD methodologies were used and which research methods were employed during the different stages of the research/design process.

Once the smart heating system was integrated into the jacket, the wearable prototype of the smart outdoor jacket for rock climbers was effectively created, which marked the beginning of the final testing phase. Although the initial stages were divided into two processes with the aim of simplifying this complex task, most processes were informed by initial findings from stakeholders (climbers) and were developed with their perspectives in mind. Thus, each stage of the garment design development took into account the outdoor climbing activities along with the range of climber's dynamic movement, environment, climbing equipment, and the potential placement of the system elements within the jacket to provide maximum freedom of movement, ergonomics, and functionality. The development of the smart outdoor jacket for rock climbers was a complex process that required the integration of multiple interconnected aspects to achieve the desired usability, ergonomics, and functionality in the final prototype. This process is detailed step by step in Chapter 5, "Development of an Ergonomic and Functional Rock-Climbing Jacket".

Figure 3.12

The process of the development of a prototype of a functional and ergonomic smart-outdoor jacket for the rock-climbers



3.4. Limitations of Using HCD and UCD Approaches

This section discusses the limitations associated with the use of HCD and UCD approaches. The main feature of UCD is that it prioritises human factors and ergonomics (HF/E) requirements by focusing design activities on how users can, want, or need to interact with a product, rather than forcing users to alter their behaviour to fit the product (Sun et al., 2018b). HCD further emphasises human comfort and preferences. Nevertheless, there is growing evidence that positioning the end consumer/user at the centre of the design process without regard to other necessary elements of the design process can lead to unintended consequences, potentially harming global systems that are vital to human well-being (Borthwick et al., 2022), for example through the manufacture of items which might be desirable to consumers, but are resource intensive and with a short lifespan.

Thus, the UCD is often criticised for its utilitarian and narrow approach which can lead to prioritise convenience and comfort over other critical factors such as the unsustainability of e-textiles (Dulal et al., 2022; Eppinger et al., 2023; Köhler et al., 2011; Loomia Technologies Inc, n.d.) and other unwelcome long-term consequences associated with clothing manufacturing (Girling & Palaveeva, 2017; Mithun et al., 2018; Sun et al., 2018b). For example, the survey analysis presented by Eppinger et al. (2023) found that e-textiles currently play a minor role in sorting and recycling processes, with about one-third of companies reporting issues with recycling these materials. Although e-textiles are partially recognised during sorting, existing sorting and recycling technologies and machinery are not designed to process them effectively. Additionally, the low volume of e-textile waste has resulted in a lack of urgency to develop specialised recycling solutions. According to Loomia Technologies Inc. (n.d.), electronic waste (e-waste) often ends up in developing countries, where it is burned to recover metals, creating significant environmental and health issues. Moreover, existing e-waste disposal and recycling programmes are generally not equipped to handle e-textiles, and increasing market volumes will exacerbate waste issues, including logistical problems, unless recycling practices are improved (Eppinger et al., 2023). It is recommended by some experts that the trend of technological convergence should be evaluated from a life cycle perspective (Köhler et al., 2011). It is recommended that technology developers and product designers incorporate waste prevention measures at the early stages in the development process (Köhler et al., 2011). In addition, enhancing the recyclability and recycling rates of e-textiles may involve expanding current regulations in the process of product design to include guidelines for integrating sustainable solutions of end-of-life disposal and addressing existing shortcomings in the recycling industry (Eppinger et al., 2023).

Furthermore, these approaches have not been widely adopted due to cost-benefit trade-offs considerations (Vredenburg, 1999). For instance, collecting and analysing data on how users interact with a product in specific environments is both time-consuming and expensive (Sun et al., 2018b). In addition, UCD methods are often tailored to specific contexts, making them difficult to apply as a universal standard across general design practices.

There is also a viewpoint that the fundamental assumptions underlying the process of designing need to be re-evaluated (Cruickshank & Trivedi, 2017). Wakkary (2021) argued that design must confront its impact on nonhuman species and the materials extracted and reduced for human use. This involves a radically different understanding of humans as having "co-evolved" with things, that we are a "prosthetic creature" that is so tied to technology, matter, and non-human beings that they have become part of us and shaped us. This clearly opens the door to rethinking not only the role that things play in design, but the role of design itself (Wakkary, 2021).

Overall, HCD and UCD approaches have a limited concept of the environment as that which mankind inhabits and uses, and ignores environmentally centred issues such as human impacts on the environment. A life-centred design approach that provides a more holistic perspective by decentring humans, has been suggested instead (Borthwick et al., 2022).

3.5. Conclusion

This chapter presents the research framework, methodology, methods and techniques employed in the research. Although the research is multidisciplinary, the epistemic foundation of the research was grounded in the field of ergonomics (IEA, n.d.; Tosi, 2020a) while the methodological framework was guided by User-Centred Design (UCD) across all stages of the project. To elucidate why the term "user" is applicable to wearers - despite its predominant association with information technology and human-computer interaction - the evolution of the UCD approach was briefly reviewed. According to Ferraro and Ugur (2011), two primary reasons justify this terminology:

- UCD is frequently described as Human-Centred or People-Centred Design, where the wearer (as a human) is central to the design process and hence termed as a user;
- in the domain of smart garments, designers employ the UCD approach to develop wearable technologies or wearable computers. In this context, the wearer functions as the user of these technologies, capable of evaluating design prototypes, suggesting modifications, and integrating final products into their routines (Ferraro & Ugur, 2011).

Both reasons are pertinent to the application of the UCD approach in the development of smart outdoor clothing for climbers. Integrating UCD into the research facilitated an understanding of the context, problem framing, and design development of ergonomic, functional, and intelligent rock-climbing apparel based on a comprehensive insight into user (climber) needs, expectations, and usage contexts. The chapter introduced a simplified interaction system among the climber, clothing, climber’s abilities and climbing condition, which was developed into a model illustrating the relationship between the elements and sub-elements of this system, highlighting their dynamic nature, material selection, and the integration of wearable smart technology.

The chapter reviewed various UCD methods and provided a detailed account of specific methods utilised in this research, including questionnaires, observation, and prototyping. Prototyping was emphasised as a crucial component within UCD approach. Detailed information regarding prototype types and prototyping techniques were presented, along with a simplified model of the prototyping design process for rock-climbing clothing and its components, including a diagram explaining the prototype testing and evaluation process.

This design process was summarised in a diagram showing the different stages of the development of a functional and ergonomic smart-outdoor jacket for rock-climbers. This diagram captured how the process involved two parallel processes as the jacket and the smart heating system were developed separately. The jacket and heating system were designed with each other in mind, with regards to such issues as the optimal placement of sensors and heating elements in terms of both the practicality of the garment and the feasibility of the electronics. The process of manufacturing these two elements then separated, after which the two design streams were combined into the final jacket.

The chapter concluded with a discussion of the limitations associated with the Human-Centred Design and User-Centred Design approaches.

Overall, this chapter described the methodological approaches used and discussed how the research design serves to address the research objectives of the project.

CHAPTER 4. DATA ANALYSIS AND FINDING INTERPRETATIONS

This chapter presents findings from the primary data collections that were used to inform the development of an outdoor jacket for rock climbers integrated with smart technologies. In accordance with the UCD approach adopted in this study (see Chapter 3), the primary data collection consisted of a survey and observation of climbers. The initial data gathered from the questionnaire distributed to experienced rock climbers informed the selection of articles of outdoor rock-climbing clothing for further analysis.

4.1. Survey

The survey component of the study was designed to gain a deeper understanding of the climbers' experiences, issues, and preferences related to clothing (Novikova et al., 2023). The questionnaire, titled "Rock climber's clothes - Satisfaction, preferences, requests and needs of rock climbers", was administered online using the Qualtrics platform (https://www.qualtrics.com/). In spite of extensive publicising only seven participants, six males and one female who identified themselves as advanced or intermediate level climbers, took part in the survey. The participants had all been rock-climbing from 5 to more than 10 years. While the number of respondents was lower that initially envisaged (for discussion of that limitation, see section 7.11), this smaller group of experienced climbers provided rich data which was both relevant and useful.

Participants were asked about preferred types and styles or designs of clothes for outdoor rock-climbing, and the brands of clothes they prefer to wear while rock-climbing, especially traditional climbing, mountaineering, or winter (ice) climbing. Key findings identified types and brands of preferred clothing, and features respondents considered useful, such as pockets, fit, fasteners, or a hood. Other findings included climbers' fabric and fibre preferences, colour preferences, and their attitudes towards durability issues, thermoregulation issues, and smart technologies. A qualitative heuristic approach was used for the data analysis (Moustakas, 1990; Nielsen, 1994). Open-ended questions were analysed using a content analysis approach to understand participants' perceptions and experiences with their existing clothing. As most of the survey questions were open-ended and required qualitative interpretation, statistical techniques - such as coding large volumes of numerical data - were not applied. Instead, due to the small sample size, I conducted the analysis manually, identifying key themes and issues emerging from participants' responses. The results were summarised in tables, models, and diagrams and are discussed in this chapter. The full report generated by Qualtrics can be accessed in Appendix C. The findings from the survey highlighted climber's needs and preferences, their problems with existing clothing, and potential areas of design intervention. These insights helped to inform the next design stages of the research.

All respondents indicated that their preferred rock-climbing clothes involved a jacket and pants. Two respondents also suggested they liked to wear a jacket together with semi-overalls (pants with bibs). Only one respondent preferred to wear overalls/suits. Two respondents also mentioned that they liked to wear shorts, t-shirt, and tights when rock-climbing. In addition, one respondent explained that he preferred wearing heavier industrial grade clothing that is often a hybrid of professional clothing such as ski patrol pants and specific clothing pieces that suit the climb and conditions. For example, they would wear an old Norsewear brand black woollen singlet for autumn trad climbing. Participants also identified six well-known brands of outdoor rock-climbing clothing they liked to wear, namely Sivera, Black Diamond, Arcteryx, NorthFace, PrAna, Marmot, and Kalborn.

Almost all participants wore helmets while rock-climbing with only one respondent answering they wore a helmet only “sometimes”. More than half of the respondents wore hoods, and 75% of them needed the hood to be able to cover the lower part of their face to offer protection against the wind. Most respondents have had a negative experience while wearing a hood as it tends to obstruct the climber’s vision and hearing. This information was considered at the stage of selecting the articles of outdoor rock-climbing garment to determine what type of garment to focus on for further analysis (see below). In terms of head coverage, it emerged that, while 86% of the respondents wore helmets while climbing, about 57% also wore hats or cap at times.

71.43% of the respondents indicated they used pockets. Participants identified the preferable number of pockets in a jacket to be between two to four. The respondents were asked to indicate the best placement for pockets with regard to equipment placement, movement, and accessibility and other factors. All respondents suggested that chest pockets (internal and outer) were the best option for a jacket. Pockets on sleeves were described as good but not always convenient to use. Respondents commented that the placement of pants pockets was particularly difficult due to the positioning of the harness, which would often block access to the pocket (as shown in Figure 4.1). Respondents commented that “while they (pockets in pants) are good for general purpose climbing they are not useful when wearing a harness”, that “pockets in the legs of pants often are blocked by a harness”, and that “pockets that are in the legs should be lower than a harness”.

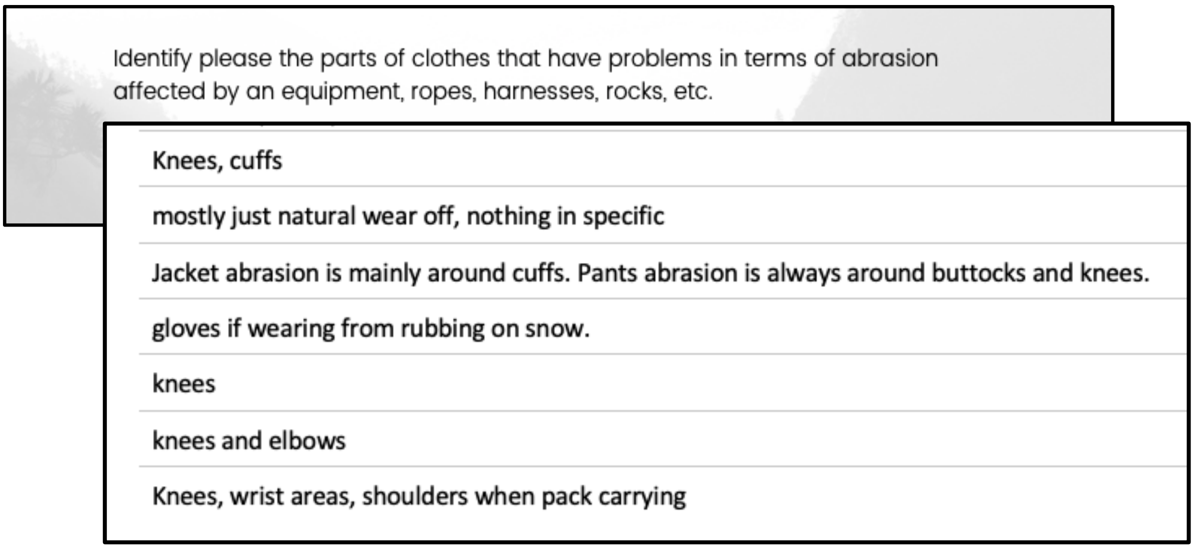
Figure 4.1

Pocket in climbing pants restricted by a harness (circled area)

Respondents were asked to identify parts of clothing that have problems in terms of abrasion affected by equipment, ropes, harnesses, rocks. This question was open-ended. The results showed that jacket abrasion was mainly around the cuffs, while in pants abrasion was around the knees (see Figure 4.2). In terms of durability problems, climbers also mentioned the knee area in pants (28.57%) and legs in general (19.05%). The areas of a sleeve and cuff in jackets were noted as being affected by durability issues (40% and 33.33% respectively) (see Figure 4.3).

Figure 4.2

Answers about abrasion problems in rock-climbing clothing



Identify please the parts of clothes that have problems in terms of abrasion affected by an equipment, ropes, harnesses, rocks, etc.

Knees, cuffs

mostly just natural wear off, nothing in specific

Jacket abrasion is mainly around cuffs. Pants abrasion is always around buttocks and knees.

gloves if wearing from rubbing on snow.

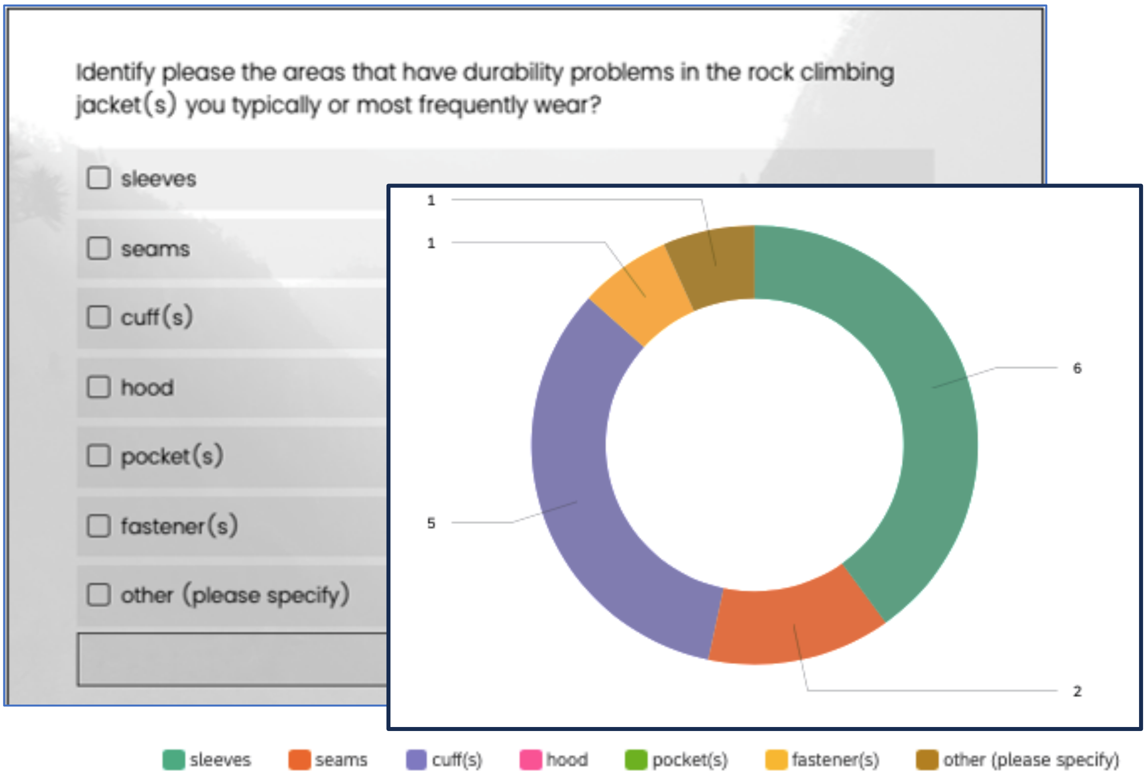
knees

knees and elbows

Knees, wrist areas, shoulders when pack carrying

Figure 4.3

Results for a question about durability problems in the rock-climbing jacket



Several questions were related to the microclimate inside the clothing layers. Respondents were asked to identify specific experiences with climbing clothes in relation to temperature (heating or cold) and humidity (wetness) while rock-climbing. Only one respondent noted that they have not had any negative experience related to clothing microclimate. The rest of respondents mentioned microclimate discomfort as in the experience when they have been hot and wet while rock-climbing or cold while belaying or having a rest, especially if it was windy. Two respondents shared their negative experiences with jackets that were to heavy and not breathable and caused their body to heat up quickly. A few respondents mentioned having had sweat withdrawal problems as their sweat became trapped inside the jacket layer. Respondents further commented that in alpine climbing clothing can also get wet from the snow.

Respondents were asked how many layers of clothing they usually wear and how they normally regulate the microclimate inside clothing layers (level of humidity or temperature) while rock-climbing. The experienced climbers specified that they would wear at least two layers of clothing and that the microclimate inside clothing layers tends to be regulated mostly by opening zippers or collars or by using different clothing options. If a climber got too hot or cold, they have to stop and take off or put on another layer, which is why most adopt a multi-layer approach to their clothing. Interesting answers were received for the question "Have you had any negative experiences while removing or putting on clothing while rock-climbing?". More than half of the respondents have experienced difficulties during this action. One respondent answered:

> "Yes. I have had multiple negative experiences removing or putting on clothing whilst rock-climbing. All of the experiences were either caused by fatigue or being in too much of a hurry to take care. Once I ripped my climbing pants in a catastrophic way on my crampons when I was putting them on. This was due to the zippers down the leg not working as expected. Definitely human error but also a very cold nite *[sic]*."

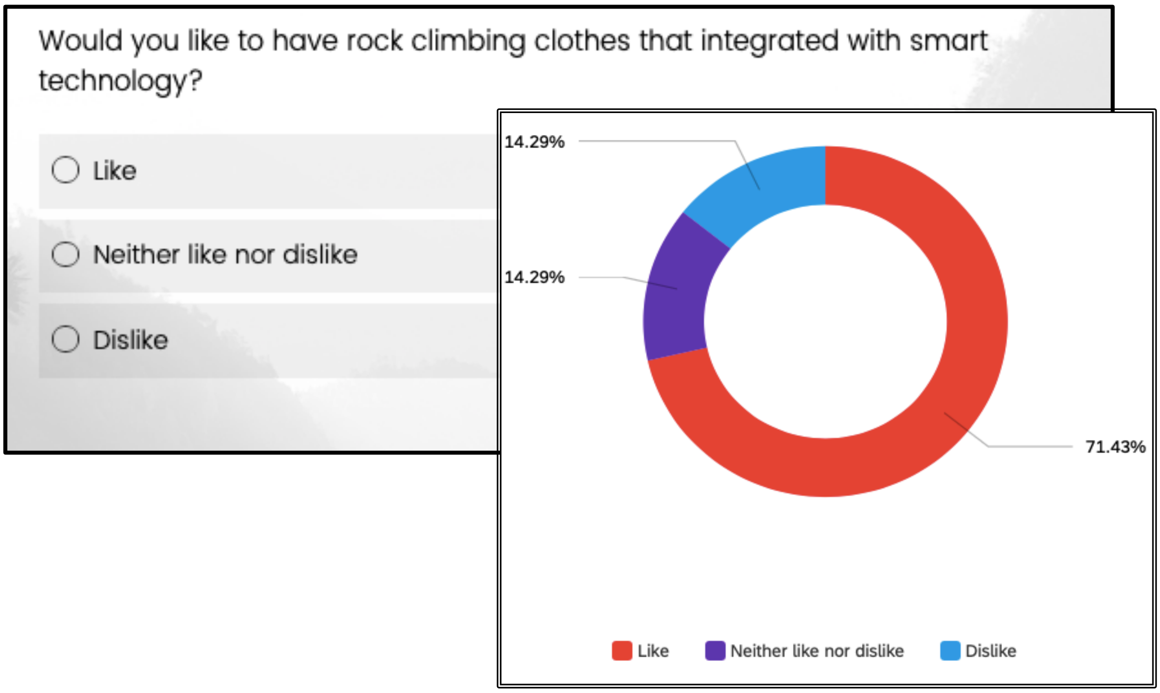
In terms of the preferences that climbers developed through experience over time, all respondents mentioned fabric and fibre preferences as they favoured stretch fabric and mixed synthetic and natural fibres. In relation to colour preferences, some respondents specified bright colours for safety, while others preferred quiet colours that blend into the environment. However, it was also mentioned that it was "nice to have options" as colour choices were often limited, especially for women in New Zealand. The types of fasteners which were rated most convenient for rock-climbing clothes were zippers and Velcro fasteners (Velcro tapes).

The factor that respondents considered most important when purchasing their outdoor rock-climbing clothes was the fit of the garment, while fabric type and cost came in at second place. Clothing fit, practical design, and durability of material were also important factors for rock-climbing clothing as garments with those attributes are more likely to have longer lifespans (Klepp et al., 2020). This means climbers wear and use garments for a longer period, which helps extend their lifecycle, thus making them more sustainable. This point was also supported by climbers' responses on how often they would purchase rock-climbing clothes - once a year or even every two years.

There were several questions in the survey regarding clothing and smart technology. Firstly, respondents were asked "Have you used any smart devices while rock-climbing? Please specify". Most respondents (71.43%) answered that they have used different smart devices. These included smartphones with a global positioning system and, for looking at the route topography, a smartwatch or a Garmin watch, and a barometer to measure the height and rate of climb. Also, barometers were used to monitor pressure changes that may indicate impending changes in the weather before they would be visibly apparent. None of the respondents had used any integrated smart clothing while rock-climbing. However, 71.43% of respondents said they would like to have rock-climbing clothes integrated with smart technology (see Figure 4.4).

Figure 4.4

Results for Question 33 - 'Would you like to have rock-climbing clothes that integrate with smart technology?'



Participants were also asked for their opinion on which sensors would be more important for rock-climbing clothing. The results of this multiple-choice question are summarised below in Table 4.1. Based on the answers collected from the survey, experienced climbers would like to have outdoor rock-climbing clothes that integrated with smart technology to measure and regulate the temperature and humidity level inside their clothing and to measure body vital signs. However, one climber specified that "weather, location and perhaps passive communication" may be more important than sensor capability.

Table 4.1

Results for Question 34 – 'In your opinion, which sensors are more important for rock-climbing clothing? (You can choose more than one option)

Proposed Answers:	%	Total number of answers
measuring and regulating temperature inside clothing	26.32%	5
measuring and regulating humidity inside clothing	26.32%	5
measuring and tracking movements	15.79%	3
measuring body vital signs (temperature, pulse rate, respiration rate, blood pressure etc.)	26.32%	5
other, please specify bellow	5.26%	1
Total	100%	19

The findings obtained from the survey played a pivotal role in informing subsequent stages of the research. Thus, data related to climbers' preferred brands and types of outdoor rock-climbing styles and designs facilitated the selection of existing outdoor rock-climbing garments for analysis and guided the stages of design development for the jacket. The clothing analysis results are presented in the next section.

4.2. Clothing Analysis

The purpose of the analytical study of outdoor rock-climbing sportswear that is currently available on the market was to provide a detailed analysis of the existing technical design solutions of such clothing. This served to provide a better understanding of current clothing ranges for outdoor climbing in terms of their performance, functionality, and materials selection. The analysis focuses on the brands and types of clothing identified by experienced rock-climbers in the survey. Respondents mentioned seven well-known brands including Sivera, Black Diamond, Arcteryx, NorthFace, PrAna, Marmot, and Kalborn. The brand Kalborn was excluded from the analysis as the clothing is designed without a specific rock-climbing focus. After selecting different types of clothing from these brands, detailed design information were collected from the companies' websites.

The criteria for selecting the types of clothing to be analysed were based on the preferences listed by the experienced climbers for outdoor climbing clothes in terms of pattern construction, functionality, and ergonomic solutions. The analysis also assessed the materials and types of fasteners used as well as the price of each item. The types of outdoor rock-climbing clothing which are commercially available are mostly jackets and pants, including bibs. For extreme cold climate conditions, warm overalls are produced, but there are not many models available on the market. Sets of semi-overalls and jackets are more commonly available. Table 4.2 presents the articles of clothing and their amounts related to the brands that were included in the analysis.

Table 4.2

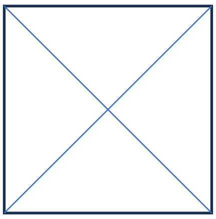
Types and brands of clothing chosen for analysis

The articles of clothing	Brand of clothing						Total
	Black Diamond	Marmot	NorthFace	Arcteryx	PrAna	Sivera	
Pants	1	-	-	2	1	1	5
Bibs	1	-	1	-	-	-	2
Jacket	1	1	1	3	-	2	8
Overalls/suit	-	1	-	-	-	-	1

The analysis of these sixteen articles of clothing involved an initial examination and systematic description. For this analysis, the predominant source of information was descriptive information and images from the manufacturers/sellers' websites. Information gauged from actual samples of clothing (in-store or those belonging to friends) were also considered. Each article of clothing was evaluated by the researcher who has a pattern-making background and expertise in the textile and garment design fields. In this process, the general characteristics of clothing were evaluated, including materials, display weight, and price. Additionally, a deep analysis was conducted of specific constructive details of clothing with regards to their functions in the garment. The analysis of the Alpine light pants - Men's by Black Diamond presented below illustrates the process used in relation to a specific item of clothing (see Figure 4.5 and Tables 4.3 and 4.4).

Figure 4.5 (Image removed due to copyright restrictions)

Appearance of the Alpine light pants - Men's (brand Black Diamond)



Note. Image from https://www.blackdiamondequipment.com/en_US/product/recon-bibs-mens/?colorid=8641

Table 4.3

Characteristics of the Alpine light pants - Men's (brand Black Diamond)

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Pants	An ultralight wind barrier, the Black Diamond Alpine Light Pants are the three-season solution for light, packable weather protection. Designed with a single-weave, four-way stretch fabric, they pack down so you can shove them deep into the recesses of your pack, and the DWR treated finish gives you a layer of shelter when light precip rolls in. Two rear drop pockets and zip thigh pockets stash essentials, and a ladder lock belt with belt loops and adjustable cuffs dial in the fit.	• Ultralight single-weave construction • DWR* treatment • Two rear drop pockets • Zip thigh pockets • Seat gusset • Ladder lock belt with belt loops	Four-way stretch woven with DWR finish (150 gsm, 85% nylon, 15% elastane)	290 g	$110 USD
https://www.blackdiamondequipment.com/en_US/product/recon-bibs-mens/?colorid=8641					
Note. *Durable water repellent (DWR), a treatment that is applied to the outermost fabric layer. DWR reduces the surface tension of the fabric, so that water simply rolls off.					

Table 4.4

Analysis of some details of the Alpine light pants - Men's (brand Black Diamond)

Figure	Description	Function/Comments
	Zip thigh pocket with diagonal access	**Ergonomics** The pocket's placement does not interfere with the position of a harness, thus ensuring unrestricted access. **Protection** Zipped pockets prevent loss of belongings while climbing.
	Cord-lock technology in hem of pants	**Comfort, ergonomics** This type of hem allows for pants to be fixed tightly around ankle if needed.
	Ladder lock belt with belt loops	**Protection, Ergonomics, Comfort, Fit** Additional lock to prevent the button opens.
	Seat gusset	**Ergonomics** Seat gusset allows for more movement in the hip and leg area allowing the climber to have a larger range of motion

The full report of this analysis can be accessed in Appendix D. Following the tabulation of this report, a comparative analysis of the information was conducted to identify commonalities, differences, and relevant issues. The findings of this analysis are presented below.

4.2.1. Fibres and Fabric Characteristics

Based on the analysis of fabric selections, fabrics made from synthetic fibres were more prevalent than natural fibre options. For example, the brand *prAna* uses 95% recycled nylon and elastane for their rock-climbing pants. A composition of nylon and elastane fibres is common to all brands. This fibre combination is used in different proportions, for climbing pants and some jackets, where flexibility is important. Incorporating elastane fibres into fabrics provides high tensile properties. Elastane fibres, also known under trade names such as Spandex, Lycra, or Dorlastan, have exceptional elasticity, with an extension-at-break greater than 200% and showing a rapid recovery when tension is released (Senthilkumar et al., 2011). These fibres exhibit rubber-like behaviour with high reversible extension up to 400 - 800%. These fabric characteristics enable freedom of body movement by reducing the fabric resistance to body stretch. Rock-climbing pants, but less commonly jackets, can be made of fabric that consists of natural fibres in combination with synthetic fibres. In addition, some manufacturers use fabrics with flexible weave or knit structures along with stretchable fibres to provide these properties. For instance, Black Diamond uses a single-weave, four-way stretch woven fabric that consists of 85% nylon and 15% elastane for their Alpine Light Pant. Other represented manufactures also use nylon or stretchy nylon/elastane blend textiles for outdoor rock-climbing clothing.

4.2.2. Durability

Areas of clothing that have durability problems are often strengthened with fabrics that prevent punctures and rips, or that have abrasion-resistant properties. Manufacturers also use textile materials with different types of finishing, such as durable water repellence (DWR), to improve the durable characteristics of clothing. DWR reduces the surface tension of the fabric, so that water simply rolls off. For instance, Recon Stretch bibs-men’s (Black Diamond) has reinforced parts of pants with nylon double-weave fabric with a DWR finish. The lower-leg exterior of the Men's Summit L5 Futurelight™ Full Zip Bib (North Face) made from 75D x 100D 141 g/m² Futurelight™ 3L-91% recycled polyester, is reinforced by 9% polyethylene Spectra® ripstop with 100% recycled nylon tricot backer and DWR finish.

4.2.3. Protection

Brands such as Marmot and Sivera that make rock-climbing clothing for extremely cold weather conditions provide superior wind and water protection and warmth for “summit bid-worthy adventures” by using 100% Nylon for the outer layer of clothing and different types of insulation. For the WarmCube™ 8000M Suit and the Unisex West Rib Parka, Marmot combines 800-fill-power goose down and Pertex Quantum® fabric (100% Nylon, Dobby, 70g/sqm). Sivera also uses high-quality goose-down SmartDown FP 700+ 501g with hydrophobic treatment for insulation. In addition, many manufacturers develop their own technologies to improve the characteristics and functionality of rock-climbing clothing. For example, Marmot uses their own, patent-pending, WarmCube™ construction technology for ultra-comfortable warmth in extreme conditions.

From an analysis of fasteners that manufacturers use in their clothing, different types of fasteners were identified, including zippers, buttons, snaps, Velcro tape, and elastic. Fastening systems in rock-climbing clothing provide mobility and protection. Thus, some manufacturers use technical zipper vents in pants and jackets for ventilation to prevent overheating. For protective and functional clothing, fasteners must be positioned for comfort and easy access (Shanley et al., 1993), and can aid in the putting on and taking off procedure (Michaelson et al., 2018).

4.2.4. Pattern Engineering

Climbing pants, jackets, and overalls were assessed using commercially available samples of clothing and information from the manufacturers' webpages. A detailed analysis of the design solutions for the selected types of high-performance clothing designed for outdoor climbing identified the main principles of pattern engineering for such clothing. The focus hereby was to identify the main principles of pattern engineering construction for such clothing used to provide optimal fit, mobility, ergonomics, and comfort. A summary of this analysis is presented below.

Climbing Pants. The main features identified in the patterning of climbing pants through this analysis included:

- the waistline is fitted higher, so it does not sit under a harness;
- adjustable waistband;
- attached, adjustable suspenders for bibs;
- seat gussets allowing for more movement in the hip and leg area, allowing the climber to have a wider range of movement. Seat gussets provide more crotch room for high leg lifts;
- articulated pattering of the knees area. This feature is incorporated by the addition of extra darts around the knee area to make this area less constricted, thereby to provide ergonomics and comfort while climbing;
- correct length with options for rolling up and incorporating functional adjustments, for example adjustment on the bottom of the pants, allowing them to be used as 3/4 shorts;
- an anatomical design that provides an optimal fit that is realised by addition of extra darts, correct eases, and the pattering of the constrictive lines which duplicated the shape of a body;
- some pants have zippers on either side of the legs for ventilation;
- pockets with easy access. Pockets are placed so that they would not be blocked by a harness;
- pockets are usually zippered to protect belongings from falling out. Thus, to provide a better fit and comfort the line of pocket's access must be straight as a zipper cannot be inserted into a curved pocket seam allowance.

Climbing Jackets. The main features in pattern construction for jackets and overalls designed for climbing are:

- fit that provides freedom of movement with room for layers under a jacket;
- a front and/or a back yoke are typical for rock-climbing jackets. The shoulder dart is converted into a back yoke line. For women's rock-climbing clothing a bust dart may be converted or partly converted into a front yoke line;
- hem lines may be straight or with a slight drop-tail, with adjustable hem drawcord mostly. For example, in the Alpha AR jacket men's (Arcteryx) Cohaesive™ hem adjusters function as Hemlock™ to prevent a jacket from slipping out from under a climbing harness;
- the jackets designed for cold weather conditions have a protective inner skirt with stretch panel and gripper elastic;
- some manufacturers (Arcteryx, North Face) use a seamless shoulder line design which makes carrying a pack more comfortable;
- two main types of sleeve construction were identified during the analysis of existing clothing: a plain sleeve and full sleeve. It is interesting that a raglan sleeve, which is a preferred style for sportswear, was not detected among outdoor rock-climbing clothing made by the selected brands. The most likely reason for this is the restriction of arm movement. As many manufacturers use non-stretchable fabric in their jackets, a raglan sleeve may restrict the sort of upright arm movement that is a very common body position in rock-climbing.
- sleeves may have an elbow dart to provide ease of motion and better fit;
- some clothing has lift gusseted underarms;
- sleeve hems are primarily finished with a cuff. The cuffs may be relaxed to fit over gloves or, conversely, are close-fitted around a wrist. The cuffs are mostly adjustable with Velcro.
- hoods are adjustable and helmet compatible. The hood may have adjustments along the hood face opening length to make it more contoured and/or horizontal adjustments for volume regulation. Generally, hood adjusters are glove-friendly. All analysed jackets have an attached hood integrated with a tall collar to protect the lower part of the face from the wind. For example, the Sabre LT jacket - Men's (Arcteryx) has an attached adjustable and helmet-compatible hood with an integrated tall collar that covers the chin, mouth, and nose tip.
- overheating and other thermoregulation issues are solved by including armpit zip vents. For greater convenience, two-way zips are used;
- pocket configuration: hand pockets, chest pockets, and internal pockets were identified as the primary types. Some jackets may have sleeve pockets on one both sides. The pockets are mostly zippered. The pockets should be easy-to-reach even when wearing equipment so the placement of a harness and rope must be considered. For instance, in the Mission Ski Shell - Men's (Black Diamond) there are two concealed-zip hand pockets, two concealed-zip chest pockets and a zip

sleeve pocket with an internal stretch mesh pouch and two skin-compatible, internal stretch-mesh drop pockets.

The findings from this garment analysis informed the design and pattern engineering solutions and materials selection for the jacket designed as part of this research project which is discussed in detail in the next chapters.

4.3.Observations

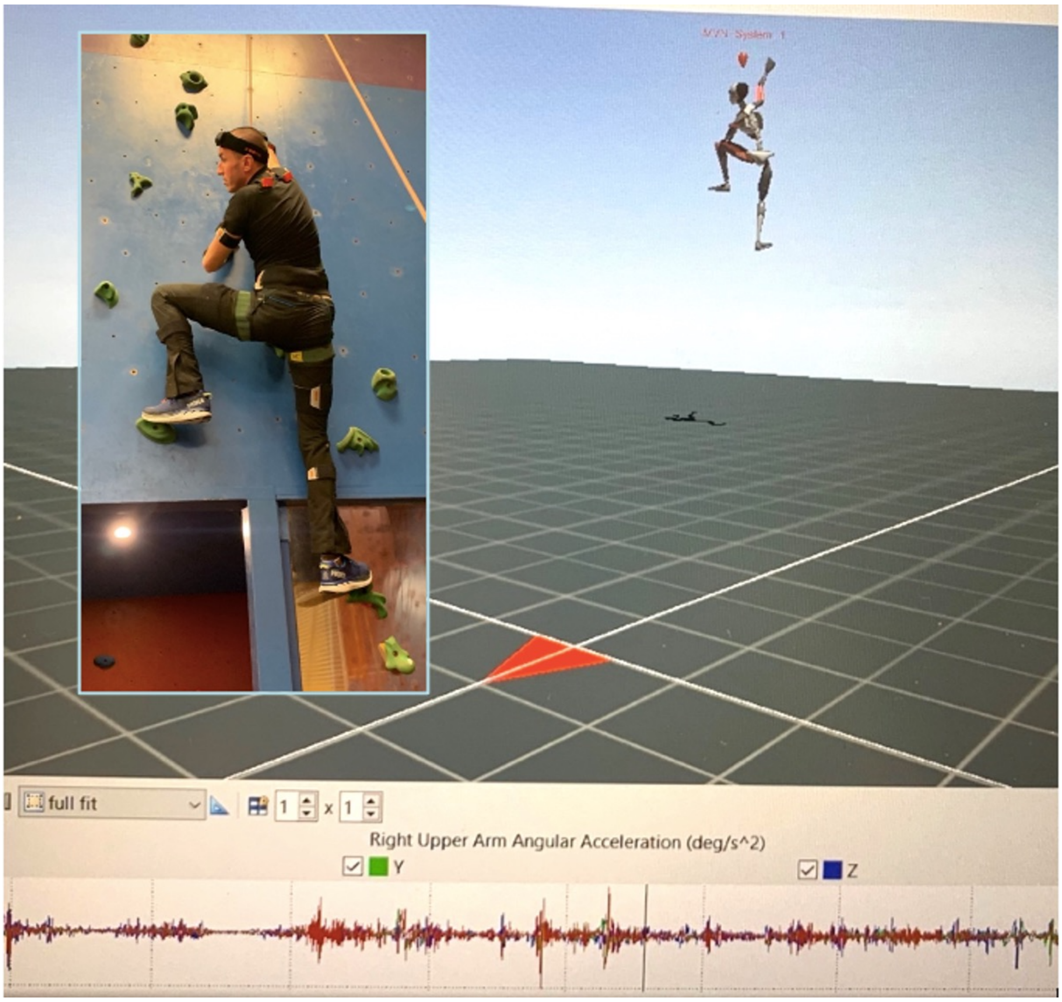
As previously described in the Chapter 3, the observation session took place on an indoor climbing wall at Sports Performance Research Institute New Zealand (SPRINZ), located in Auckland University of Technology's Millennium gym. For the observation phase of the research, two experienced climbers were recruited based on their climbing expertise and availability. Participants for this session were selected from among those who completed the initial survey, which included a final question asking whether they would be willing to participate in subsequent stages of the study. Therefore, the primary selection process took place during the survey phase. For the observation, the Xsens system technology, specifically the MVN Awinda Straps System (Xsens Technologies B.V., 2020) as well as manual measurements were used. The system provided data on the position, orientation, and kinematic characteristics of each body segment with respect to an earth-fixed reference coordinate system. The focus was on determining the raising parameters of key body segments, such as the arms, legs, and back, as well as the angular parameters of main joint angles, which were evaluated using the MVN software. The raising parameters were evaluated and calculated manually using CAD software in combination with the video and photo data and manual body dimensions obtained during the observation sessions.

The first stage of the observation session involved synchronising the MVN recording with photo and video data. This synchronisation process was crucial for gaining a better understanding of the biokinetics involved in the climbing process and identifying the relevant parameters for evaluation. Manual correction was performed to address any time discrepancies between the MVN data and video recordings.

The MVN Analyze/Animate application provided various viewing options, including a 3D character in the 3D viewport and orthogonal views. To ensure consistency, a similar viewpoint to that in the photo or video screenshots was used for analysis (see Figure 4.6). In addition, the video and screenshots incorporated graphical representations of the kinematic data obtained from the MVN system. Figure 4.6 shows an example of the synchronisation process between the MVN data and photos, highlighting the integration of multiple data sources for comprehensive analysis.

Figure 4.6

An example of the MVN and photo synchronisation



The data obtained from the observation sessions was exported to an Excel spreadsheet for further analysis. The spreadsheet contained comprehensive information about each session, including general session details, kinematic data for each body segment, joint angle parameters, and their corresponding positions and orientations. This dataset includes various metrics such as velocity, acceleration, centre of mass, rotation, and more.

In this study, anthropometrical characteristics were analysed in terms of the development of ergonomic clothing in the stages of design and pattern engineering, while usually, such characteristics are used to assess indoor and outdoor rock-climbing performance. For instance, Ezzy et al. (2018) investigated the anthropometric measurements, endurance, strength, climbing techniques, and training characteristics of sport climbers to gain insights into how these factors influence outdoor red-point performance (red-point refers to successfully climbing a route). Different methods and tests were utilised to calculate these characteristics and regression analysis was used for further assessment. Ezzy et al. (2018) noted that, since there were no significant differences detected between bilateral measurements in the study, only dominant arm/hand data were analysed and reported.

Identification of the physiological and anthropometric determinants of sport climbing performance was also the objective of Mermier et al.'s research (2000). The findings of this study indicated that the training component uniquely explained 58.9% of the total variance in climbing performance. The anthropometric and flexibility components explained 0.3% and 1.8% of the total variance in climbing performance respectively.

Magiera and Roczniok (2018), on the other hand, sought to explore the similarities and differences in the anthropometric, physiological, and training characteristics of advanced rock climbers. Their findings for the range of movement of the lower limbs at the hips indicated that the participants' flexion fell within expected norms (approximately 120°) for individuals in the same age group (18–40 years). However, for abduction, the range of movement was significantly greater at 51.3 ± 6.95° compared to the norm of 40°. Flexibility when holding the body close to the wall in the 'frog' position (see in Figure 4.7 below) showed the greatest differentiation among the participants.

The current study provided an analysis of dynamic stretching characteristics that were considered during the stages of design and flat pattern development. The term "dynamic stretching characteristics" refers to the changes or variations in body dimensions or measurements during dynamic movement or stretching activities. In the context of rock-climbing clothing, these characteristics can be described using terms such as:

1. Dynamic elongation: refers to the increase or extension of body dimensions during dynamic movements.
2. Dynamic extension: describes the stretching or lengthening of body segments or measurements during dynamic actions.
3. Dynamic flexibility: refers to the degree to which body dimensions can change or adapt during dynamic movements.
4. Dynamic range of motion: describes the extent or scope of body movements and the corresponding changes in body dimensions during dynamic actions.

These terms highlight the dynamic nature of stretching or movement and how it affects the body dimensions or measurements relevant to the design of rock-climbing clothing. Thus, the MVN data of dynamic range of motion that were recorded during the observation sessions were used to analyse the angular parameters of the hip, knee, shoulder, and elbow joints measured in degrees. The hip, knee, and shoulder joints allow for rotation in three directions: flexion(+)/extension(-), abduction(+)/adduction(-), and internal(+)/external(-) rotation (Zhang, 2021). Table 4.5 presents the maximum and minimum values of each angular parameter recorded across the three observation sessions. This table provides a summary of the joint angle parameters observed during the climbing sessions and thereby offers insights into the range of motion and variability of the selected joint angles.

Table 4.5

Parameters of joint angles while climbing

Parameters (deg)	Abduction (max)	Adduction (min)	Internal Rotation (max)	External Rotation (min)	Flexion (max)	Extension (min)
Joint angles	First session					
Right Hip	49.23	-9.37	29.86	-16.99	119.75	-
Left Hip	43.84	-17.49	34.21	-10.58	119.7	-3.03
Right Knee	7.03	-24.68	31.77	-20.8	154.6	-
Left Knee	4.39	-26.52	31.75	-19.24	155.78	-
Right Shoulder	69.94	-24.92	79.47	-41.5	106.15	-64.26
Left Shoulder	62.87	-6.48	90.67	-53.9	111.01	-94.29
Right Elbow	-	-	-	-	117.7	-11.92
Left Elbow	-	-	-	-	131.77	-17.55
Second session						
Right Hip	44.41	-14.24	29.57	-22.89	132.28	-0.75
Left Hip	41.08	-19.78	32.11	-25.61	114.54	-
Right Knee	5.56	-29.79	27.21	-10.88	168.65	-
Left Knee	7.57	-21	12.57	-15.47	121.68	-
Right Shoulder	33.09	-86.88	107.97	-83.75	180	-179.9
Left Shoulder	78.37	-12.48	69.93	-73.09	119.17	-33.57
Right Elbow	-	-	-	-	123.46	-7.05
Left Elbow	-	-	-	-	100.24	-12.73
Third session						
Right Hip	48.95	-19.44	41.96	-15.55	144.1	-3.6
Left Hip	54.25	-31.8	47.49	-38.29	150.25	-
Right Knee	6.01	-45	57.11	-19.46	154.44	-0.44
Left Knee	8.21	-29.51	38.83	-20.82	163.1	-5.15
Right Shoulder	-	-88.66	179.76	-179.96	179.82	-179.97
Left Shoulder	87.78	-	89.41	-157.56	127.99	-136.71
Right Elbow	-	-	-	-	128.2	-13.74
Left Elbow	-	-	-	-	117.66	-17.29

The table illustrates the extensive range of motion displayed by the climber during climbing. Overall, flexion showed the maximum parameters for the presented flexible joints. Notably, hip flexion, for example, involved raising the leg in front of the body (Zhang, 2021) and exhibited a range of motion between 115 and 150 degrees. The knee joint displayed varied flexion spectrum, encompassing angles between 122 and 169 degrees. Moreover, the knee joint allowed for up to 57 degrees of internal rotation during climbing. The shoulder and elbow joints demonstrated a range of motion up to 180 and 132 degrees, respectively. Among the joints, the shoulder exhibited the greatest abduction of up to 88 degrees, whereas the knee joint showed minimal abduction, measuring at only 8.2 degrees. These dynamic stretching characteristics should be considered in the design of rock-climbing apparel (as shown in Figure 3.4) to determine the allowances made for dynamic ease, also referred to as "movement ease", for the different parts of clothing, ensuring that it accommodates the dynamic movements and stretching requirements of climbers. If these dynamic stretching characteristics were ignored, the significant tension and pressure of fabric would be generated around the contact points of clothing and body parts, reducing comfort at those points and impeding movement significantly.

In addition to the computer assisted assessment, a manual evaluation was conducted on certain body dimensions and angular parameters. To facilitate this assessment, a series of dynamic posture images were selected and analysed using the computer-aided design software, AutoCAD (see Figure 4.7). This approach allowed for an intricate examination of body dimensions and angular measurements within the dynamic climbing context. The data assessed using CAD software was subsequently collated with manually acquired body dimensions from the observation sessions. Overall, these measurements demonstrated commensurability, indicating approximate equivalence or comparability.

Dynamic elongation characteristics were further elucidated through the computation of disparities between body measurements in static and dynamic positions. For instance, in the posture depicted in Figure 4.7, the inner length of the leg from the crotch level to the ankle level, passing through the highest point of the knee cup, fluctuates between 2.5% and 13.5% contingent upon the knee joint angle, ranging from 180 to 10 degrees, respectively. Similar assessments were conducted for various other body measurements, including arm length, back length, and so forth. Consequently, the length of the back from the back neck point to the waistline varies from 3% to 12.2% based on the arm position during climbing. Likewise, the length of the arm from the armpit back fold point to the wrist line ranges from 4.5% to 26.5% during climbing activities. These parameters merit consideration in pattern engineering, particularly in relation to specific pattern details such as sleeve length, pants length, crotch length in pants, and back length. For instance, the examination of dynamic anthropometry unveiled that the most substantial dynamic elongation in pants is concentrated in the segment associated with the inner length of the leg and the distance from the waistline to the crotch fold. Therefore, for the pattern of climbing pants, extension is imperative along the crotch line of the back parts of the pants and the inner cut line of the back parts of the pants (see Figure 4.8). Additionally, adjustments to the overall length of the pants are necessary.

Figure 4.7

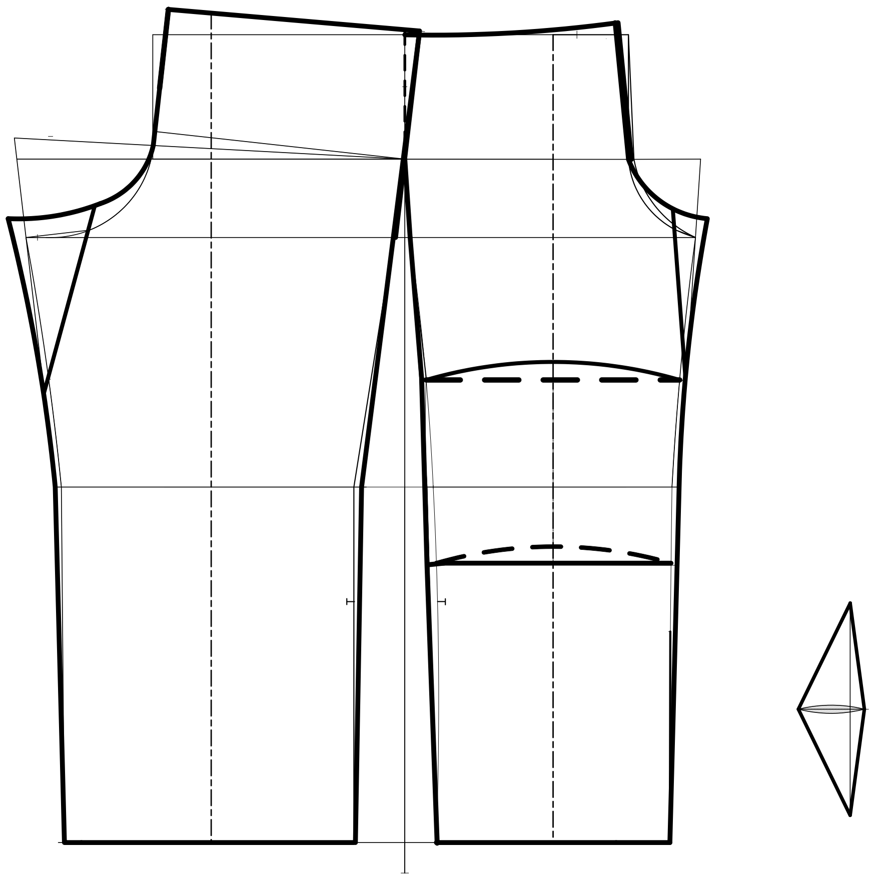
Assessing of the dynamic posture using the CAD software

Further advancements in clothing design, based on this study, encompass the enhancement of overall functional fit. For instance, to alleviate restriction of movements a gusseted crotch should be incorporated into the climbing pants to improve flexibility. In accordance with fabric pressure analysis and joint angle findings, it was determined that the elbows in jackets and the knees in pants endure the most constriction during climbing activities. Therefore, design enhancements in these specific areas should be deliberated upon. Few strategies may be employed to address these problematic areas:

- Utilisation of stretch textile materials characterised by both flexibility and high abrasion resistance.
- Implementation of pattern engineering techniques such as the incorporation of dynamic ease and/or the strategic addition and manipulation of extra darts.

Figure 4.8

An example of modification the patterns of climbing pants considering dynamics parameters



4.3.1. Limitations of the Xsens System Technology

The Xsens system technology represents an innovative motion tracking system capable of furnishing data pertaining to the position, orientation, and kinematic attributes of each body segment relative to an earth-fixed reference coordinate system. In the context of developing rock-climbing apparel, emphasis was placed on determining the angular parameters of main joint angles, evaluated through the MVN software, and scrutinising the raising parameters (dynamic elongation and extension) of key body segments, such as the arms, legs, and back. These parameters underwent manual evaluation and calculation utilising CAD software, augmented by video and photographic data, as well as manual body dimensions acquired during observational sessions. Notably, the Xsens system data did not contribute to defining these parameters comprehensively, as its primary function is to furnish a range of information, such as data regarding body segment coordinates, velocity, or acceleration, without specifically capturing dynamic stretching characteristics.

Moreover, the challenges of accurately assessing the difference between key body landmarks in static and dynamic positions arose due to the complex floor levels involved in real climbing scenarios. During the observation sessions, the climber engaged in real climbing and did not merely imitate movements on the floor. Therefore, the software scenario capturing the climbs included multiple floor levels, and this may have caused inaccuracies in the post-processing calculations due to the difference between the evaluated key body landmarks in static and dynamic.

4.4. Conclusion

This chapter presents the analysis of the data collected and interpretations derived from various stages of the research process, encompassing surveys, analyses of commercially available clothing, and observational sessions. These data identified a number of issues pertinent to the design and development of rock-climbing apparel.

The survey served as a valuable tool for gaining insights into climbers' experiences, issues, and preferences regarding clothing, thereby identifying their needs and potential areas for design intervention. In line with the UCD approach, the findings obtained from the questionnaire completed by experienced climbers played a pivotal role in informing subsequent stages of the research.

For instance, insights received from the survey regarding climbers' preferred types, styles, and designs of clothing for outdoor rock-climbing, as well as their favoured clothing brands, facilitated the selection of existing garments for analysis and guided the stages of design development for the jacket. The insights gained from both the survey and the analysis of existing rock-climbing clothes informed optimal solutions regarding pocket placement, hood configuration, fabric specifications, and other design components. Moreover, the survey responses identified the most problematic areas of clothing in terms of abrasion and durability issues. Consequently, recommendations were provided on how to reinforce these areas to enhance durability and longevity. Additionally, inquiries regarding thermoregulation concerns and the integration of smart technologies suggested that these would be desirable features for end users.

The analysis of existing outdoor rock-climbing sportswear contributes to the field of ergonomic and functional rock-climbing clothing by offering valuable insights into design aspects, pattern engineering solutions, performance of existing clothing ranges for outdoor climbing, functionality, and materials selection. This data collected delivered information concerning fibres and fabric characteristics, durability issues and corresponding solutions, as well as protective functionalities. Furthermore, the analysis offered a detailed examination of design solutions for represented types of high-performance clothing specifically designed for outdoor climbing. It enabled the identification of key principles of pattern engineering essential for such apparel that ensure optimal fit, mobility, ergonomics, and comfort for climbers.

The data collected during observation sessions contributes to the field of ergonomic rock-climbing clothing design by providing insights into the movement dynamics and anthropometric considerations of climbers. By employing advanced motion capture technology, manual measurements, and CAD analysis, the research shed light on the specific parameters and joint angles that play a significant role in the design of functional and ergonomic clothing for climbers.

The findings emphasise the importance of understanding the unique biomechanics and movement patterns associated with rock-climbing. The angular parameters of the hip, knee, shoulder, and elbow joints were identified, providing crucial information for the development of clothing patterns that allow for an optimal range of motion and comfort during climbing activities. Incorporating articulated patterning around pivotal joints, such as the knees or elbows, through the inclusion of additional darts, stands to enhance flexibility and expand the wearer's range of motion. Seat gussets can provide more movement in the hip and leg areas, allowing for a wider range of motion during high leg lifts. Moreover, the incorporation of appropriate ease and dynamic ease allowances in the clothing design would ensure that climbers can manoeuvre with freedom and comfort while maintaining requisite levels of flexibility and protection. Furthermore, the research acknowledged the limitations of using motion capture technology to capture dynamic stretching characteristics. The discussion highlighted the importance of combining manual measurements with CAD analysis to provide a comprehensive understanding of climbers' body dimensions and movement patterns.

These findings and insights informed the development of designs for rock-climbing clothing and the incorporation of smart technologies into the clothing. These developments are adressed in the next chapter.

CHAPTER 5. DEVELOPMENT OF AN ERGONOMIC AND FUNCTIONAL ROCK-CLIMBING JACKET

Clothing development is a complex, step-by-step process that begins with sketching and ends with a finished product. For this project, an outdoor jacket was chosen due to its importance in keeping vital body parts warm in a cold mountain environment and its suitability for being equipped with sensors and devices for data collection. Outdoor jackets typically cover half of the wearer's body, allowing for free movement, and their durable fabric protects against external stimuli (Lee & Baek, 2021). In designing the rock-climbing jacket for this project, several factors were considered to ensure ergonomics and functionality: the range of movements, including dynamic movements; the placement of the smart heating system components; the positioning of rock-climbing equipment; the number and placement of pockets; and other design considerations.These design considerations were informed by the model of the final climbing apparel design system (see Figure 3.4).

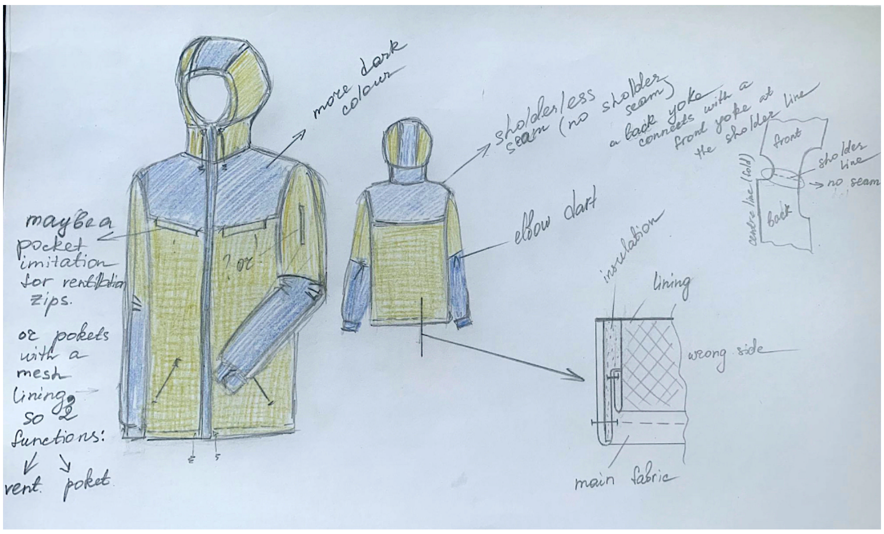
This chapter provides detailed descriptions of the various design stages and the decisions made in designing the outdoor jacket. The first section focuses on the early sketches

5.1.Sketching and Technical Description of the Jacket

The first step in the development of clothing is translating initial concepts and ideas onto paper through drawing an initial sketch, also known as creative drawing. Sketches can be done freehand, using a template croquis, or created digitally. The initial sketch of the jacket was based on the analysis of existing outdoor rock-climbing clothing and the preferences of experienced rock climbers (see Chapter 4). It also considered the placement of smart heating system components that were meant to be integrated into the jacket. An initial sketch of the jacket is shown in Figure 5.1.

Figure 5.1

An initial sketch of the jacket for rock-climbing

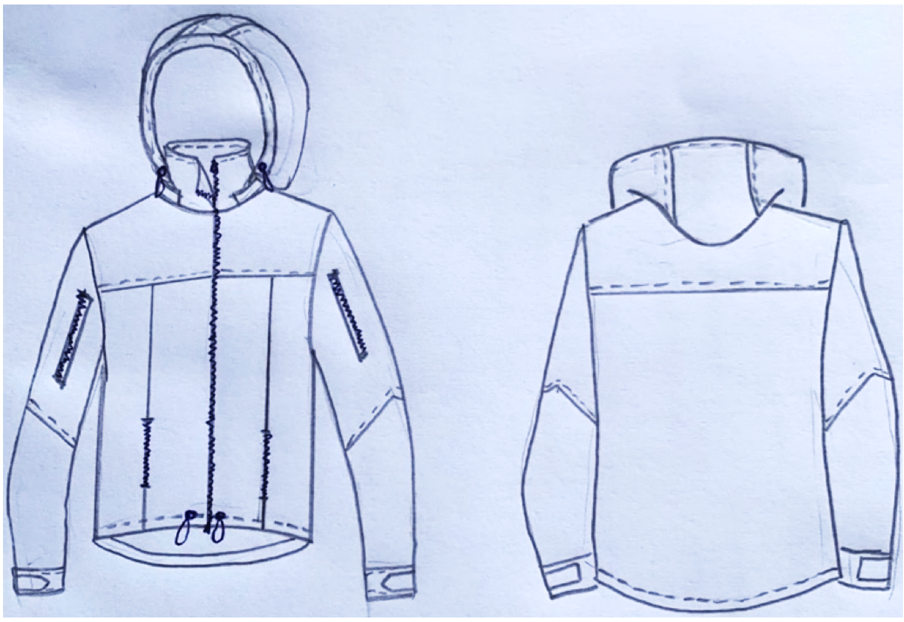


This sketch incorporates possible solutions for different parts of the jacket, reflecting my background in pattern engineering and expertise in garment processing. However, some of these solutions were dismissed as the design developed. For example, one solution was to add a pocket imitation opening along the connection line between the front yoke's bottom edge and the top front bodice edge to provide additional ventilation. However, when the heating pad was placed near this line, the initial concept of a vent opening was reconsidered and abandoned, as an automatically regulated heating system might conflict with the vent opening. Instead, a pocket with an additional vent function placed on the sleeve was considered and utilised for the final design of the jacket. The sketch above also features a proposal for processing the bottom edge of the jacket using all suggested textile materials, which is shown as a technical drawing of the suggested cut for this part of the jacket.

At the next stage of garment development and production, a technical drawing of the garment was created. This technical drawing depicts every part and specific features of the garment, such as pockets, collars, and closures, with basic constructive lines, seams, and stitching lines clearly outlined. It serves as a design document that includes sketches and specifications of the proposed clothing product (Baukh, 2023), utilising standard symbols, measurements, and notation to convey the technical aspects of the garment design. The drawing typically includes both front and back views of the garment and may also contain side views and x-rays of certain areas as optional extras. Technical drawings can be hand-drawn or created with vector drawing software. The primary purpose of a technical drawing is to assist fashion designers in clearly communicating the ideas and construction of the design to the entire team, including the technical aspects. Whether used for pattern making, production, or presentation, technical drawings help designers convey the details, dimensions, and specifications of their garments. A simple hand-drawn technical drawing of the jacket is presented in Figure 5.2. It can be seen that the technical drawing differs slightly from the initial sketch. A style line was added to the front bodice part, and the pockets were designed along this style line. While the seamless shoulder is not explicitly presented on the drawing, it was intended that this design feature would remain.

Figure 5.2

A technical drawing of the jacket



To prevent any miscommunication, a technical description of the garment should be provided, clarifying all technical aspects and offering further instructions. In the Russian Federation, the technical description of a garment must comply with specific standards. For instance, outdoor clothing must adhere to “Technical Standards. GOST 25295-2003. Outerwear of coat-suit assortment. General specifications” (TsNIIShP, 2006).

According to this standard, the technical description for the model of the garment should include:

- A title page with the name of the garment and an identification number of the standard.
- Drawing and description of the garment, indicating the locations of the pockets (external, interior, watch pocket, and back pocket), trims, etc.
- A table of measurements of the finished product, maximum deviations from nominal values, and measurement locations for shoulder and waist group products.
- A list of materials used: main, finishing, decorating, interfacing, insulating, lining, and closures, along with their placement.
- Features of product manufacturing.
- Additional requirements for symmetry of the pattern, stripes, cells.
- Methods for processing cuts, securing pockets, vents, and trouser bows.

As similar standards could not be found in other databases, the Russian standards were followed to describe the jacket technically (see Table 5.1).

Table 5.1

The technical description for outdoor jacket for rock-climbing according GOST 25295-2003

Title: The male outdoor jacket for rock-climbing features a standard comfortable fit. The jacket is integrated with an electronic heating system that is placed inside between the insulation layer and the main fabric layer.
Construction features: • A yoke on the top side of the front and back bodice with a seamless shoulder line. • Two zipped pockets located on each side in the vertical style line on the front bodice. • The right pocket includes a functional opening (2 cm) for the USB wire to connect to a power bank to run the heating system. • A two-way open zipper for the central line of the jacket. • An adjustable and helmet-compatible hood configuration attached by a zipper, made of three parts. • A tall collar that covers the chin and mouth. • Plain sleeves that finish with adjustable cuffs with Velcro. • Sleeves include an elbow dart manipulated into the style line to provide more freedom of movement and additional style. • Two zipped sleeve pockets with mesh lining which may also be used as extra vents. • A hem line with a slight drop-tail and an adjustable hem drawcord. • Reflective strips on the front and back parts of the jacket.
Material specification: The jacket is made of the following textile materials: membrane fabric (Taslan) in two colours (sandy and blue) for the main fabric; insulation; three types of lining: graphene and polyester+viscose fabric for the main lining, mesh fabric for the sleeve pocket lining; some parts of the jacket are stabilised with strips of interfacing; reflective strips.
The size of the jacket is 182-100-88, which corresponds to size L.

5.2. Development of Flat Pattern and Toile

The next stage of the development of the jacket is pattern engineering. The process of pattern drafting is one of the most complex and significant stages in clothing design and development. The task of creating flat clothing construction (pattern drafting) must meet a set of necessary requirements, such as choosing the correct body measurements corresponding to size, optimal amounts of ease, tolerance, and allowance, the choice of an appropriate method of pattern engineering, accurate calculation, and a consistent system for pattern construction drawing.

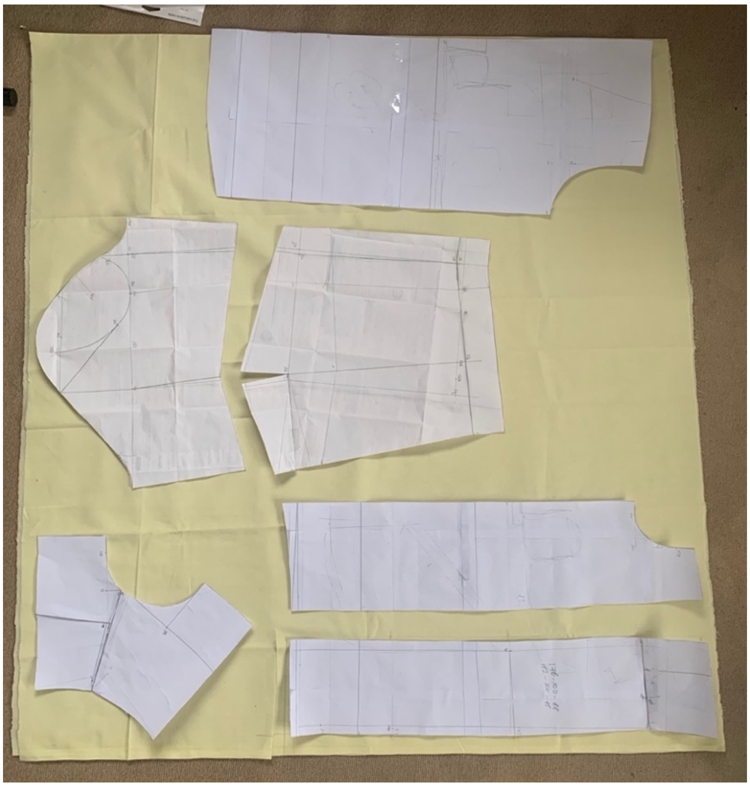
There are many methods and techniques for pattern drafting. For each type of garment, a block pattern is created. This basic pattern serves as a foundation for drafting patterns. The block pattern is important as it reflects the fit and type of the clothing, and ease is determined considering different factors. Using various manipulations, a pattern engineer can then create the sewing patterns. Patterns can be done either freehand or digitally, utilising different software such as 2D CAD or 3D virtual fitting programs. In this project, different pattern-making techniques were used.

At the initial stage, a flat paper pattern of the jacket was created. For this purpose, the unified methodology for constructing men's clothes used by the member countries of the Council for Mutual Economic Assistance (capacious CEV) was employed (TsNIIShP, 1988). This methodology was chosen because it meets the requirements for clothing design in mass production and can be used with automated design systems (CAD). Additionally, this methodology employs systematised and scientifically approved ease, formulas, and sequences for constructing drawings. The technique of radius is used for pattern drafting of curved areas by approximation with arches of circles, such as armholes, front and back necklines, etc. The methodology includes its own system for the designation of constructive lines and points on the basic grid, notches, and annotations. As decisions are made regarding the type of zipper or topstitching, the drawing may be updated.

At the next stage, a toile was created. A toile is an early version of the finished garment made up in inexpensive textile material to test the garment's size, fit, balance, and look. The sewing pattern was laid on muslin fabric, cut out, and then sewn together by hand to create the toile (see Figure 5.3).

Figure 5.3

The sewing patterns laid on the muslin fabric



Following the creation of the toile, it was fitted on an experienced rock climber (Figure 5.4 a-c). The toile did not include details such as a collar, hood, or cuffs, as they were unnecessary to the purpose of the toile, which was to check whether it matched the design intent in terms of silhouette, fit, balance of the garment, placement of constructive lines, length of the jacket and sleeve, and details like the sizes and positions of outer pockets. The toile was also used to determine if the fabric sits smoothly across the body and is not pulled anywhere or has excess fabric.

Figure 5.4

Initial fitting of the toile on a model

a) front b) back c) side

Survey feedback, analysis of existing outdoor clothing, and motion analysis were all considered in the overall design and pattern engineering process through the integration of specific parameters. During the fitting of the toile, the climber was asked to remain stationary to assess the general fit and balance of the garment, and then to simulate specific climbing arm movements in order to evaluate ergonomic performance in the upper body area. The motion tracking data confirmed the areas subjected to the most extreme ranges of movement.

In the fitting process, it became apparent that the lower armhole line needed to be enlarged to allow sufficient freedom for arm movement. Based on an empirical approach and drawing on my background in pattern engineering, it was determined that lowering the line by 2.5 cm along the side seam would address the identified issue. The flat pattern was subsequently revised to incorporate this adjustment. The other parameters checked were satisfactory. The possible placement of the components of the heating system was also marked. As the experienced rock climber was involved in the fitting process as a model, his opinion was important and considered during the further development stages of the jacket to create solutions that align closely with user requirements. This was in accordance with the UCD approach of involving the user throughout the project development process (see Chapter 3).

5.3. Development and Assessment of the Rock-climbing Jacket Using 3D Virtual Fitting Software

The contemporary preferred solution for developing clothing is using virtual fashion design software. There are a number of 3D programmes available on the technology market internationally, such as CLO 3D (South Korea), 3D Style (China), and Lectra (France), among others. These fashion design software programmes provide functional tools to create virtual garment visualisation on a 3D mannequin in static and dynamic poses, featuring cutting-edge simulation technologies specifically developed for the fashion industry. Virtual samples have remarkably reduced material waste and labor-intensive tasks throughout the supply chain, specifically during the preproduction stages (Seonyoung, 2024). Brands using 3D digital garment design and development processes have recorded up to a 75% reduction in sampling, and a 50–75% reduction in time spent on product development (Kuzmichev & Yan, 2022). The functional range of this software covers realistic design, real materials simulation, pattern manipulations, virtual fitting on an avatar, pattern revision, and the evaluation of features such as clothing stress, strain, and pressure points. For rock-climbing clothing developed according to the concept of ergonomics, 3D programmes are thus a valuable tool to check the sewing patterns before cutting the real fabric. By using 3D dynamic movement simulations, it is possible to conduct an initial fabric stress assessment on different pressure points of the clothing, allowing its comfort level to be evaluated.

Viziteu et al. (2021) explored the applicability of computerised 3D virtual clothing simulation programmes specifically for the development of patterns for men’s rock-climbing pants. The authors selected three designs of climbing pants, compared the layout of patterns, and analysed their appearance through virtual garment fit maps. CLO 3D software was used to visualise how the clothing items would fit and perform in different stress scenarios. The results showed that the pants can be optimised and pressure comfort can be improved by analysing the pressure points, stress, strain, and fit maps, however, the accuracy of the programme's analysis depends on the choice of fabric.

Another study by Papachristou and Anastassiu (2022) described the complementary use of both 2D pattern and 3D virtual prototyping technology to upgrade regular clothing available on the market through the automated incorporation of wearable antennas, reducing the chances of compromising the garment's elegance or comfort. The authors also described the functionality of various commercial software modules and implement particular design examples, proving the efficiency of the software-based methodology and leading the way for more complex configurations (Papachristou & Anastassiu, 2022).

The development of upper body cycling clothes, such as a cyclist's jersey T-shirt, using 3D-to-2D flattening technology is described by Liu et al. (2016), who focused on evaluating cycling clothes' dynamic wear comfort. The 3D virtual-reality technology was applied to simulate cycling. A novel pressure-measuring method was proposed to measure static and dynamic clothing pressures in a virtual environment. Different software products were employed in this research, including CLO 3D.

The effectiveness of 3D virtual fitting technology when visualising the fit and silhouette of pants was investigated in the paper by Song and Ashdown (2015). The authors analysed the similarities between real and virtual fit using 20 fit locations, 3 lower body shapes, and fit status. Optitex PDS 3-D Runway Creator software was used in this research. The authors concluded that this technology was not generally effective for visualizing pant fit, as the virtual pants diverged from the actual pants in front silhouette, waist placement, and hip tilt shape for females, etc. (Song & Ashdown, 2015).

Jeong and Hong (2015) described the development of the ergonomic pattern from the 3D human body reflecting cycling posture and extensibility of the stretch fabrics. In this study, relationships between the reduction rates of the 2D pattern obtained from the 3D human scan and resultant clothing pressure were explored to improve the fit and pressure exerted by the reduced clothing pattern. The optimised reduction rates were determined with the proposed reduction rate (Jeong & Hong, 2015).

The research by Liu et al. (2017) also proved the effectiveness of using a 3D garment CAD software for garment fit evaluation. The authors proposed a machine-learning-based model to predict garment fit and estimate it without any real try-on. Compared with traditional garment fit evaluation methods, the proposed approach has a number of advantages: 1) continuous improvement of the model's performance with new learning data, 2) independence from any real try-on, and 3) removal of human involvement. The effectiveness of this proposed method was validated using a set of test samples (Liu et al., 2017).

For this project, I used the 2D-to-3D concept and the following software:

- 2D CAD programmes Grafis (https://www.cadrus.ru/grafis/) and Corel Draw to develop garment patterns and insert them to 3D software;
- 3D fashion design compatible software CLO 3D and 3DStyle were used as the design tools to visualise a design of the jacket, its virtual fitting and fabric stress assessment in dynamics.

The flat sewing patterns that were developed and checked via initial fitting of the toile on a model, were scanned and revised in Corel Draw and Grafis. These digital patterns were then inserted in the fashion design software programmes CLO 3D and 3DStyle (see Figure 5.5).

At the initial stage, a digital helmet for rock climbing was chosen. The helmet is an important part of the process for developing and checking a compatible helmet hood.

As analysed in the section 2.5, the current mountaineering helmet standards do not include any information regarding the size or style characteristics of helmets for rock climbing (CEN, 2012; UIAA, 2018). Thus, for the purpose of hood development, a typical helmet for rock climbing available on the market was measured. Since neither CLO 3D nor 3DStyle provide a helmet in their built-in accessories, a compatible digital helmet was chosen and inserted into the 3D fashion design software as an object (see Figure 5.6).

Figure 5.5

Sewing patterns imported in 3D fashion design program

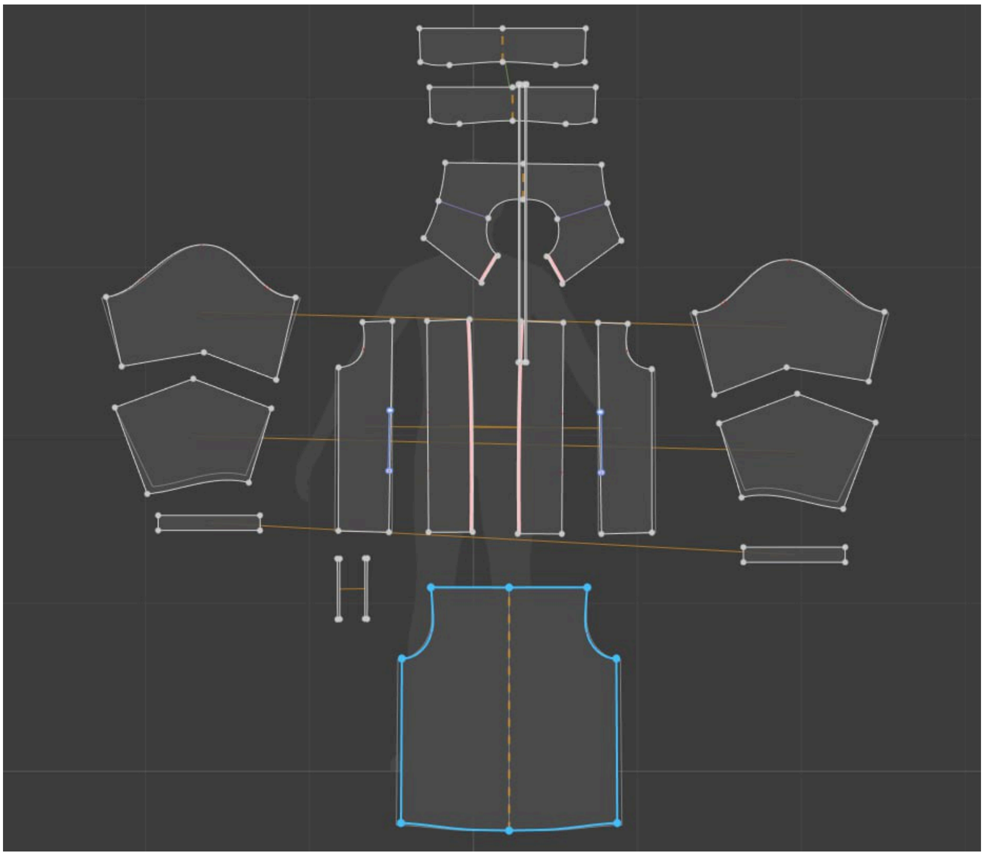
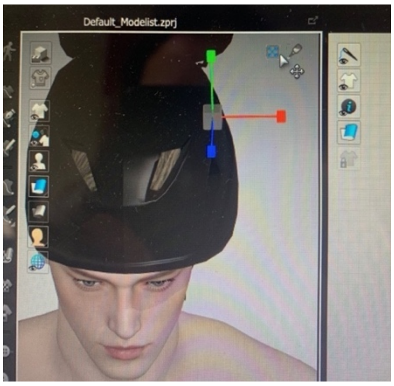


Figure 5.6

The digital helmet object

a) Digital model of helmet



b) Customising helmet in CLO 3D

At the next step, a digital human model of a climber was chosen as the basis form. For this project, a virtual male avatar was selected according to the standard body measurements ISO 7250-1:2017 (ISO, 2017): height – 182 cm, chest circumference – 100 cm, waist circumference – 88 cm (see Figure 5.7). It is also possible to customise the avatar according to fit specific body measurements. The helmet was added to the avatar as a hard object to evaluate the hood fit.

Figure 5.7

A digital human model of a climber

At the next stage, the digital sewing patterns (see Figure 5.5) were assembled at the seams and digitally sewn together around the upper body of the avatar as shown in Figure 5.8. This initial virtual fit on a digital model was made to evaluate features such as the silhouette, fit, balance, constructive and style lines, and length. In this initial evaluation, the selection of textile materials was not required, due to the fact that the specific fabrics needed would be identified and assessed in the later stages of the virtual fitting process (see section 5.4, 5.5).

Figure 5.8

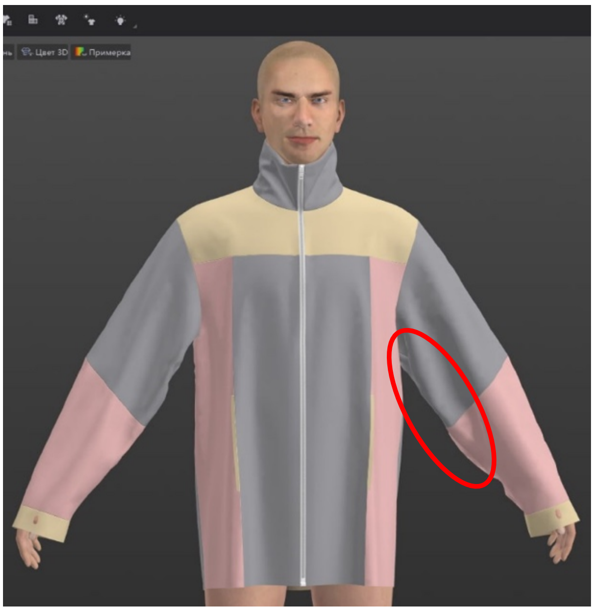
An initial fit of the jacket on the digital model of a climber

a) Front view b) Back view c) Side view

The initial fit assessment of the jacket highlighted a fitting problem in the area of the underarm sleeve seam from the armpit to the level of the elbow. Figure 5.9 illustrates a sagging defect, circled for clarity. This issue was resolved by revising the digital patterns, specifically by shortening the width of the sleeve in this area.

Figure 5.9

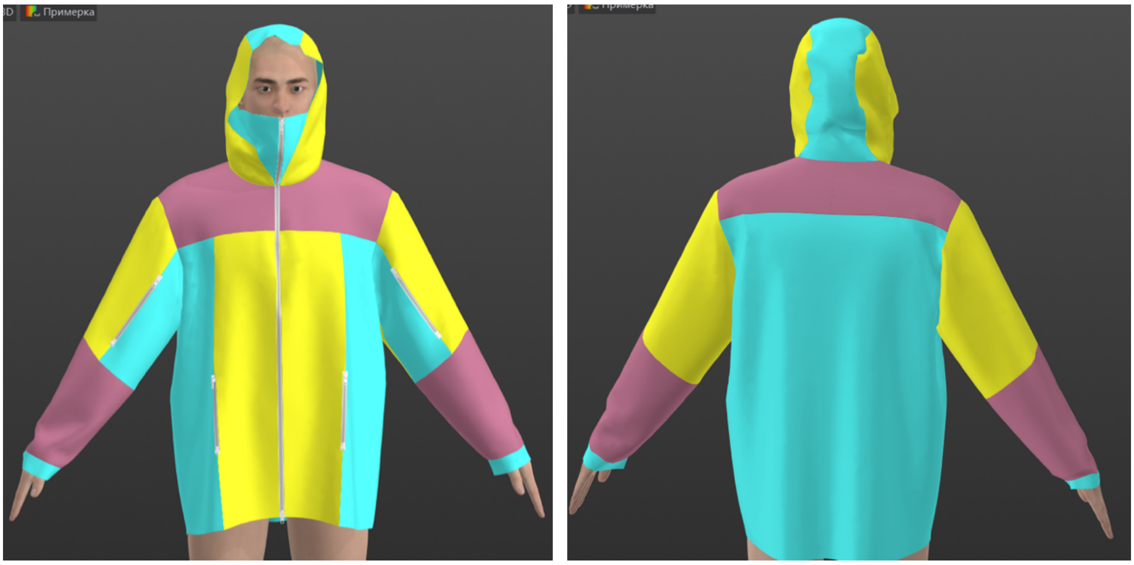
The fitting problem in the area of sleeve



Next, the collar was modified to meet the needs of experienced rock climbers, specifically to cover the lower part of the face for protection against cold wind. This modification was based on feedback received during the survey. Additionally, a helmet-compatible hood was created in the digital fashion design programme. During the second virtual fitting process, the placement of constructive cuts was identified and assessed. For instance, the placement of the cut line on the sleeve for the zipped pocket was determined. The revised sleeve pattern was also checked (see Figure 5.10). A fabric specification was not included.

Figure 5.10

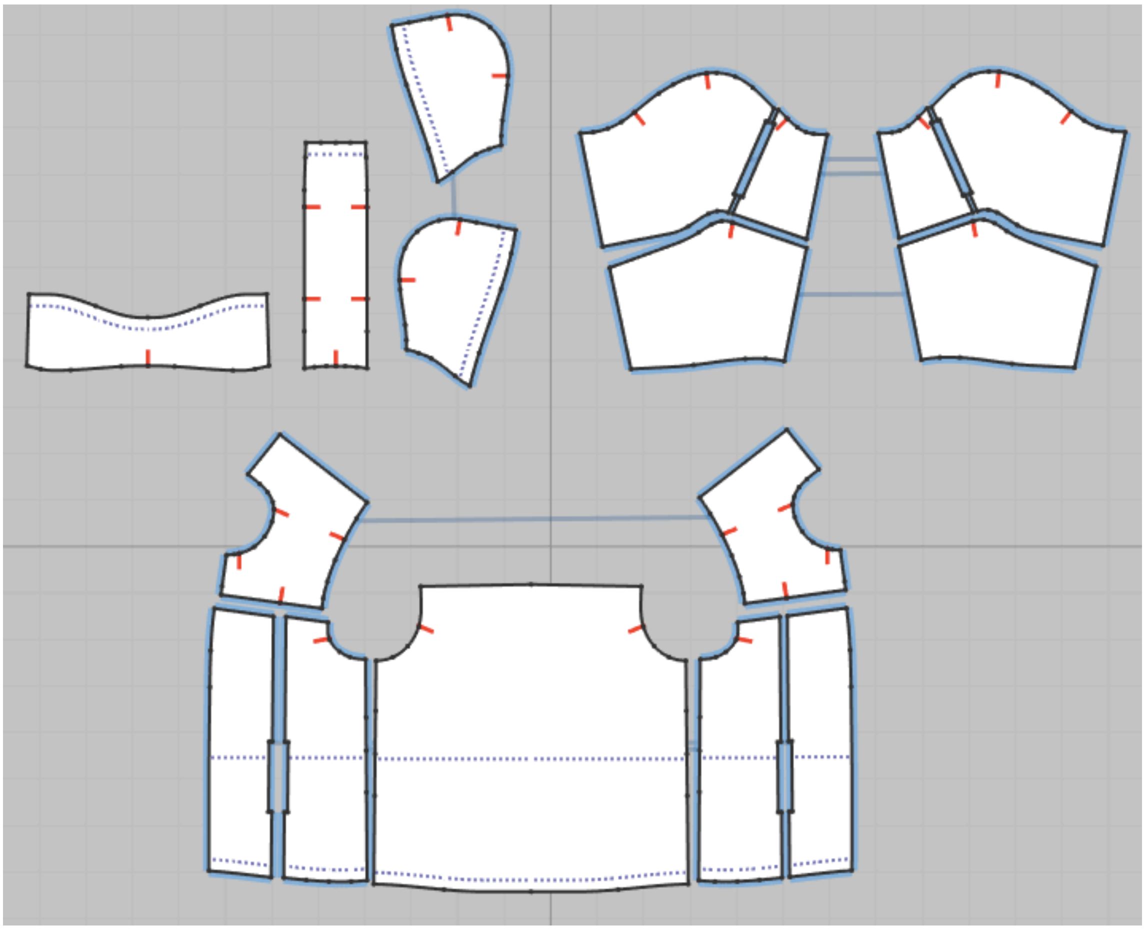
Second virtual fitting of revised jacket



During this virtual fitting process and evaluation it was decided to modify the cut line for a zipped pocket on a sleeve to make it sloping and therefore more stylish. The fit of the hood and collar was assessed on a digital model, and no fitting problems were identified. The revised sleeve also had a good fit. The final sewing patterns of the jacket, as a result of the virtual fitting process, are present in figure 5.11.

Figure 5.11

Revised sewing patterns in CLO3D software



5.4. Fabric and Colour Selection

The proper selection of fabric and other materials is an important consideration in the development of clothing. This section describes the specifications of textile materials for the rock-climbing jacket. Materials were selected based on information gathered from both the clothing analysis and the survey data (see Chapter 4) with consideration to the interaction between the elements of the climbing apparel design system (see Figure 3.4).

5.4.1. Main Fabric

For this project, a polymer-based woven polyester membrane fabric called Taslan (South Korea) was selected as the main material (see figure 5.12). Taslan exhibits notable strengths, including robustness and durability coupled with rapid drying capabilities and efficient moisture-wicking properties. The base polyester is coated with the water-repellent Nuva coating, a substance with similar properties to Teflon®, rendering the fabric both showerproof and stain resistant. These characteristics are expected to extend the garment's lifecycle, thereby contributing to its sustainability by promoting longer wear and use. This main fabric was selected in two distinct colours, as illustrated in Figures 5.12 (a) and 5.12 (c). Figure 5.12 (b) provides a close-up view of the texture of the membrane material under 10x magnification. The image reveals the polymer coating on the reverse side of the material, characterised by a fine pore structure that facilitates breathability. The fabric width is 145 cm, and the weight is 125 g/m².

Figure 5.12

Main fabric 'Taslan'

a) Taslan fabric, sand colour (right side) and white wrong side

b) Taslan fabric, right and wrong sides (zoom 10 times)

c) Taslan fabric, blue colour (right side) and white wrong side

5.4.2. Lining Material

At the next stage, the lining textile materials were selected. These materials play a significant role in enhancing the comfort, durability, and visual appeal of garments by offering supplementary insulation, moisture management capabilities, and structural reinforcement. For an outdoor rock-climbing jacket, a number of materials were selected for the lining. Firstly, a novel material composed of graphene fibres was selected for integration as a lining in the back and front bodice segments, spanning from the neckline to the waistline. This innovative lining fabric, manufactured in China, boasts additional heat storage functionality (see Figure 5.13 (a)). Another woven lining material consisting of a blend of 50% viscose and 50% polyester was also chosen (see Figure 5.13 (b)). This fibre composition combines the high strength and durability characteristic of polyester with the breathability of viscose fibres, which are derived from cellulose and offer better sustainability. This fabric is a low-cost option and was earmarked for use in the sleeves, bottom bodice segments, and pockets of the jacket. Additionally, a mesh-structured lining fabric was chosen for the sleeve pockets to provide supplementary ventilation as required.

Figure 5.13

Lining materials selected for the jacket

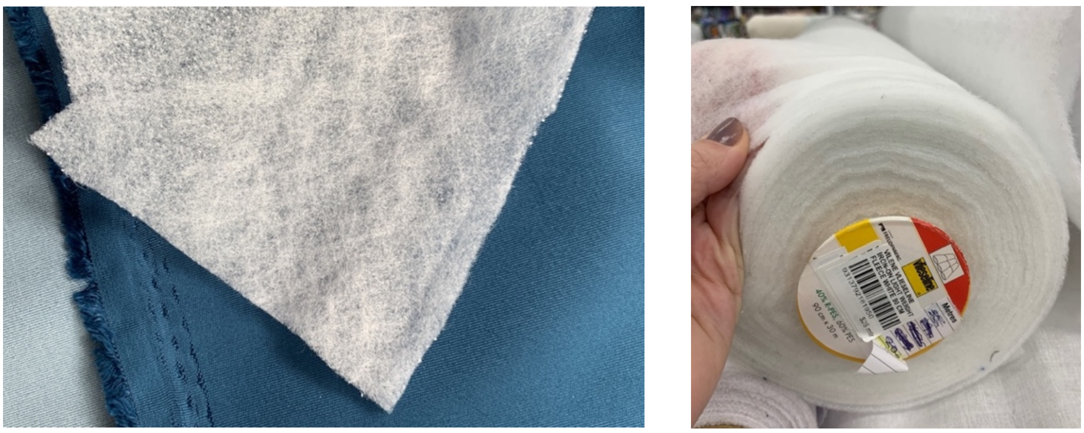
a) Lining material composed of Graphene fibers   b) Lining material 50% viscose and 50% polyester

5.4.3. Insulation, Interfacing, and Other Materials

For the insulation layer, the synthetic lightweight material Vilene Vlieseline Fleece, with a width of 90 cm as depicted in Figure 5.14, was selected. Manufactured in Germany, this lightweight insulation material comprises 40% recycled polyester and 60% polyester. The incorporation of recycled polyester fibres in textiles helps to mitigate potential negative environmental impacts, thereby enhancing the overall sustainability of the garment. The application of the insulation layer was intended to be limited to the bodice parts of the front and back of the climbing jacket, with no intended use in the sleeves. This insulation material was chosen based on the sustainability aspects of the fibre composition and being an ideal thickness based on the calculations derived from the optimal thickness of all layers of the developed climbing jacket, as detailed in Appendix B. Interfacing was applied to stabilise specific areas of the jacket, such as the cuff and pocket entries.

Figure 5.14

Insulation fabric



Furthermore, various components including zippers, Velcro tape, and elastics, among others (see Figure 5.15), were selected for the jacket to facilitate diverse functional fits. An open ended zipper was selected as a front fastener system in the rock-climbing jacket to provide easy access to belay loop for safe attachment with a carabiner while belaying or rappelling (as shown in figure 5.34(a), section 5.7). Additionally, reflective stripes were incorporated into the design for enhanced safety considerations.

Figure 5.15

Selection of other materials

a) An open ended zipper for the front fastener

b) Elastics for adjustments

c) Plastic cord locks

d) Velcro tapes

e) Invisible zippers for pockets and threads

5.4.4. Selection of Materials and Colour Using Fashion Design Software

The fashion design programmes offer the functionality to select fabric types and/or properties (e.g., texture, draping, elasticity). The section above presented the specification of the textile materials for the jacket. These materials were converted into virtual fabrics by selecting similar characteristics, colours, and structure in the fashion design software. The initial colour selection is shown in Figure 5.16. For this purpose, the virtual jacket was placed on the avatar and draped again.

Figure 5.16

Initial colour selection

a) Front view b) Back view c) Side view

e) Front view e) Back view f) Side view

For safety reasons, and in response to the survey results (see section 4.1), that indicated climbers valued visibility, it was decided to add reflective stripes (see Figure 5.17). In the event of a fall, these stripes may help locate a climber among the rocks. Furthermore, based on the survey results that experienced rock climbers preferred quiet colours for clothing the colour concept was changed to incorporate two different environmental colours in the jacket: blue and sand. This colour selection is presented in Figure 5.18.

Figure 5.17

Colour selection and addition of reflective stripes

Figure 5.18

Colour selection (third variant)

The third variant of colour selection appeared acceptable, but it was decided to swap the blue bottom and sand top parts of the sleeve to create a more harmonious look, particularly in the top part of the sleeve and shoulder area. The reflective stripes on the sleeves were removed on further reflection for safety reasons to prevent blinding of the rock-climber while climbing. The final version of colour selection presents in figure 5.19.

Figure 5.19

The final version of colour selection of the jacket

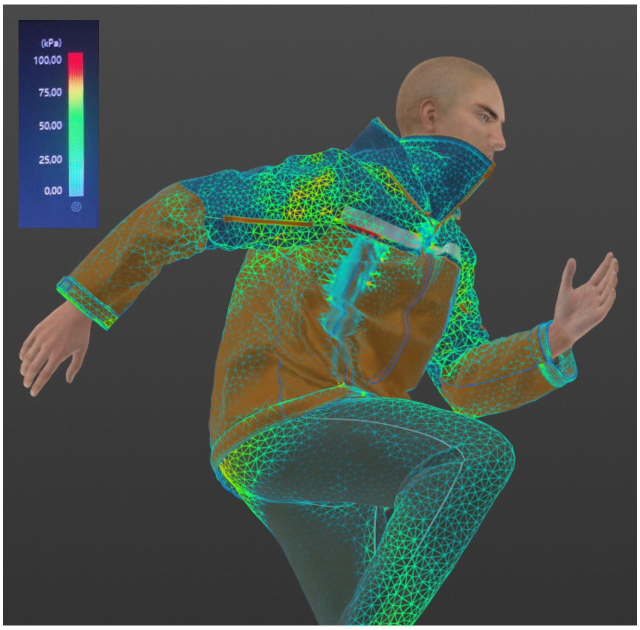
5.5. Assessment of Outdoor Rock-climbing Jacket Using 3D Clothing Simulation

Clothing for rock climbers should fit well, be comfortable and functional, and should not restrict any body movements needed for climbing. As it was mentioned in Chapter 4, dynamic anthropometry is important for rock-climbing clothes. Therefore, dynamic ease allowances were added to the pattern parts to ensure they accommodate the dynamic movements and stretching requirements of climbers. Next, a dynamic display mode was enabled to utilise 3D simulation technology was used to evaluate the fit, strain, and fabric stress of the jacket on the virtual model in dynamics postures. These dynamic postures were chosen from the range of movements provided by the software. Since there were no postures related to rock-climbing exercises exactly, those postures with a high amplitude of motion were chosen for evaluation. It is expected that the clothing in the chosen postures would represent similar behaviour and stress as while the rock-climbing activities. Five of chosen postures are presented in Figures 5.20-5.24.

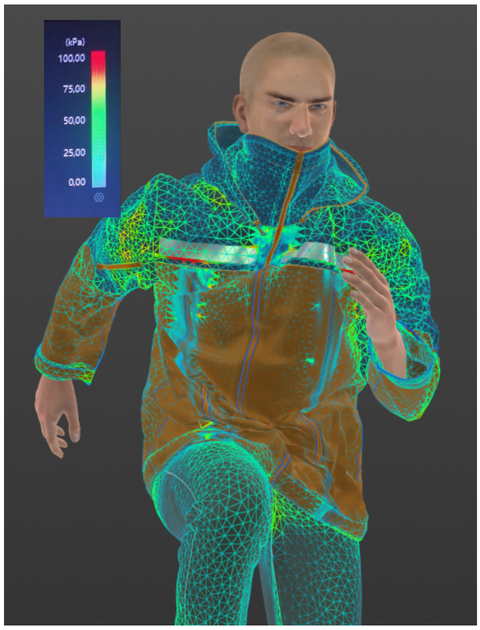
Assessment of the fabric strain and stress and the fit of the jacket on the virtual model in dynamic postures was conducted based on range of colours displayed by the software. During climbing, the identified features of clothing may change significantly, leading to variations in wearing comfort. Thus, differences in fabric stress and clothing pressure at the same point, in both static and dynamic conditions, can be important indicators of changes in wearing comfort at that point (Liu et al., 2016). Therefore, these parameters were evaluated in static and dynamic postures according to the distribution chart of contact pressure points. These characteristics also reflect the stress level of clothing: if the fabric is under significant tension, it is shown in red, while the opposite is shown in green (Viziteu & Curteza, 2021). If the area of green is larger, the clothes exert less pressure on the body and are thus under less stress. The precise measurements of stress characteristics at various contact points on the jacket were determined using the stress map within the 3DStyle platform.

Figure 5.20

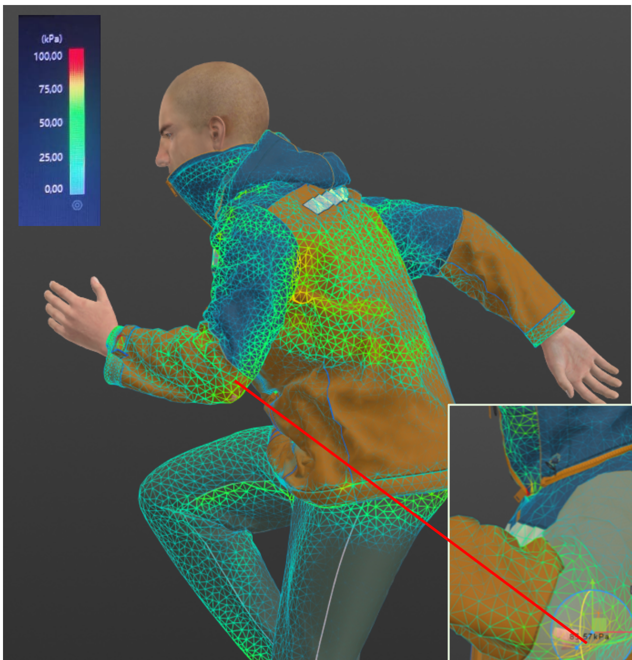
A posture #1



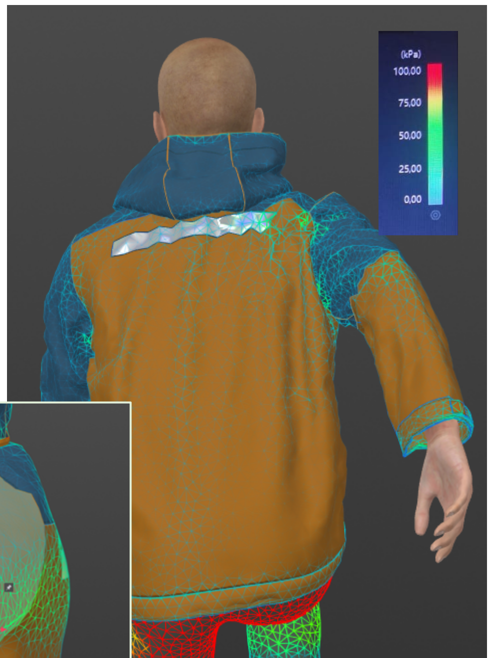
a) Side view



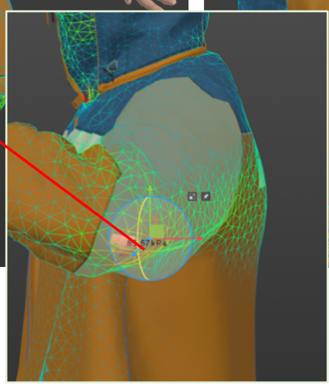
b) Front view



c) Side view



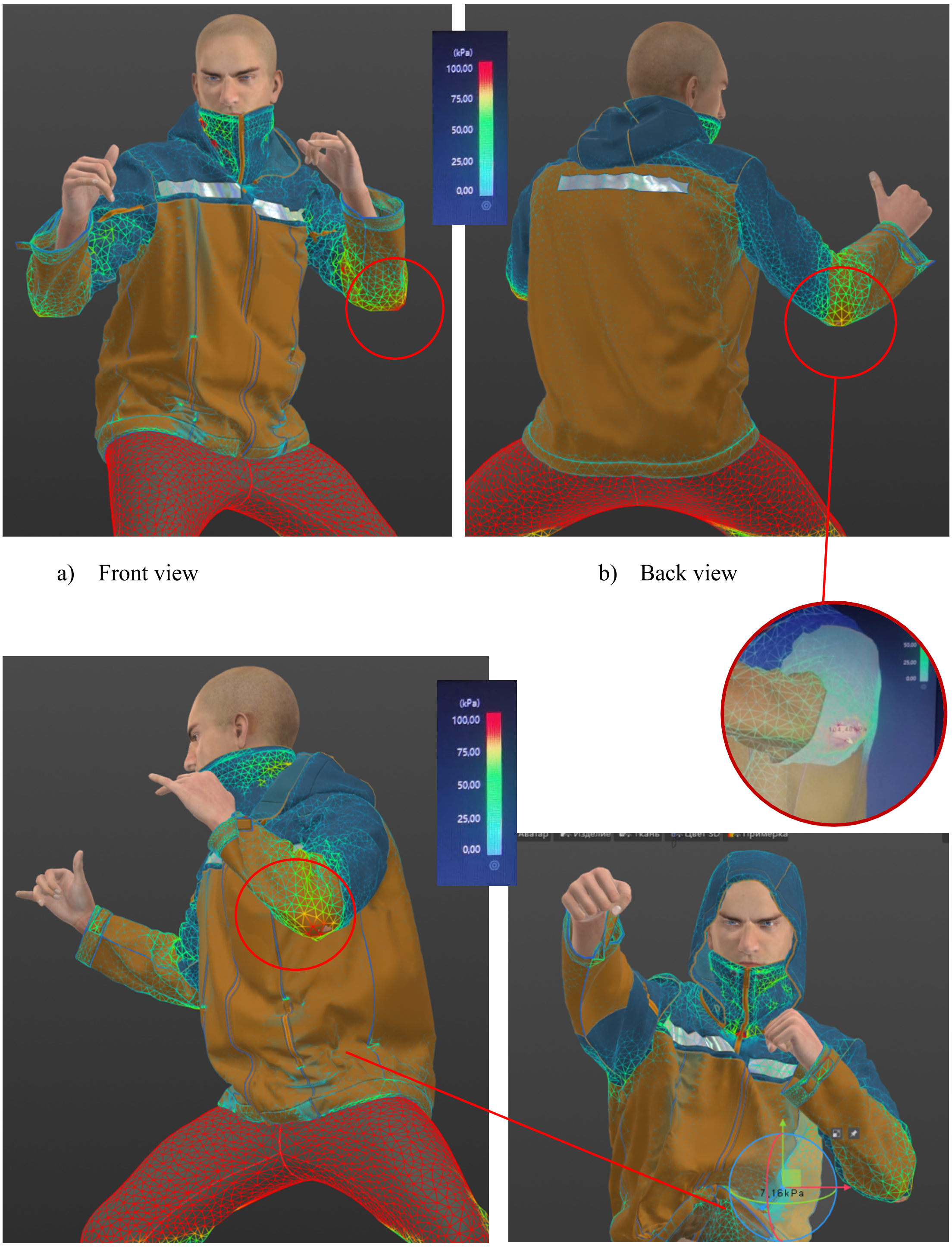
d) Back view



e) Parameter of fabric stress

Figure 5.21

A posture #2



a) Front view

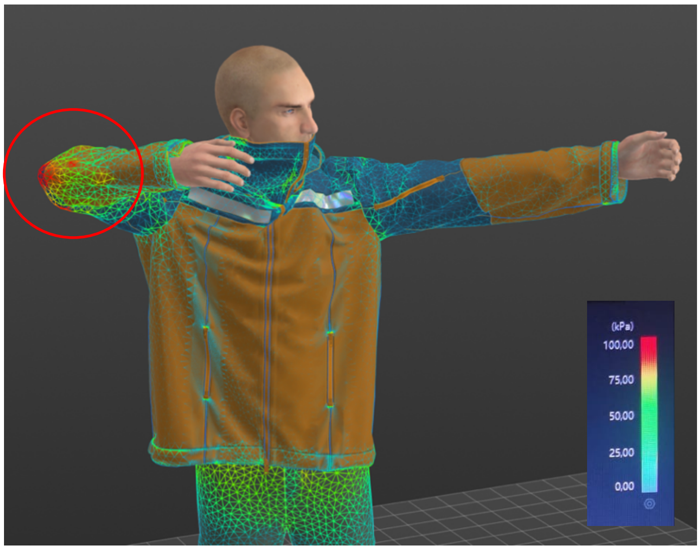
b) Back view

c) Side view

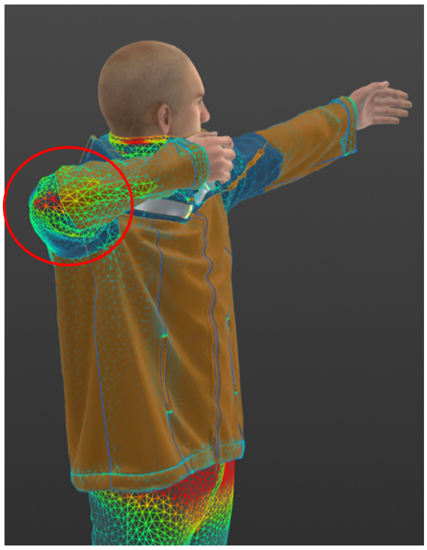
d) Parameters of fabric stress

Figure 5.22

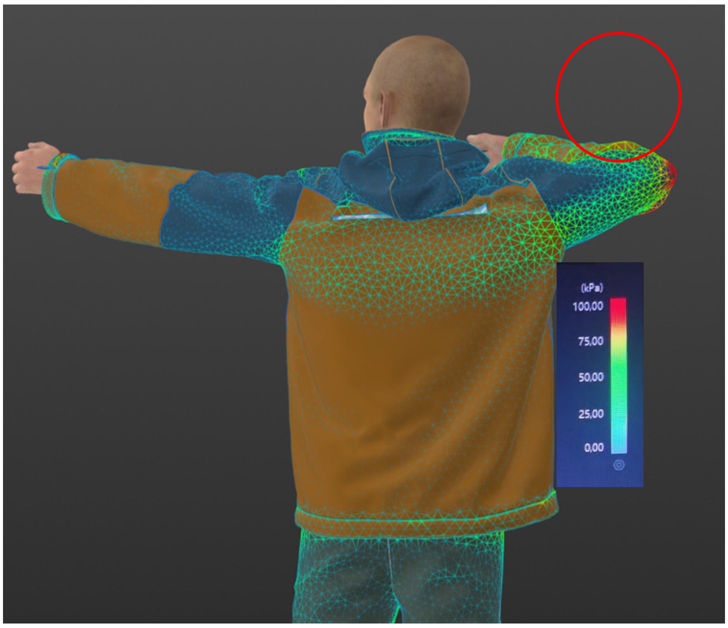
A posture #3



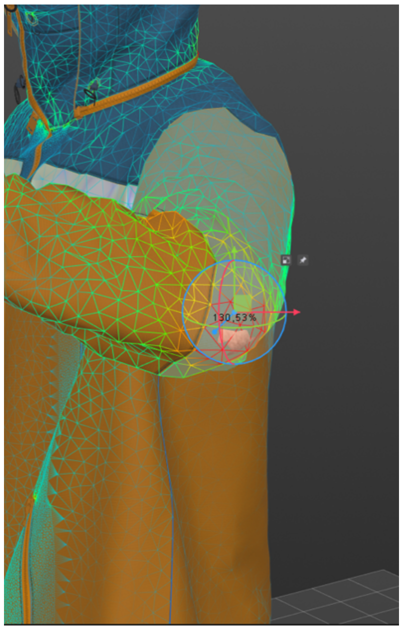
a) Front view



b) Side view



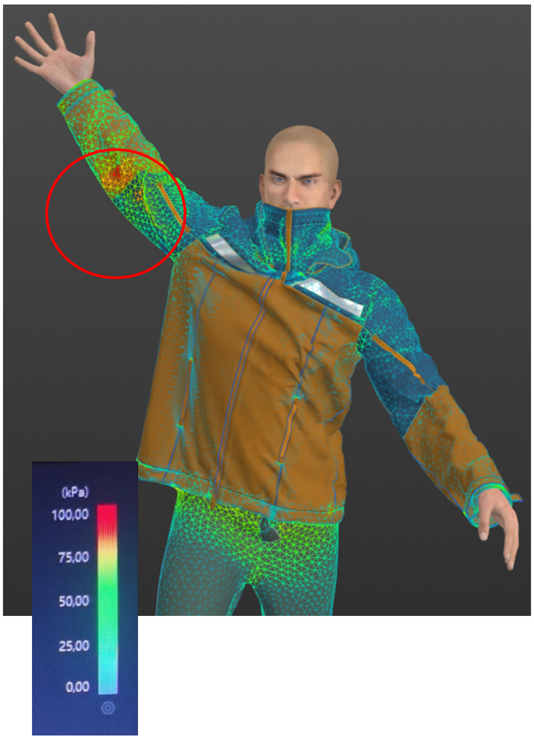
c) Back view



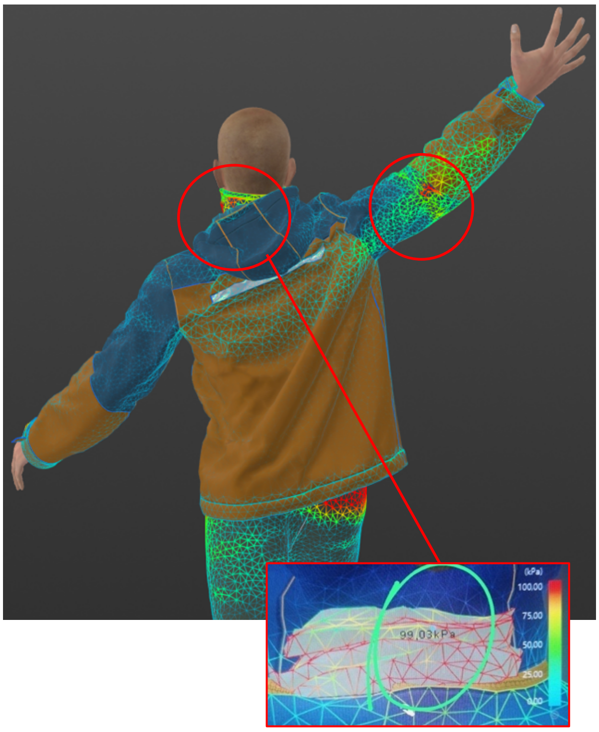
d) Parameter of fabric stress

Figure 5.23

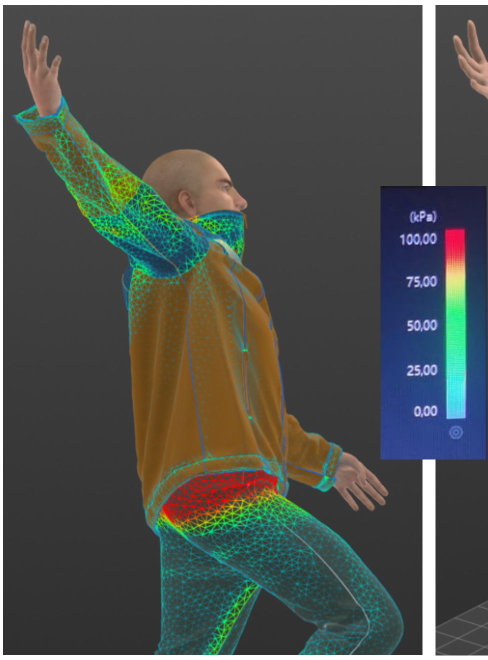
A posture #4



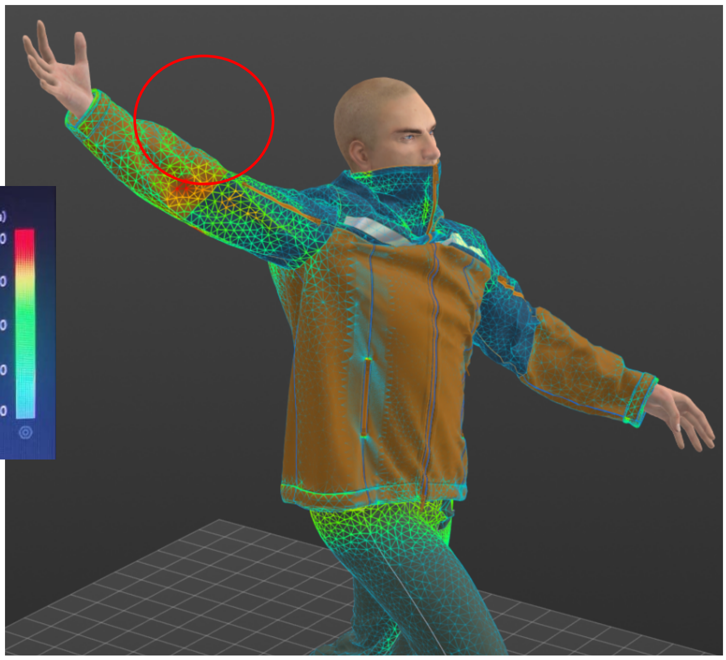
a) Front view



b) Back view and parameter of fabric stress



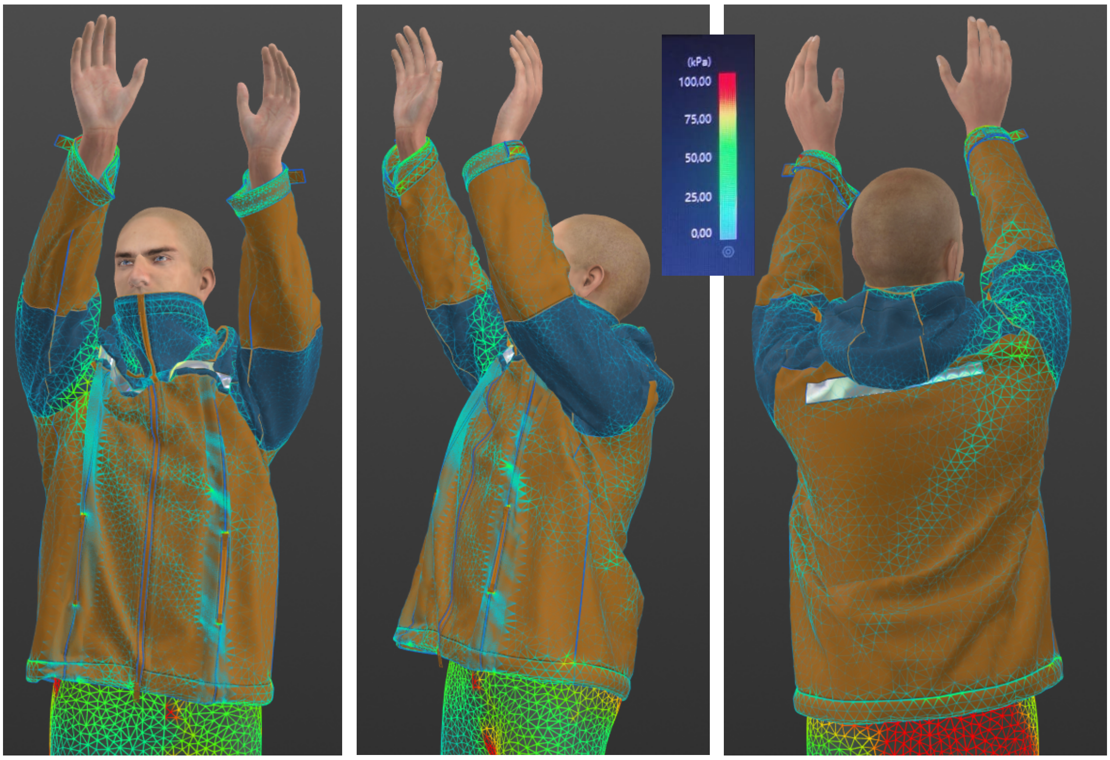
c) Side view



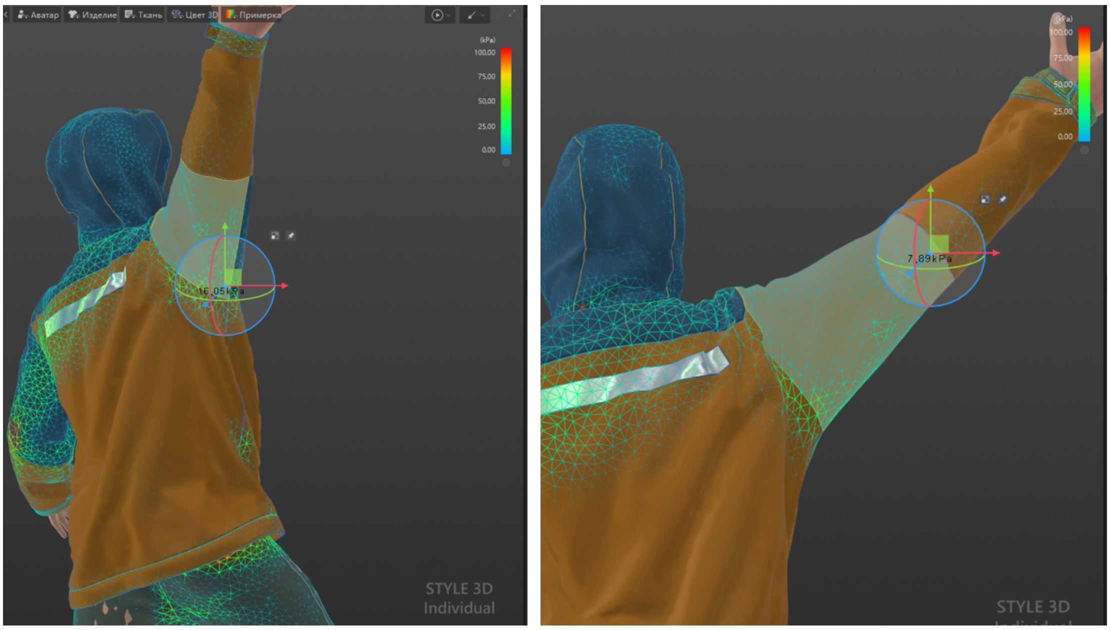
d) Side view

Figure 5.24

A posture #5



a) Front view b) Side view c) Back view



d) Parameters of fabric stress

The stress map shows the external stress causing garment distortion per area of the fabric. Stress is marked by a range of colours and numbers (Viziteu & Curteza, 2021). The figures depicted below illustrate several of these parameters. The red colour on the stress map indicates the strongest stress (100 kPa), while the blue colour indicates zero distortion (0.00 kPa). It is evident that the highest fabric stress parameter occurs at the elbow pressure point, ranging from

85.54 to 130.53 kPa. The highest parameter was observed during movement simulation with the arm almost fully bent at the elbow, as depicted in Figure 5.22, posture #3. It should be noted that such a high-pressure level of the fabric per section was transient and lasted only a few seconds, suggesting minimal movement restrictions. This particular posture, characterised by maximal elbow flexion, is relevant to archery and is not related to climbing. However, this posture was examined due to its joint elbow angle. Dynamic climbing arm movements primarily involve reaching upwards. In such positions, the stress level of the fabric indicates green, signifying a minimal level of distortion (the fabric is within normal conditions) and no movement restrictions, as shown in Figure 5.20 (e) and Figure 5.24 (d).

In contrast, the pants exhibit a high level of fabric stress. However, it is important to note that the pants were not part of the design and were added as a default by the programme. The development of climbing pants was thoroughly canvassed by Michaelson, (2015) and Michaelson et al., (2018) and the applicability of computerized 3D virtual clothing simulation programs for the development of patterns for men's rock-climbing pants are described in Viziteu et al. (2021). A detailed discussion of the requirements of climbing pants was presented in section 4.2. A summary and recommendations for improvement of the design and flat patterns for rock-climbing pants are presented in section 4.3 in Chapter 4.

The fabric strain was also additionally assessed using a strain map, which illustrates the degree of clothing distortion resulting from external stress. This distortion rate is quantified in percentage and depicted in a colour diagram, where red signifies a distortion rate of 120%, while blue indicates no distortion at 100%. This is illustrated in Figure 5.25 below, where the map delineates the degree of tension caused by pressure itself on various segments of the clothing. This strain map, in general, provides an understanding of how much the deformation of the garment fabric occurs after being worn on the virtual model. If a segment of clothing is depicted in red, the fabric is stretched beyond 120%. The orange to yellow area denotes that the fabric stretch is between 110% and 120%. The green areas indicate that the fabric conforms to normal conditions. The strain assessment was conducted within a 3D simulation mode of Style3D software to identify the extent to which the garment stretches when worn on the virtual model engaged in dynamic poses.

It is evident that the fabric undergoes some degree of deformation during the movement of the model. Therefore, a comprehensive assessment of the fit of the jacket should be done in its entirety, incorporating an examination of fabric stress and strain alongside an assessment of body pressure distribution. Notably, both the strain map and the pressure map exhibit data that align closely with intuitive expectations. The utilisation of the body pressure function facilitated the evaluation of this parameter specifically within the sleeve area, which is represented by the apparent fabric stress as shown in Figure 5.26 below.

Figure 5.25

Strain map (examples of some parameters)

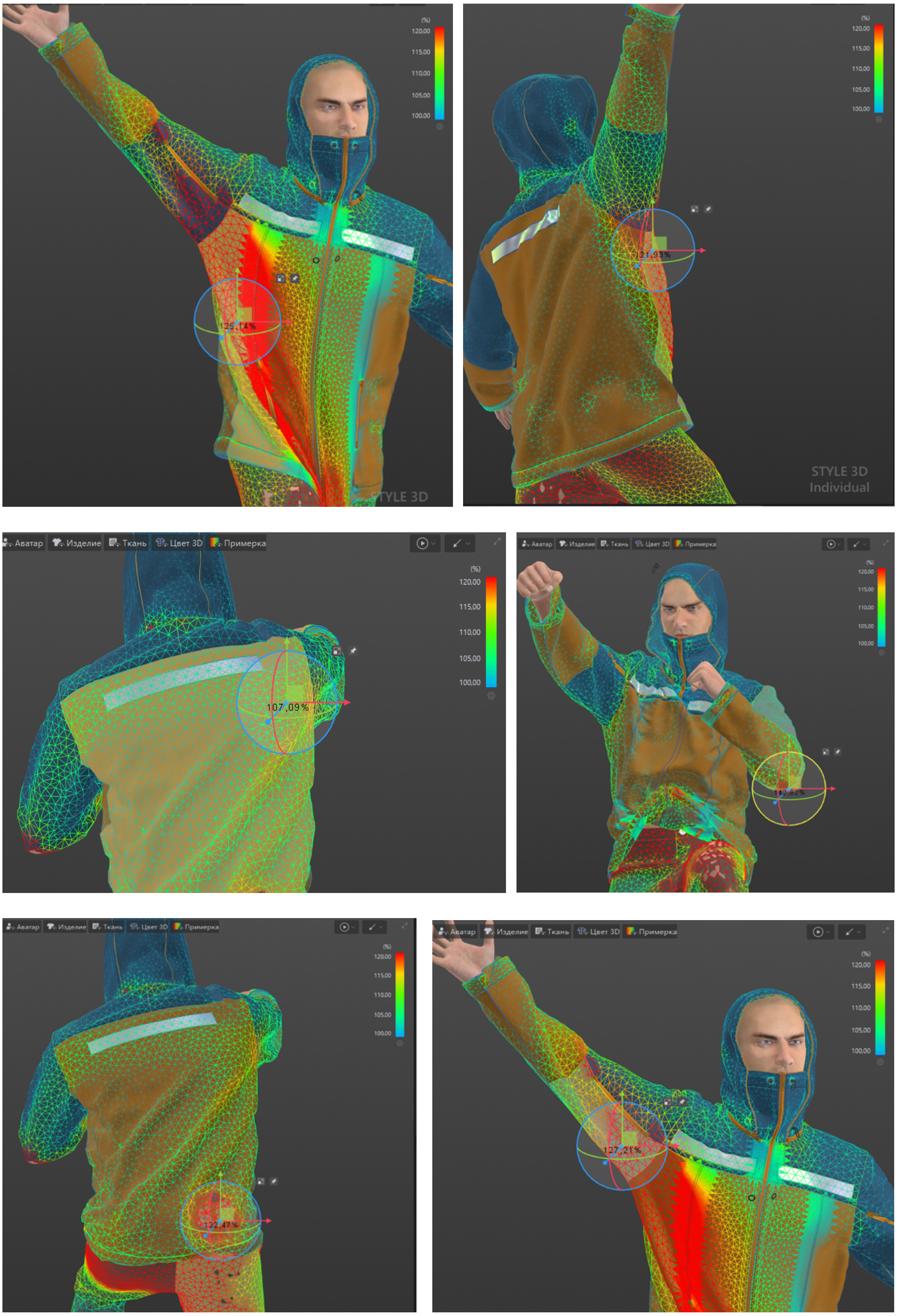
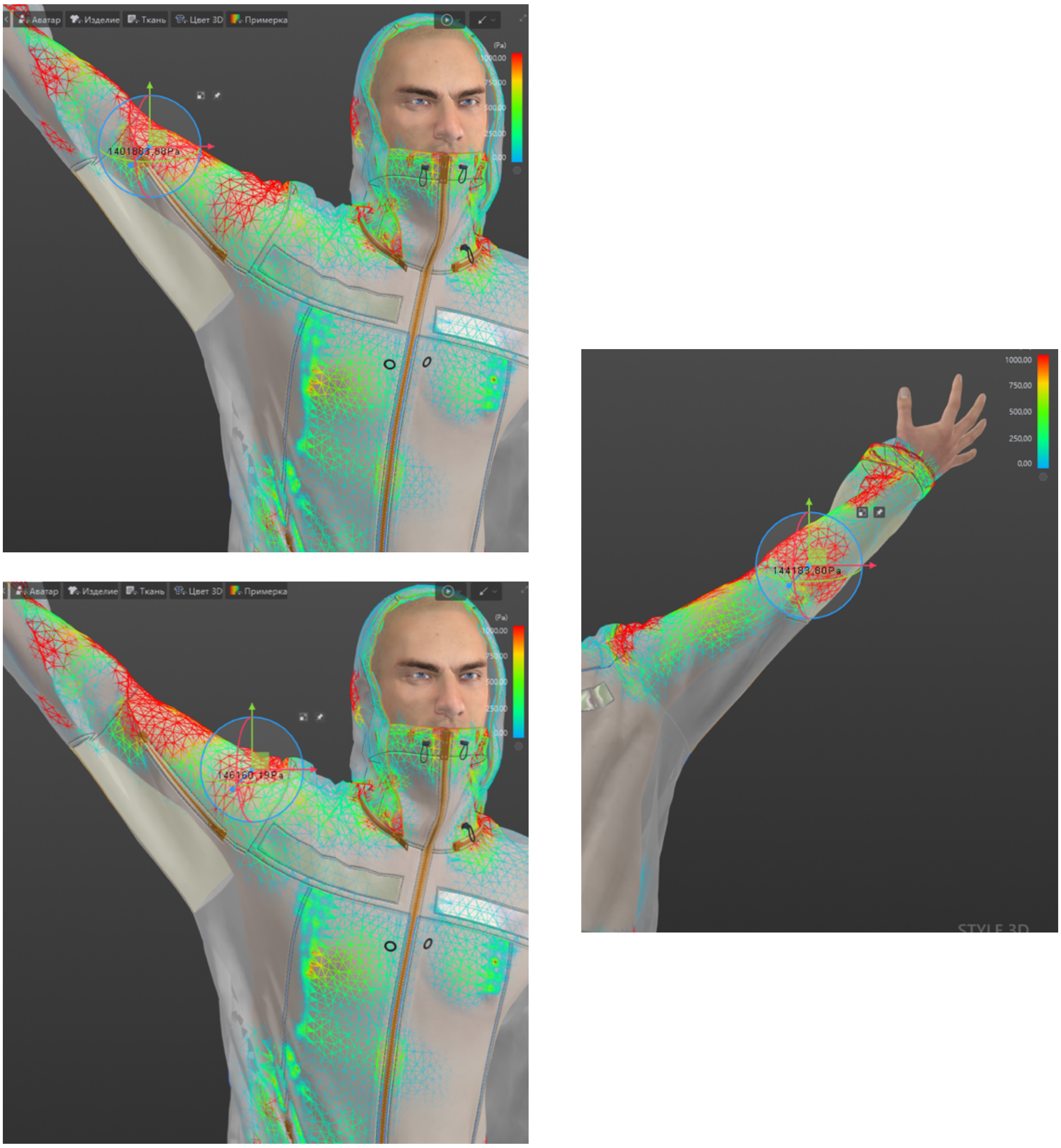


Figure 5.26

A body pressure map



The assessment revealed that the jacket presents a good fit almost across various dynamic body positions, with the body experiencing a generally comfortable level of pressure. However, minor areas of concern arise around the elbow area, where fabric deformation and stress occur at contact pressure points during high-level rotations or flexion/extension of the elbow joint, particularly when exacerbated by very high amplitudes of movement. Theoretically, this could lead to slight discomfort during climbing, primarily due to maximal elbow flexion; however, it is noteworthy that such extreme elbow flexion is atypical in climbing scenarios. During climbing, arm positions primarily involve reaching upwards, wherein the fabric demonstrates an optimal level of strain, stress, and pressure. Consequently, the jacket exhibits a good fit and can be considered comfortable and ergonomic in both static and dynamic postures that are typical for its intended purpose.

5.6. Final Modification of the Jacket Flat Patterns

After assessing the fit and comfort characteristics of the jacket on a digital model in static and dynamic postures using the 3D simulation mode in 3DStyle, the final flat patterns (see Figure 5.27) were inserted into Grafis CAD to arrange the optimal layout of these parts for printing. As no design modifications were required following the 3D simulation, the results validated the accuracy and effectiveness of the design and pattern engineering solutions, as well as the appropriateness of modifications made during the 3D fitting process, which were described in Section 5.3. Seam allowances were added around the edge of the fabric for the pattern so it could be sewn (see Figure 5.28). It is also possible to perform pattern grading in this software to adjust the base size pattern to create other sizes. Figure 5.29 presents an example of pattern grading in Grafis.

Figure 5.27

The final flat patterns of the jacket

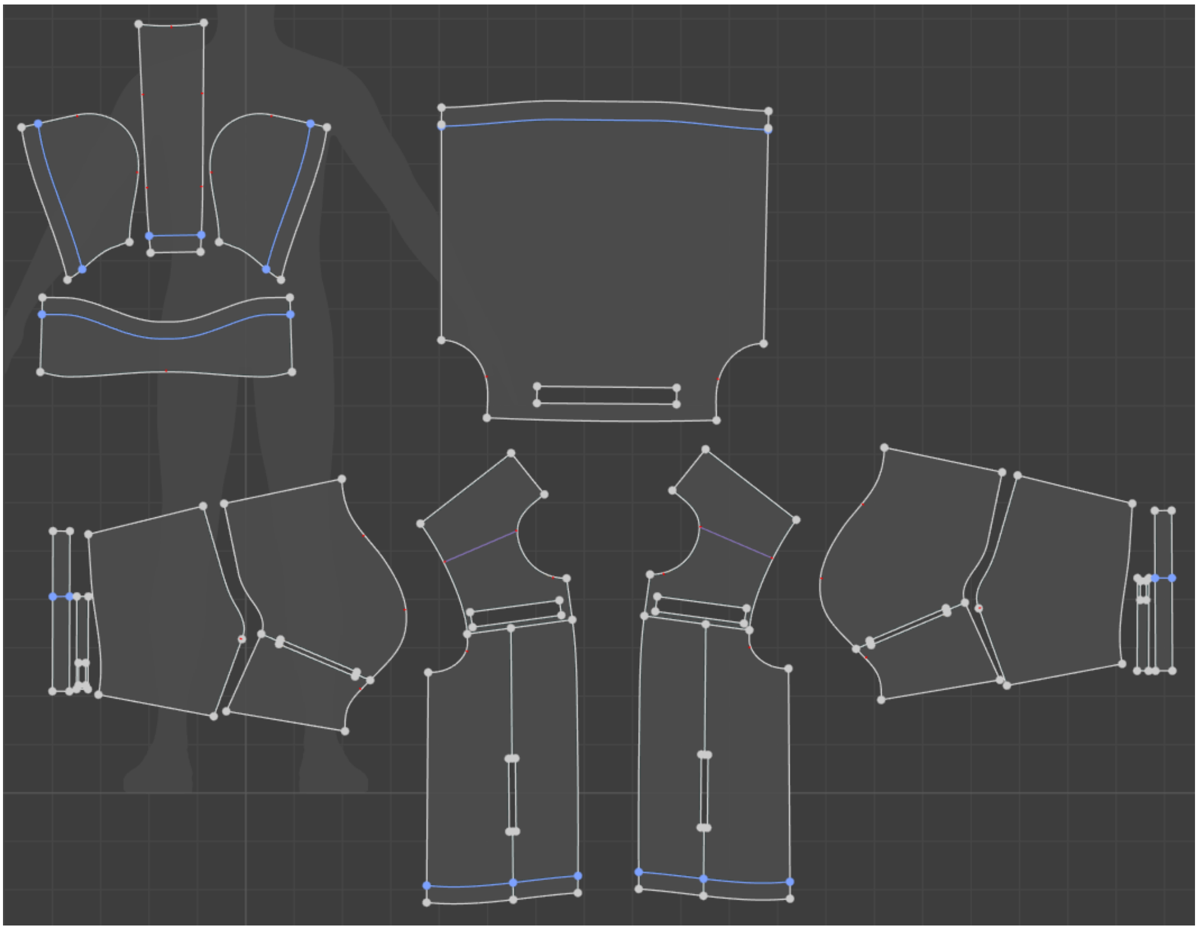


Figure 5.28

Proposed layout pattern parts for printing

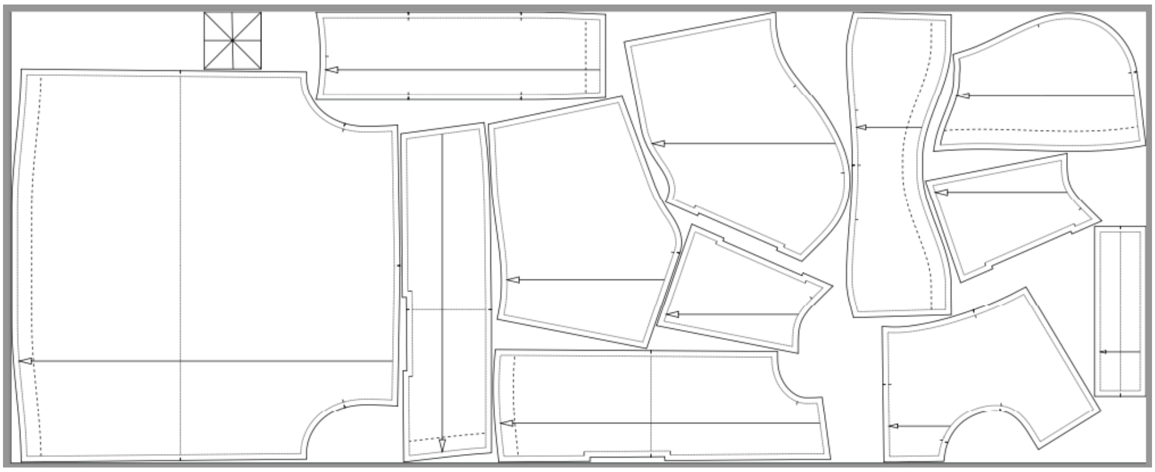
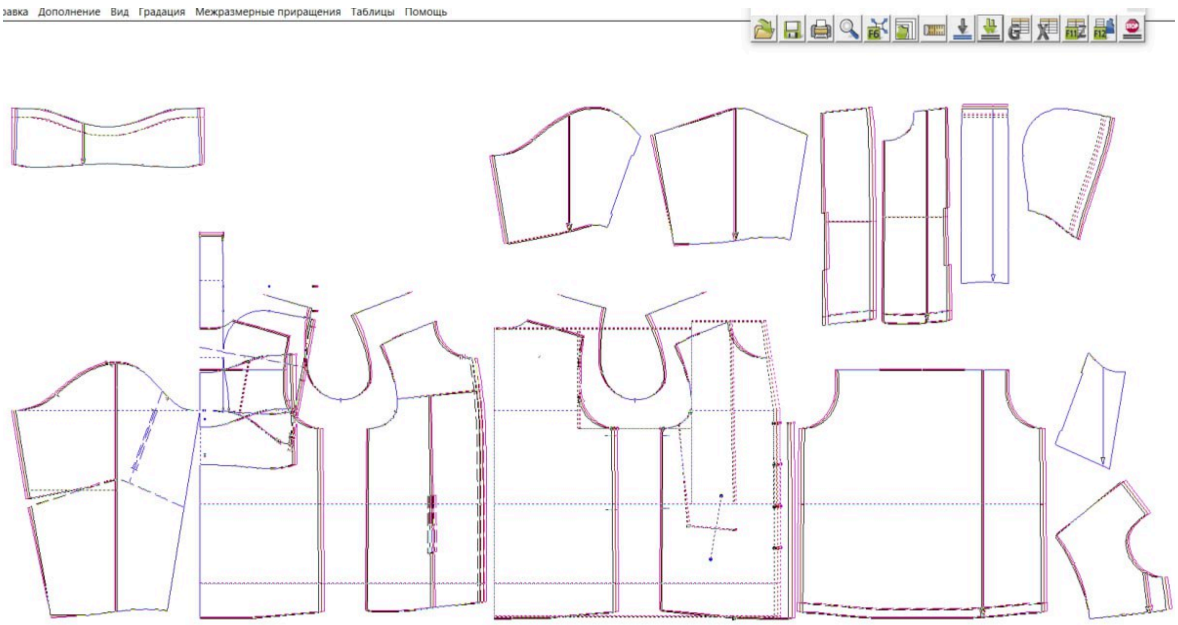


Figure 5.29

Pattern grading (an example)



5.7. Fabrication of the Jacket

The next stage of the development for the outdoor jacket designed for rock climbers involved the creation of an actual jacket. Figure 5.30 illustrates the process of sewing and checking the sleeves. It can be observed that the anatomical shape of the sleeves was achieved through pattern engineering techniques, such as adding movement ease, modifying the curved seam lines of the sleeves, and manipulating elbow darts. These employed techniques were justified through the process of data analysis and findings interpretation (see Chapter 4). During clothing analysis stage of the project, it was identified that an anatomical shape of sleeves is preferred for outdoor rock-climbing garments. This was further supported by the observations related to joint angle parameters (see Table 4.5), which indicated a significant range of motion in the elbow joints of rock climbers. While a similar sleeve shape can be achieved for some fabrics through ironing, membrane fabric is rigid and it is not recommended to iron it. Therefore, the ergonomic sleeve should be developed through techniques of pattern engineering in the initial stages of the design process. Based on insights gathered from surveys with experienced climbers, zipped sleeve pockets were designed. Since the selection of zippers was not the main focus of this project, a general-purpose invisible zipper was initially used for the jacket's sleeve pockets. However, for outdoor rock-climbing sportswear, this type of zipper proves to be unreliable, and therefore more durable zipper options should be considered.

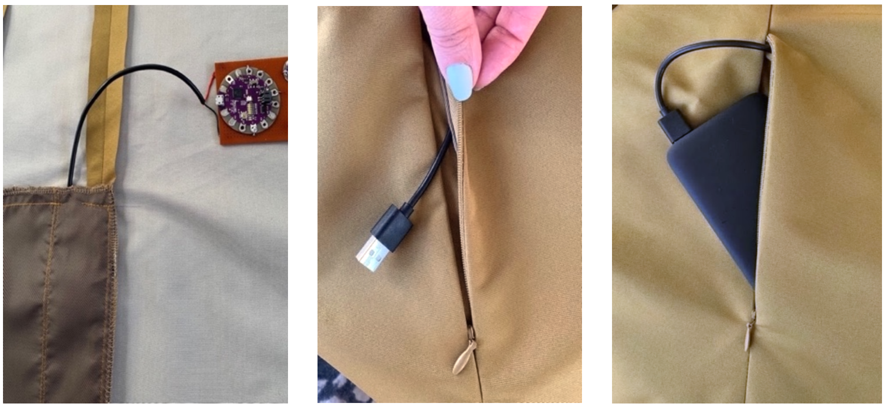
Figure 5.30

The process of sewing and checking the sleeves

The jacket design features an integrated smart heating system consisting of several components (see section 6.2), including a power supply with a USB connector. During the clothing design stage, one consideration was the development of a technical opening to provide easy access for connecting the USB cable to a power bank. Consequently, a technical opening was incorporated into the right pocket. Figure 5.31 illustrates this technical opening and its connection to a power bank.

Figure 5.31

The technical opening for USB connector



The focus in the second fitting process was on evaluating the toile of a hood and a collar on the rock climber model, both with and without a helmet. The side seams and the seams of the sleeves and body were not connected before this fitting process. However, the general fit, balance, and length were assessed during the second fitting. Figure 5.32 depicts the fitting process.

Figure 5.32

Fitting of a hood toile and a collar toile

One consideration regarding the hood was that it might restrict the climber's vision while climbing. This issue was highlighted in the survey, where most respondents noted that they had a negative experience with hoods, particularly due to a restriction of their vision or hearing. The solution, proposed by the researcher, was creating an attachable hood that can be removed as needed. Some manufacturers design the hood as a single piece with the collar, which may further restrict visibility. The hood developed for this prototype consists of three parts that can be attached with a zipper and adjusted around the face (see Figures 5.33 (a) and 5.33 (b)). To prevent water infiltration in the event of rain, the zipper is covered with a strip of the main fabric (see Figure 5.33 (c)). Once the design of the hood was finalised, the jacket was assembled by sewing the main seam lines.

For the fastener system of the jacket an open-ended zipper was selected for the front fastener to provide easy access to the belay loop for safe attachment with a carabiner while belaying or rappelling and for ergonomics (see figure 5.34 (a) and (b)). The top part of the zipper was covered by the main fabric to prevent direct skin contact with the metal slider (see figure 5.34 (c)).

Figure 5.33

Assembly of an attachable hood and connection with a zipper

a) Zipper attached with an outer part of the collar and a neckline

b) An assembled hood with a zipper and adjustable around the face line

c) Attachment hood with a jacket by a zipper

Figure 5.34

The fastener system of the jacket (a front zipper)

a) Access to belay loop via an open ended zipper

b) Access to belay loop attached with carabiners via a zipper

c) Processing of the top part of a zipper

The process of integrating the conceptual prototype of the heating system within the jacket is detailed in the section 6.5 in Chapter 6. Following the attachment of the insulation layer, which contained the heating system components, to the outer shell of the jacket, the lining was sewn and incorporated into the jacket. The lining was composed of two distinct fabrics, which are described in more detail in section 5.4.2. The process of adding the lining shell to the outer shell of the jacket is illustrated in Figure 5.35.

Figure 5.35

A process of connecting lining with a jacket

a) Process of connecting the lining shell with an outer shell (front)

b) Connection of facing, lining, and jacket

c) Sewing lining of sleeve and bodice

d) Process of connecting the lining shell with an outer shell (back)

The bottom hem of the jacket was sewn and top-stitched 1.5 cm from the edge to allow for adjustments. The lower part of the sleeve was finished with a cuff that can be adjusted with a Velcro tape. In addition, adjustments were made to the face line of the hood as presented in Figure 5.36 (c). All adjustments are presented in Figure 5.36.

Figure 5.36

Adjustments of the jacket parts

a) Adjustment of cuff with Velcro tape

b) Adjustment of the hem line

c) Adjustment of the hood

5.8. Assessment of Fit and Ergonomics of the Outdoor Rock-climbing Jacket

To evaluate fit, comfort and ergonomics of the jacket, an observation session was conducted on an indoor climbing wall with a model, who has significant rock-climbing experience. All observations adhered to Ethics Application 21/171 (see Appendix A). The evaluation of the created jacket in static conditions confirmed adherence to the intended design specifications regarding fit, jacket and sleeve length, pocket placement, and smooth fabric alignment across the body without any undue tension or excess material (see Figure 5.37 (a)). Figure 5.37 (b) illustrates the final version of the proposed design of the jacket created in 3D fashion design software. The actual jacket closely matches the fit of its digital counterpart.

Figure 5.37

Actual and digital versions of the jacket in statics

a) The actual jacket b) The virtual jacket

The general fit, comfort, and ergonomics of the jacket in dynamic conditions were assessed during the climbing session (see Figure 5.38), both by the researcher with garment engineering background, and by the experienced rock climber model. For the assessment of ergonomics and relative usability, the climber was interviewed following a brief climbing session. The interview questions encompassed various aspects of usability and ergonomics:

1. Is the jacket comfortable?
2. Is the jacket lightweight?
3. Is the jacket suitable for climbing?
4. Are there any visibility restrictions?
5. Are there any movement restrictions?
6. Is it convenient to use climbing gear while wearing the jacket?
7. Can you feel any component of the heating system while wearing the jacket?
8. Is it convenient to use a backpack while wearing the jacket?
9. Can you feel any component of the heating system while wearing the jacket and using a backpack?
10. Is the jacket sufficiently warm?
11. Is the jacket fashionable?

12. Do you like the material and colour selection of the jacket?
13. Would you like to have this jacket in a real mountain environment?

The climber responded to these questions using five-level Likert scales (1 = strongly disagree/no; 2 = disagree; 3 = neither agree nor disagree; 4 = agree; 5 = strongly agree/yes) (Mcleod, 2023; Mokhlespour Esfahani & Nussbaum, 2018). The responses were documented and are presented in Table 5.2. Overall, the climber expressed satisfaction with the jacket's fit, design, usability, comfort, and ergonomics. However, regarding question #10, the climber noted that the jacket was too warm for indoor climbing, which is understandable given it was designed for outdoor environments. Unfortunately, in compliance with Ethics Application restrictions, the observation session had to take place indoors on an artificial climbing wall.

Table 5.2

Answers to questions about various aspects of usability and ergonomics of the jacket

Number of question	Answer (1 = strongly disagree/no, 5 = strongly agree/yes)
1	5
2	5
3	5
4	1
5	1
6	5
7	1
8	5
9	1
10	3 (too warm inside)
11	4
12	4
13	5

The examples of dynamics postures for evaluation of the jacket during an observation session are presented in Figure 5.38. As shown in Figure 5.38(a), there are no restrictions preventing access to the belay loop for secure attachment with a carabiner and rope, which is significant for safety. Figures 5.38(a) and 5.38(b) demonstrate that the safety harness is not impeded or restricted by the jacket, confirming that the length of the jacket is appropriate. The jacket's fit was also evaluated dynamically by comparing it to static conditions. The fit in dynamic wear for these two positions did not significantly deteriorate compared to static conditions. During climbing, there was no significant dynamic pressure or fabric stress and strain at the back. However, some visible fabric stress was observed around the sleeve insertion area (see Figure 5.38 (b)). Although the climber did not report any discomfort or movement restrictions related to this area. Conversely, the elbow area, which exhibited considerable fabric stress during 3D movement simulation (see section 5.5), was well-fitted and comfortable during climbing. This supports the effectiveness of the engineered pattern solution for achieving an ergonomic sleeve shape.

Figure 5.38

The observation session for assessment of the jacket characteristics in dynamic postures

Figure 5.39 presents a comparison between the jacket's behaviour in real-world movements and simulations conducted using 3D fashion design software. The overall fit and fabric stress observed in the digital representation of the jacket closely align with those observed in the physical garment. This correspondence validates the effectiveness of using 3D fashion design technology for the initial evaluation of garment fit as well as fabric stress and strain characteristics in both static and dynamic conditions.

Figure 5.39

Comparison of jacket's behaviour between real and simulated climbing dynamic postures

a) Dynamic posture during climbing (front view): real vs 3D movement simulator

b) Dynamic posture during climbing (side view): real vs 3D movement simulator

c) Dynamic posture during climbing: real vs 3D movement simulator

The following three images (see Figure 5.40) illustrate the fit and fabric stress characteristics of the jacket during climbing, depicting typical dynamic postures observed in such activities. The images demonstrate that the jacket maintains a good fit and allows unrestricted movement for the climber. No restrictions could be observed when using climbing gear. This confirms that the jacket is comfortable and ergonomic and accommodates the needs of climbers.

Figure 5.40

The observation session for assessment of a jacket characteristics in dynamic postures

It was important to assess the precise placement of the heating system components to ensure that climbers cannot feel them during climbing or when using a backpack. For this purpose, the climber was requested to assume a posture that would induce maximum fabric strain and stress, as depicted in Figure 5.41. The arrows specify the positioning of the heating system components inside the jacket. Additional evaluation was conducted while wearing a backpack (see Figure 5.41 and 5.42). During these assessments, the climber did not report any unusual sensations related to the integrated wires, sensors, or other elements of the system. Furthermore, these components were not visibly discernible through the fabric, indicating that the integration concept of the heating system was successful.

Overall, based on a visual observation on-site, photos and videos taken during the observation session, and the interview with the climber, it is evident that the jacket meets the required levels of ergonomics, comfort, fit, safety, and functionality.

Figure 5.41

Placement of the wearable electronics inside the jacket

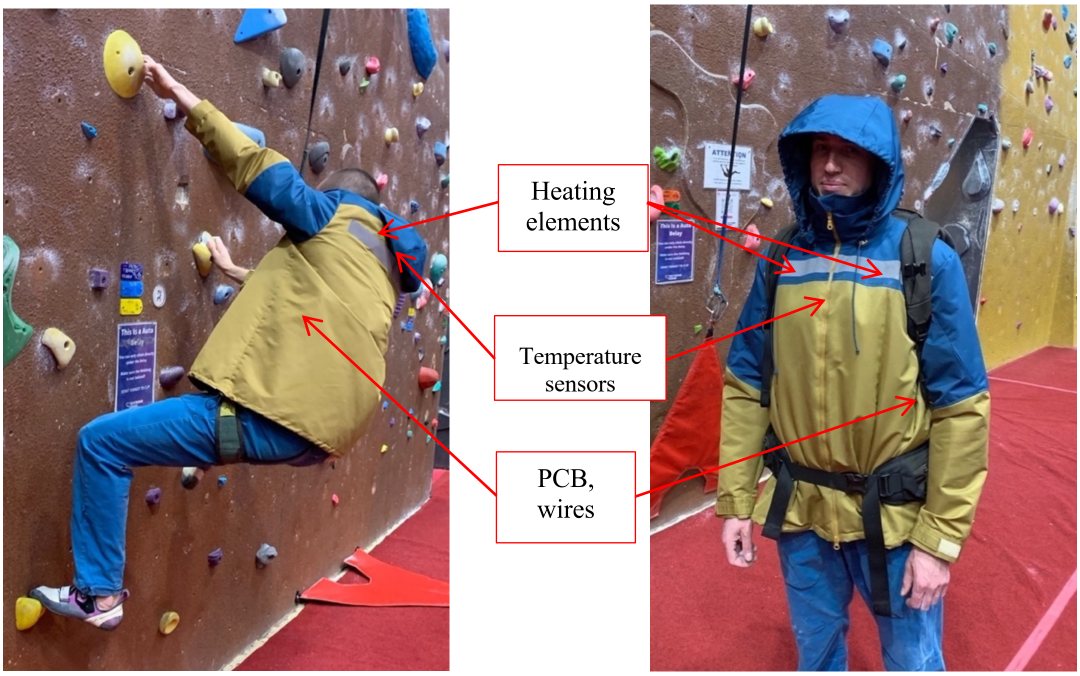


Figure 5.42

Placement of the wearable electronics inside the jacket while wearing a backpack

5.9. Conclusion

This practical chapter detailed the development process of an outdoor jacket designed for rock-climbing integrated with wearable technology. It comprehensively covered each stage of creating the jacket, starting from initial sketches to assessing its characteristics while worn by a climber during ascend on an artificial climbing wall. Each section not only outlined the process but also discussed related considerations, methods, instruments, and proposed solutions used to at ensure that the jacket is ergonomic and functional for rock-climbing activities.

Thus, in the stage of design development many factors were considered, including the range of movements required, placement of the smart heating system components, positioning of rock-climbing equipment, adequate pocket placement and quantity, as well as other constructive design features and considerations tailored to climbers' preferences.

The chapter also described the pattern engineering process, detailing the methods and techniques used to create initial flat clothing constructions and sewing patterns. Additionally, it described the initial fitting of the toile on a model, illustrating the process of pattern verification and modification prior to digitalisation.

Besides traditional approaches to garment development, the information technology, specifically virtual fashion design software, was employed and assessed as a contemporary and prominent instrument to create virtual garment, enabling visualisation on a 3D mannequin in both static and dynamic poses, digital fitting assessments, and evaluation of fabric strain and stress characteristics through 3D simulation modes. The fit and fabric stress characteristics of the designed jacket in static and dynamic body postures were analysed through virtual fitting and real-world observation conducted on an indoor climbing wall. The results corresponded, validating the effectiveness of employing 3D fashion design technology for the initial evaluation of garment characteristics under both static and dynamic conditions. Overall, the advantages of 3D design software in augmenting the garment design process are evident, allowing designers to visualise concepts in real-time, conduct preliminary testing, and evaluate the fit and comfort of clothing in static and dynamic scenarios through virtual try-ons.

During the observation session, the general fit, comfort, and ergonomics of the created outdoor rock-climbing jacket in static and dynamics were assessed by the researcher, who has with a background in garment engineering, as well as by the experienced rock climber who represented a potential user of the smart garment. This approach adhered to the principles of UCD and provided an objective evaluation of the final product. Additionally, the precise placement of heating system components was evaluated to ensure climbers cannot perceive discomfort during climbing or while using a backpack. The climber did not report any discomfort while climbing related to the integrated electronic components during the assessment, affirming the successful integration concept of the heating system.

Overall, the created outdoor jacket can be evaluated as functional and ergonomic for rock-climbing, tailored specifically for rock climbers, accommodating for climbers' activities, needs, and preferences alongside contemporary design innovations, technologies, and advanced textile materials. As an expert in garment engineering, the researcher can affirm that the jacket exhibited a good fit both in static positions and during climbing movements. The design and assessment of the clothing in static and dynamic scenarios using 3D design software aligned with the results observed in real-world assessments. Importantly, the integration of wearable electronics did not compromise the ergonomics, fit, comfort, and safety characteristics of the jacket.

CHAPTER 6. DEVELOPMENT AND INTEGRATION OF THE HEATING SYSTEM PROTOTYPES

This chapter presents an in-depth account of the process involved developing and integrating the proposed smart heating system into the jacket with refence to the model of the final climbing apparel design system (see Figure 3.4). The primary task was to design an ergonomic and lightweight smart outdoor jacket for rock-climbing, capable of automatically regulating its internal temperature. It was decided to accomplish this smart heating system through the integration of a PID controller and temperature sensors, which would determinesthe optimal level of heat. The system that was developed operates through the use of heating elements, a central control unit, temperature sensors, and a battery pack. It ensures temperature stability by transmitting data from the temperature sensors to the central control unit, which in turn modulates the power supplied to the heating elements. This jacket was designed to be non-intrusive and as comfortable as a regular garment without any thermoregulating functions. Consequently, all components, circuitry, and wiring had to be compacted to reduce any potential discomfort for the wearer. Additionally, all components of the system would need to be placed correctly, considering different factors such as which parts of the body should be kept warm, safe distance between components, wiring connection issues, and placement of the rock-climbing equipment (e.g., rope, harness, backpack). It was also essential for the components to be seamlessly integrated into the clothing and to be washable. The research and development of this project illuminated various methods for combining electricity with textiles to produce innovative solutions. As part of the process of integrating the smart technology, the limitations inherent in contemporary e-textile technology were explored.

Strategically, two types of prototypes of this sensing system were developed: functional and conceptual. The conceptual prototype shows how a system can be best integrated into the garment. For this prototype, a customised PCB was proposed and developed in collaboration with students from the School of Engineering, Computer and Mathematical Science at AUT. This prototype represents the conceptual solution for optimal placement of the components of the wearable smart heating system inside a rock-climbing jacket developed with the goal of mass-production in mind.

The other prototype of the system was the functional one created to demonstrate how this sensing system works. It was created for the purpose of running the system, refining the code for a microcontroller unit, and ensuring a PID controller worked. The functional prototype was tested in laboratory conditions using a pocket made of textile materials to simulate a real situation where the heating pad and sensor are positioned inside a rock-climbing jacket. Testing of the functional prototype demonstrated that temperature sensor data could be effectively collected and processed by the microcontroller. Despite the prototype being in an experimental phase, the temperature readings were accurate and correctly processed. The microcontroller successfully generated variable Pulse Width Modulation (PWM) signals for the heating elements based on the specified temperature settings. The functional prototype was fully operational and ready to be used, although there is room for further improvement.

6.1. Hardware Components

6.1.1. Identification and Selection of the Components for the Heating System

The conceptual and functional prototypes of the heating system were created using a combination of custom-built and commercially available components to provide functionality along with lightweight and comfort for the wearer. Identifying the optimal choice and the placement of the components of the heating system were critical to ensure the comfort, safety, and functionality of the outdoor rock-climbing jacket. The next section describes the analysis and testing of the hardware components and provides clarification on why they were chosen for prototyping.

6.1.2. Heating Elements

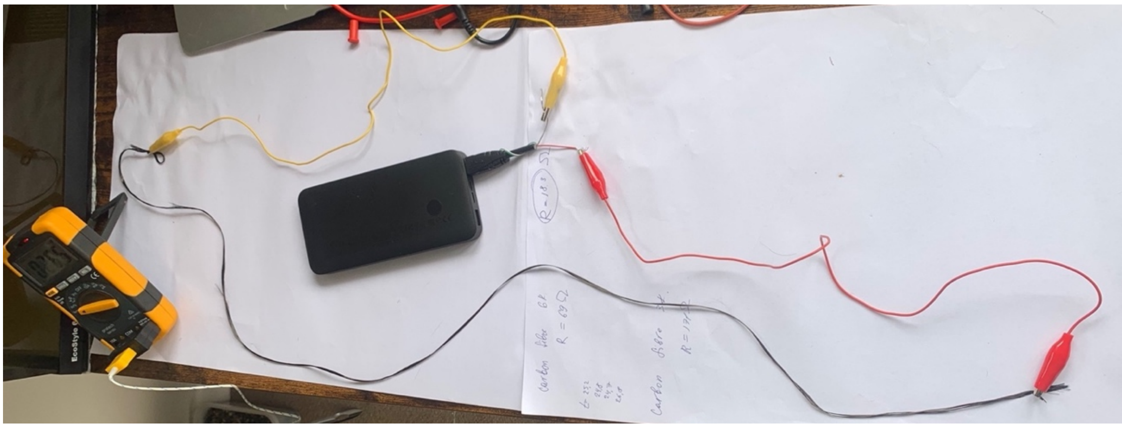
In designing the heating mechanisms for the jacket, various methods of heating within the e-textiles domain were investigated. Taking into account an analysis of the heating elements employed in commercially available heated jackets, the most common method involves the use of heat-conductive carbon fibres or yarns (see section 2.6 for more details). For this reason, samples of both pre-made heating pads and yarn consisting of carbon fibres were ordered and tested to determine their suitability for this project. To test these samples, a simple and efficient method was used by focusing on assessing two issues:

1. The ability of the yarn to heat up when current is applied.
2. The potential for the yarn to be used as an e-textile in wearable smart clothing, which involved evaluating its sewability both in its original form and after structural modifications.

To evaluate the ability of the yarn to be heated, one meter of the yarn was connected to a 5V (2.4 A) power supply, as depicted in Figure 6.1. The yarn's temperature was measured using a temperature probe fitted with a Type K thermocouple. Measurements were taken at five intervals: initially at 3 minutes and subsequently every 5 minutes. The test was terminated when the temperature readings remained stable after the third measurement. When the results were deemed satisfactory, additional tests were performed to determine if the yarn would be suitable for use as a heating system component in this jacket. The results obtained from these tests are presented below.

Figure 6.1

Testing procedure for carbon yarn specimen



Specimen #1 was a φ3mm 12K Japan Carbon Fibre Heating Wire. This silicon rubber covered carbon fibre was made as an Infrared Warm Floor Heating Cable, with the maximum acceptable temperature being up to 200℃ (see Figure 6.2 (a) and (b)).

The manufacturer provided the following specifications for the product:
Infrared wavelengths: 8-18 μm
Conductor resistance: 33±10% ohms/m
Diameter: 3±0.1mm

Figure 6.2

Specimen #1

a) Silicon rubber covered carbon fibre b) Carbon fibre (silicon rubber was removed)

Firstly, the resistance of the fibre was checked and found to be 38 ohms/M. For initial testing, one meter of the silicon rubber covered carbon fibre and one meter of uncovered carbon fibre were connected to a power bank (5.1 V, 2.4 A). The specimen labelled ‘a’ did not heat up, while the specimen ‘b’ heated up by 30 ℃ after 3 minutes. The primary issue with this type of carbon fibre is that the yarn's filament structure prevents it from being twisted into thread to bu used for sewing. Additionally, the yarn is both rigid and brittle, making it susceptible to damage.

Specimens #2 and #3 were carbon fibre wires with high temperature resistance. Specimen #2 was composed of 3K monofilaments, whereas Specimen #3 was made up of 6K monofilaments (see Figure 6.3 (a) and (b)). Both yarns were sourced from China.

The seller provided the following specifications for the product:

Tensile strength: 3530 Mpa

Tensile modulus: 230 Gpa

Density: 1.76 g/cm^3

Elongation: 1.5%

The given resistance values of carbon fibre filaments 3K and 6K are 144 ohm/m and 72 ohm/m respectively.

Figure 6.3

Specimens #2 and #3

a) Carbon fibre 3000 monofilaments b) Carbon fibre 6000 monofilaments

First, the resistance of both specimens was measured using a multimeter. It was found that the resistance of the 6K monofilament specimen matched the declared value of 70 ohms/m, while the resistance of the 3K monofilament specimen was significantly higher than the value specified on the seller's website, measuring at 171 ohms/m.

For initial testing, one meter of yarn made from 3,000 carbon fibre monofilaments and one meter of yarn made from 6,000 carbon fibre monofilaments were connected to a power bank (5.1 V, 2.4 A). No changes in temperature for neither specimen could be noted. This outcome was anticipated due to the high resistance relative to the 5.1V power supply. Both specimens share the same structural characteristics as specimen #1, and therefore were deemed unsuitable for sewing.

Specimen #4 was high conductive and tarnish resistant yarn Shieldex® 235/36 HCB, as depicted in Figure 6.4. This conductive yarn was manufactured by V Technical Textile, Inc (Germany) (Shieldex, n.d.). According to the manufacturer, the Shieldex® 235/36 x6 HCB is a highly conductive, six-ply yarn featuring a high-strength, Z 400-twisted structure with a titre of 235 dtex and a round cross-section. It offers an electrical resistance of < 30 Ω/m ± 10 Ω/m, making it appropriate for diverse applications in smart textiles and wearables, including textile conductors, embroidered sensors, actuators, and heating and lighting textiles. This yarn is composed of Polyamide/Nylon 6.6, plated with 99.9% pure silver, which contributes to its high conductivity. The yarn is also coated with nitrite rubber (+B) for additional protection against mechanical stress. It complies with RoHS and REACH standards.

Elongation: 27% ± 6%

Tenacity: 47 ± 5 cN/tex

Figure 6.4

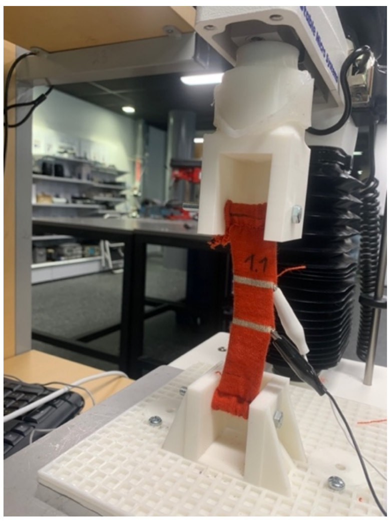
Specimen #4

Before conducting the heating test, the yarn's resistance was measured and found to be 18.3 Ω/m. During the test, the yarn demonstrated rapid heating capabilities, reaching 30°C after 3 minutes, 34°C after 5 minutes, 36°C after 10 minutes, 38°C after 15 minutes, and 40°C after 20 minutes. Given its suitability for use as a heating e-textile, an additional test was conducted in collaboration with textile and mechanical engineers utilising their laboratory facilities. First, the specimens for this test were knitted using a 14g SIG Knit machine in the Textile and Design Lab at AUT (see Figure 6.5 (a) and (b)).

Figure 6.5

Specimen #4 knitted for test

a) A knitted sample



b) A sample for a strip test

The testing of the yarn's electrical resistance after tensile stress was conducted using the Texture Analyser TA.XTplus, providing insights into the yarn's conductivity after a number of cycles. To evaluate this parameter, two standard methods were combined and modified: BS EN 62047-22:2014 (BSI, 2014) and ISO 13934-1:2013 (ISO, 2013). The sample was adapted to fit clamps that were 3D-printed, deviating from the original standards (see Figure 6.5 (b)). Some data were automatically recorded by the Texture Analyser's software, while other data were manually evaluated.

The test settings were as follows:

Test mode - tension

Pre-test speed - 1.00 mm/sec

Test speed -8.33 mm/sec (500.00 mm/min BS 4952-1992)

Post-test speed -2.00 mm/sec

Distance - 35.000 mm

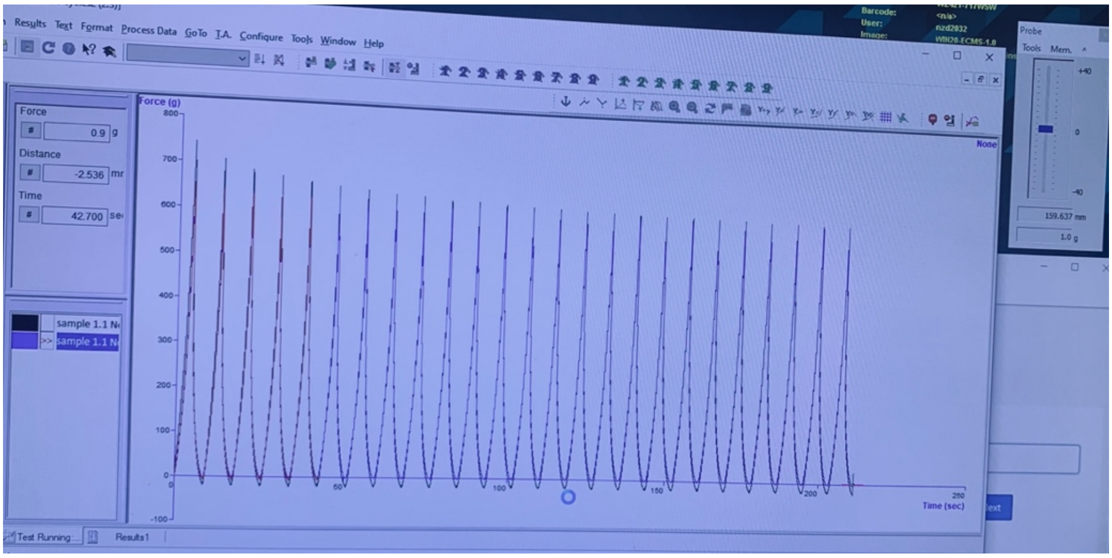
Count – 25 cycles

Start probe - 159.637 mm

The parameters were evaluated after 25, 50, and 75 cycles. Each test was conducted three times. During the tensile test, the electrical resistance increased by 43%. The graphical interpretation of the results after 50 cycles is presented in Figure 6.6.

Figure 6.6

The graphical interpretation of the test results for specimen #4 after 50 cycles



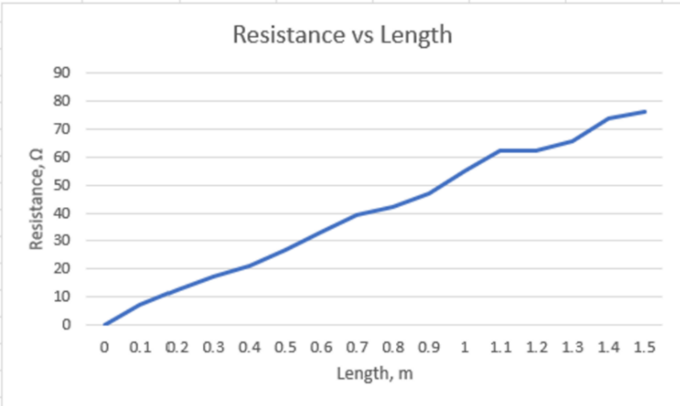
As the graphical data presented in Figure 6.6. indicates, even though the conductivity of this yarn specimen decreased after several cycles of tension testing, it remained viable for use in wearable heating elements for smart clothing. Nevertheless, further research is needed to determine the durability of these heating elements after repeated cycles of heating, washing, and other stressors.

The resistance of this conductive yarn was also tested to evaluate its suitability for use in wiring. The results of these tests are presented in Figure 6.7 below. The resistance of the yarn shows a roughly linear relationship with its length, as anticipated. However, the yarn has two significant limitations that may restrict its application in certain scenarios. First, it can safely carry a maximum current of only 100 mA. Second, its resistance is relatively high at 0.73 ohms per centimetre, compared to the standard 22 AWG wire utilised in the prototype, which possessed a resistance of 5.27 × 10-4 ohms per centimetre. Given that each heating pad requires 500 mA at full power, the conductive yarn is inappropriate for establishing power and ground connections within the jacket.

Figure 6.7

Conductive yarn testing result

Length, m	Resistance,
0	0
0.1	7.3
0.2	12.6
0.3	17.3
0.4	20.9
0.5	26.8
0.6	33
0.7	39.2
0.8	42
0.9	47.1
1	55
1.1	62.3
1.2	62.3
1.3	65.9
1.4	73.6
1.5	76.2



Specimens #5 and #6 – The pre-made Electric Heating Pads. A commercially available set of USB-powered heating pads (#5) with three temperature settings was analysed. To determine the heating method, one of the pads was opened (see Figure 6.8). It was found that the pads employ a weave of conductive yarn, identified by the seller as carbon fibre, designed to heat the surface of the pad. Testing revealed that the pads collectively draw around 1.6A, which equates to approximately 320mA per pad.

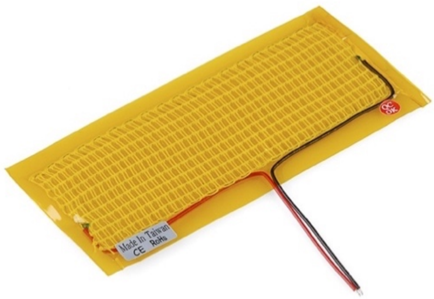
Figure 6.8

The pre-made Electric Heating #5

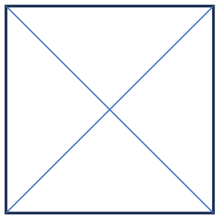
Specimen #6 - Pre-made Direct Current (DC)-powered heating pads. These thin heating pads are made from a micro metal conductive fibre (nichrome) and mesh of polyester filament, encased in a protective polyimide film (see Figure 6.9 (a)). Their low power consumption, flexibility, and minimal energy requirements make them suitable for applications such as hand warmers and other heated clothing. According to the manufacturer, the operating voltage is 5V DC with an operating current of approximately 600mA (~8.3Ω) (Sparkfun, n.d.-c). Testing of these pads revealed that each pad consumes about 550mA. The warm-up profile provided by the manufacturer is shown in Figure 6.9 (b).

Figure 6.9

The pre-made Electric Heating #6



a) The heating pad #6



b) The warm-up profile of the heating pad

(Image removed due to copyright restrictions)

Note. From "Heating Pad - 5x15cm" https://www.sparkfun.com/products/11289. Copyright n.d. by Sparkfun.

To evaluate the current draw and efficiency of the heating pad specimens #5 and #6, the USB power supply was connected to them to provide continuous readings of voltage and current. The heating pads were placed beneath a small fabric bag filled with rice, with a digital thermometer probe positioned underneath. The rice bag served as a heat absorber to evaluate the heating performance. Once the power was activated, measurements were recorded at 5-minute intervals. The initial data for testing of these heating pads are presented in Tables 6.1 and 6.2 below.

Table 6.1

Test results from heating pad #5

Time (min)	Rice Pack Temperature, ℃	Current drawn, mAh	Current, mA
0	18	0	1620
5	29	133.3	1600
10	32	265.38	1587
15	35	397.05	1584
20	38	529.05	1580

Where: Enq.1 $mAh = I * t$

Enq.2 Wh=mAh*I

Table 6.2

Test results from heating pad #6 - Yellow heating pads 4×

Time (min)	Rice Pack Temperature, ℃	Current drawn, mAh	Current, mA
0	18	0	2015
5	34	167.24	1994
10	36	331.1	1990
15	39	495.51	1988
20	42	660.01	1986

As illustrated in the tables, the rice pack's initial temperature was 18°C for both experimental trials. Upon completion of the first test using USB heating pads and their subsequent removal, the temperature of the rice pack increased to 21°C. In contrast, following the second trial with the yellow heating pads, the rice pack's temperature rose to 24°C. Based on these results, the decision was made to utilise the pre-made yellow heating pads. These pads were not only more conveniently sized but also demonstrated superior performance in the thermal test. They achieved a higher maximum temperature of 42°C compared to 38°C with the USB heat pads. Additionally, based on the measured power consumption, it was determined that a USB power bank with a minimum capacity of 6.8Ah would be required. USB power banks are widely available and typically support output powers ranging from 10W to 15W. A commonly available slim and portable power bank featuring a capacity of 10,000mAh would theoretically provide approximately 3.5 hours of operation based on the calculated requirements.

The Peak Current Draw is 2.015A, with an operating voltage of 5V, and the desired operating time is 2.5 hours. The power bank battery operates at 3.7V.

6.1.3. Conductive Fabrics

The samples of conductive fabric were investigated as alternative materials that may be acceptable for connecting the higher current tracks instead of wires. The concept to use two lines of different conductive fabric was considered. The fabric characteristics presented by the supplier are given below (LessEMF, n.d.).

The bronze Pure Copper Polyester Taffeta (see Figure 6.10 (a)):
Composition: 71±5% polyester and 29±3% copper.
Conductor: Copper plated. Continuous copper layer on polyester fibers.
Surface resistance of ≤0.3 Ω/m²
Average attenuation of ≥60dB in 10MHz – 3GHz
Fabric weight of 70±10 g/m²
Temp range: -40°C to 150°C, up to 200°C short term.
Fire point of 250℃, never self-ignite.
Fabric Thickness: 0.075mm.

The greyish conductive Ni/Cu Ripstop Fabric (see Figure 6.10 (b)):
Composition and Conductor: Nickel and copper plated on rip-stop polyester fabric
Fabric Thickness: 0.088 mm.
Surface resistance is 0.01 – 0.03 Ohm/m².

Figure 6.10

The samples of conductive fabric

a) The bronze Pure Copper Polyester Taffeta   b) The conductive Ni/Cu Ripstop Fabric

Based on the product's specifications, the conductive material examined in this study exhibits significantly enhanced resistance to tarnish and corrosion owing to its Nickel/Zinc plating (LessEMF, n.d.). It is also fire retardant, featuring a thermos adhesive film with a UL94V0 grade, complemented by a hot melt adhesive film. This construction provides superior conductive and shielding performance, offering effective protection against a broad spectrum of low-frequency electric fields and high-frequency electromagnetic radiation. This makes it particularly suitable for applications in electronics and RFID blocking. However, due to the potential for Nickel-induced skin allergies, this conductive fabric is not designed for direct skin contact.

The conductive fabric strips could be utilised to design high-current pathways for ground and power lines, which would increase the garment's flexibility. For this project, the concept that involved utilising two lines of conductive fabric (refer to Figure 6.26, section 6.5). The bronze copper conductive fabric was allocated for the 5V track, while the greyish conductive fabric was assigned to the common ground track (for signal and power ground). It was anticipated that these conductive material lines would adequately transmit the current required to operate the temperature sensors and support the operation of four heating pads.

Unfortunately, during a control test of surface resistance, both fabrics indicated higher resistance characteristics than those provided by the suppliers – up to 1.3 Ohms – resulting unstable current signals. This discrepancy necessitated the use of wires to connect the circuit components in the conceptual prototype. However, the possibility of utilising conductive fabric is discussed in Chapter 7 "Discussion", section 7.5.

6.1.4. Temperature Sensors

To accurately gauge ambient temperature, it is essential to use a high-quality temperature sensor. In developing wearable sensor technologies, evaluating various types of temperature sensors is critical. Different sensors serve specific functions, such as pure thermistors for detecting low temperatures with high sensitivity (accurate within 0.05±1.5°C) or digital integrated circuit (IC) sensors, which were employed in this project's conceptual prototype. To monitoring the temperature inside the jacket during the process of thermoregulating, two sensors were integrated, one placed on the back and the other on the front.

Digital thermometers operate using thermoresistive materials or devices which experience a change in resistance with variations in temperature. These materials generally have thermistor-like properties, responding precisely to quick temperature changes, particularly at lower temperatures. By applying Ohm's Law (V = IR), the current flow is converted into a digital readout through the thermistor. This digital readout then may be employed to regulate and maintain stable temperatures within clothing layers by programming the Micro Controller Unit (MCU) to process this reading.

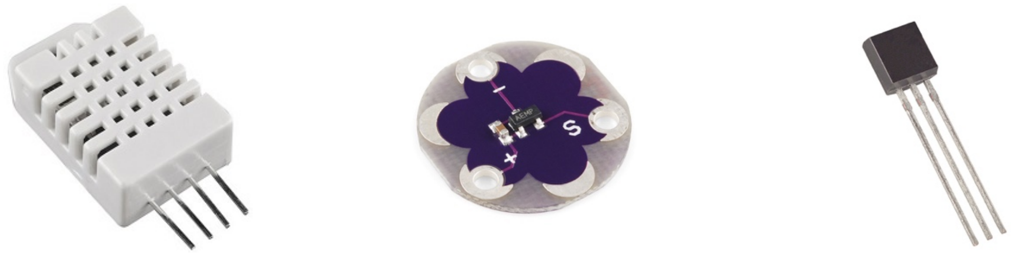
The electronics market offers a wide range of temperature sensors, including both analogue and digital types. For this project, several prototypes of heating system were developed, each incorporating a different type of temperature sensor. The initial functional prototype featured the DHT22 capacitive-type humidity and temperature sensor (see Figure 6.11 (a)). The DHT22 sensor contains a simple chip that performs analogue-to-digital conversion, outputting a digital signal with temperature and humidity data (Adafruit, n.d.). The DHT22 produces a calibrated digital signal and uses a specialised digital signal collection and humidity sensing technology, that ensures its reliability and stability (Aosong Electronics Co., n.d.).

The functional prototype of the heating system was then tested with the LilyPad Temperature Sensor MCP9700, a small thermistor-type sensor (see Figure 6.11 (b)). This sensor, part of the Linear Active Thermistor™ IC family, converts temperature into an analogue voltage (Microchip, 2014). The LilyPad sensor was selected for the functional prototype due to its suitability for wearable e-textile applications, featuring large connecting pads that can be sewn into clothing. Moreover, the LilyPad sensor also features the added advantage of being washable.

For the conceptual version of the heating system prototype, aimed at finding the optimal component placement on a jacket, a digital temperature sensor SEN-11050 utilising the DS18B20 thermometer was employed (see Figure 6.11 (c)). The DS18B20 utilises two oscillators, one sensitive to temperature changes and the other not, to determine temperature (Dallas semiconductor, n.d.). By analysing the differences in timing, the thermometer provides a high-resolution temperature reading. The choice to use such type of sensor for the conceptual prototype was driven by the superior resilience of digital sensors compared to analogue ones, particularly considering the long-term prospect of industrial production for the jacket. The DS18B20 sensor was selected for its robustness and washability.

Figure 6.11

The temperature sensors used for prototyping



a) DHT22 b) MCP9700 c) DS18B20

6.1.5. MCU and PCB

To implement the PID control, the MCU was required to run the desired program. For the functional prototype, an Arduino-compatible, sewable electronics microcontroller board was selected: the Lilypad USB Plus, developed by Leah Buechley and cooperatively designed by Leah and SparkFun for use in fabric and textiles (Sparkfun, n.d.-b). This PCB features fourteen sew tabs designed to connect components using conductive yarn or thread. From these, four tabs are designated for ground and power connections for LilyPad sensors and accessory boards, while the remaining ten tabs are allocated for input/output purposes. Each sew tab is labelled with its name and the corresponding pin number on the ATmega32U4 chip located at the center (see Figure 6.12). It is equipped with a waterproof coating and supports multiple inputs as well as a PWM output, which can be utilised to control the heating elements.

Figure 6.12 (Image removed due to copyright restrictions)

The Lilypad USB Plus PCB

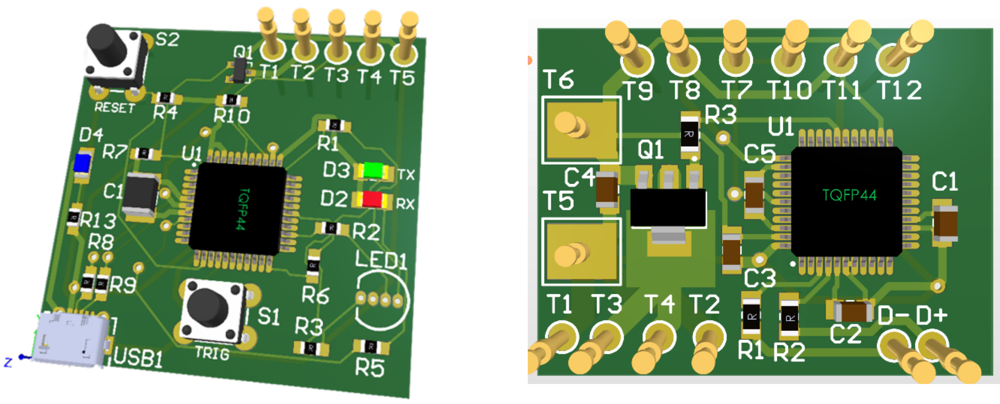
Note. From "LilyPad USB Plus Hookup Guide", https://learn.sparkfun.com/tutorials/lilypad-usb-plus-hookup-guide/all. Copyright n.d. by Sparkfun.

The Lilypad USB Plus was employed as a sewable electronics microcontroller board to evaluate the ATmega32U4 with the Arduino bootloader (Microchip, n.d.). The Microchip Technology ATmega32U4 is an 8-bit microcontroller with a USB controller, designed by Atmel. This is a low-power, AVR® RISC-based device equipped with 32KB of self-programming flash memory, 2.5KB of SRAM, and 1KB of EEPROM. It includes a USB 2.0 full-speed/low-speed device module, a 12-channel, 10-bit analogue-to-digital converter, and a JTAG interface for on-chip debugging. This microcontroller delivers up to 16 MIPS of throughput at 16MHz and operates within a voltage range of 2.7 to 5.5V (Microchip, n.d.).

In evaluating future improvements for the smart heating system, especially with the goal of integrating it into a jacket for potential mass production, several issues with the Lilypad USB Plus were identified. The device's complexity was increased by the presence of extraneous components, and the PCB tracks were found to be too narrow. Additionally, the metal oxide semiconductor field-effect transistor (MOSFET) module used did not adequately meet the power requirements. Considering these factors, a custom PCB design was proposed to replace the Lilypad USB Plus for the conceptual prototype, aiming to optimise component placement within the jacket. This custom PCB, designed in collaboration with a team of three students from the School of Engineering, Computer and Mathematical Sciences at AUT, offered the same functionality as the Lilypad USB Plus (see Figure 6.13 (a) and (b)).

Figure 6.13

The PCB layout

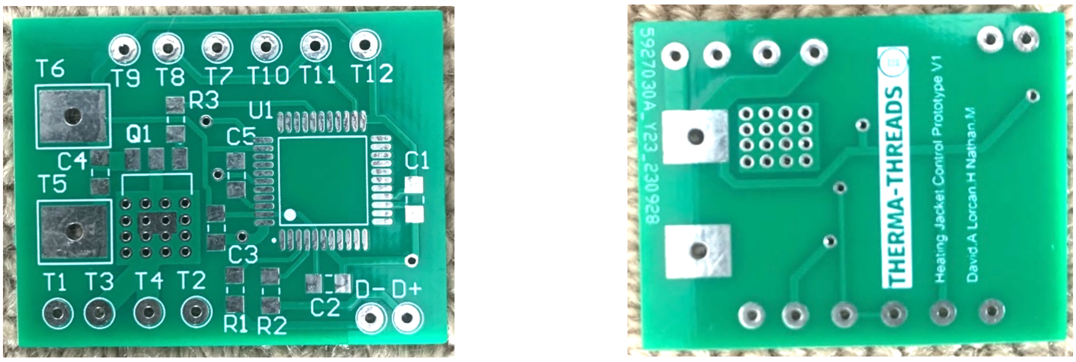


a) Proposed PCB layout (3D view) b) Revised PCB layout (3D view)

After a thorough redesign of the schematic, all non-essential components were eliminated, including the USB connector. Instead, points of connection D- and D+ were integrated into the board to serve as negative and positive data pins. The USB connector’s data lines were utilised only once for programming the microprocessor and thus were deemed unnecessary for end-user operation. Consequently, the design allowed for soldering a USB lead for programming, which could then be removed and replaced with a standard USB power connector for power supply connection. For connecting the two temperature sensors, terminals seven to twelve were included. Additionally, indicator lights and buttons were removed to streamline the design, focusing solely on essential components to enhance slimness and waterproofing (see Figure 6.14 (a) and (b)). The design was simplified to feature only an automatic mode, disregarding user input options. Furthermore, two 2mm diameter holes were drilled into the PCB to facilitate its attachment to the jacket.

Figure 6.14

Designed PCB



a) Front of designed PCB

b) Back of designed PCB

6.2. Hardware Design

6.2.1. Hardware Design of the Functional Prototypes

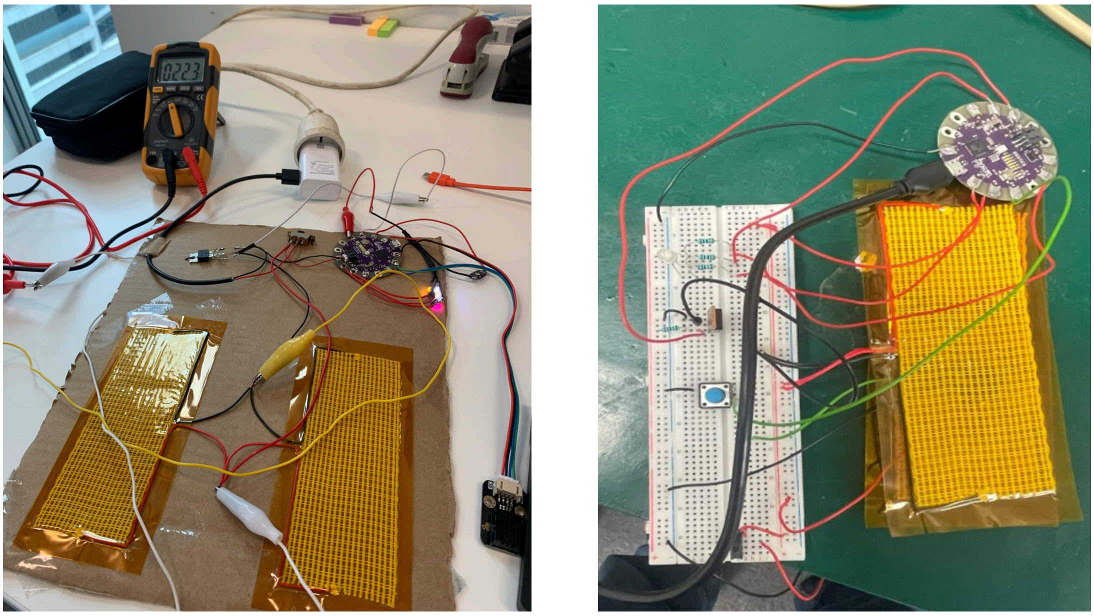
The hardware considerations for this project encompassed two types of prototypes: the functional prototype, designed to operate the smart heating system, and the conceptual prototype, focused on determining the optimal placement of components for integration into the jacket. The initial focus of this project was to develop a functional prototype. Once the essential components for the circuit were identified, an initial prototype was assembled. Figure 6.15 (a) illustrates an initial prototype.

This initial prototype was built using a circuit similar to the hand warmer design from the SparkFun website (Sparkfun, n.d.-a). This circuit incorporated the DHT22 capacitive-type humidity and temperature module, three LEDs, and two heating pads connected in parallel, all driven by a MOSFET and controlled by a switch. The circuit was powered by a 5V DC supply and managed by the Lilypad USB Plus. Although the design was straightforward and easy to understand, it contained several superfluous components and had issues with the transistor.

The second iteration of the functional prototype was constructed on a breadboard (see Figure 6.15 (b)) to evaluate the performance of the Lilypad temperature sensor, which uses the MCP9700 thermistor, as well as the rest of the circuit. The breadboard setup included a 5V power input connected to both the microcontroller unit and the source pin of the transistor. The PWM output from the MCU was connected to the gate pin of the transistor, while the heating pads were linked to the drain pin.

Figure 6.15

Functional prototypes setup

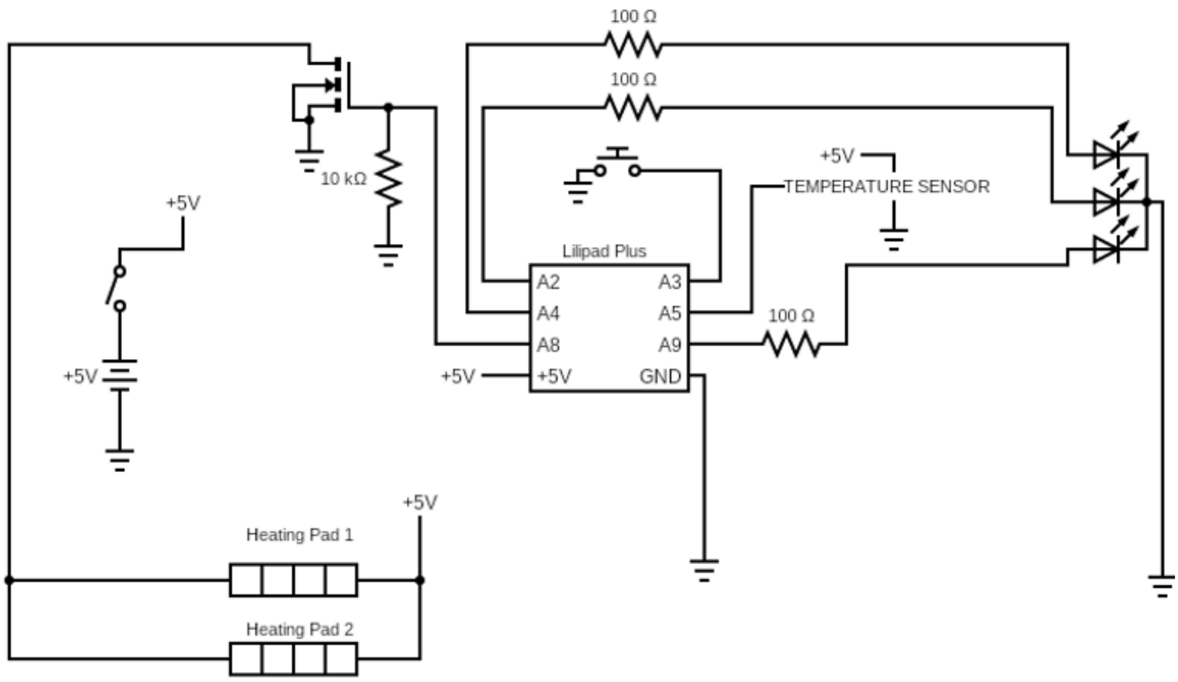


a) Prototype Setup (DHT22 sensor) b) Prototype Setup (MCP9700 thermistor)

Initially, the design mirrored that of existing commercial products, featuring a button to toggle between four operational states: 1/3, 2/3, full, and auto. This button allowed users to manually control the heating percentage, which facilitated the testing of the basic functionality of the PID control system. For this prototype, the three separate LEDs from the first prototype were replaced by a single multi-coloured LED, accompanied by three 100-ohm resistors, that served to indicate the current heating mode of the jacket. The heating modes were represented as follows: green mode, where the MCU generated a square wave with a 33% duty cycle; yellow mode, with a 66% duty cycle; red mode, with a 99% duty cycle; and blue mode, where the duty cycle varied based on external conditions. Each mode's duty cycle corresponded to specific temperatures measured by the heating pads: 24°C for green mode, 31°C for yellow mode, and 33.5°C for red mode. The schematic of this prototype is presented in Figure 6.16.

Figure 6.16

The schematic of the functional prototype



A third iteration of the functional prototype was developed to refine the MCU code and ensure the PID control functions correctly. This version of the prototype was constructed on a Veroboard, utilising a Lilypad Plus USB, a single heating pad, and a Lilypad temperature sensor (see Figure 6.17). This circuit operated with a five-volt power supply. A picture of how the circuit was tested is presented in Figure 6.18. While the prototype was fully functional and operational, it was not yet optimised for ideal performance and not set up for mass production.

Figure 6.17

Refined prototype circuit on Veroboard

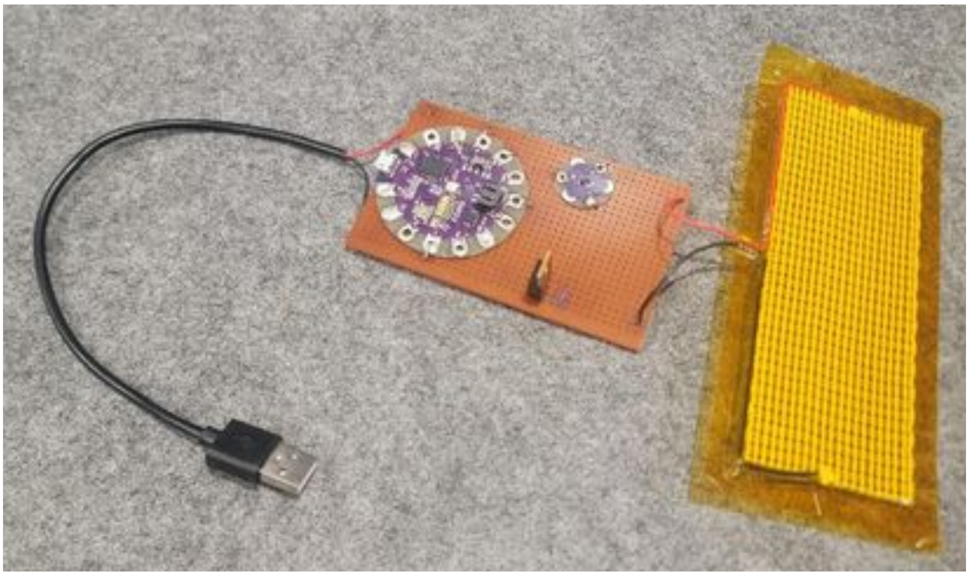
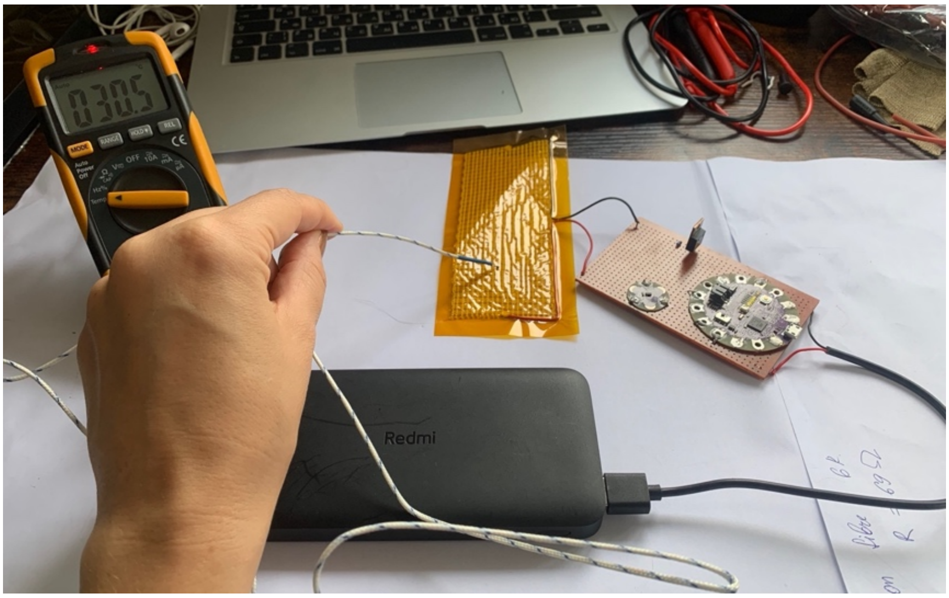


Figure 6.18

Testing of the refined prototype



6.2.2. Hardware Design of the Conceptual Prototype

As mentioned above, the second hardware consideration for this project involved the development of the conceptual prototype aimed at finding the optimal placement of the system components for integration into the jacket. The conceptual prototype lays out a vision for future improvements to enhance the functional prototype, enabling its use for industrial production. Given the interdisciplinary nature of this project, these future improvements would entail collaboration with professionals from various fields. For instance, the design of the customised PCB for the conceptual prototype was developed in collaboration with students from the School of Engineering, Computer, and Mathematical Science at AUT. The details of this PCB are thoroughly described in section 6.2.5. The essential components required for assembling the circuit of the conceptual prototype were identified and presented in Table 6.3.

Table 6.3

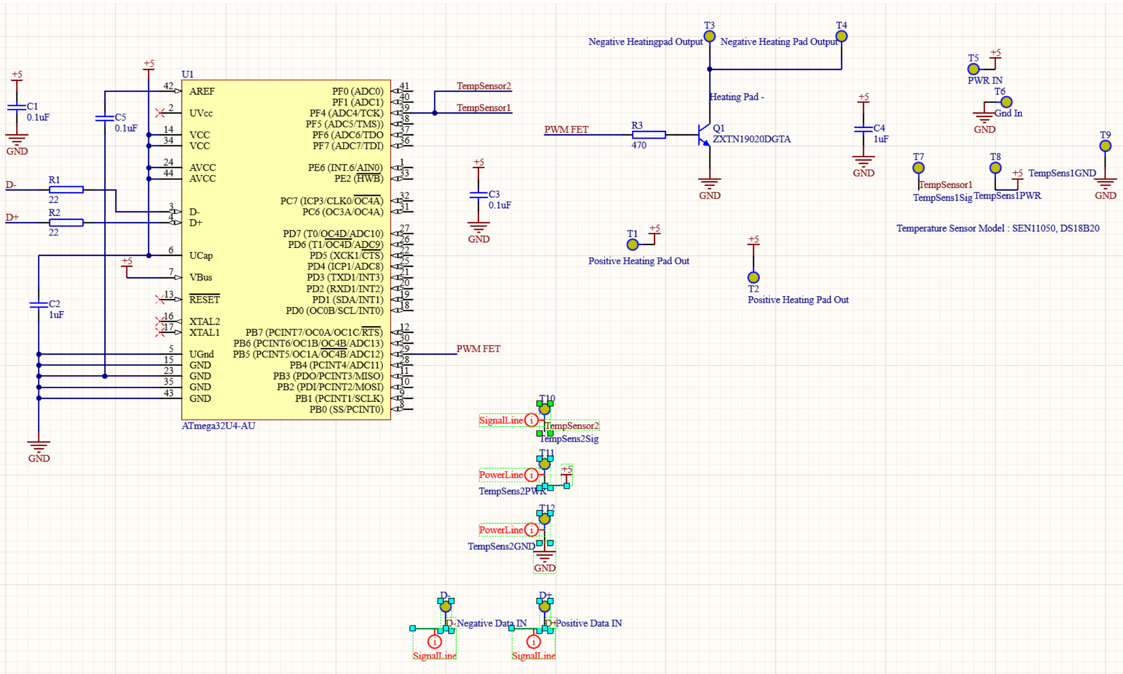
Materials list for a single prototype unit

Product name	Quantity
1206 22W Resistor	2
1206 0.1uF Capacitor	3
1206 1uF Capacitor	2
1206 470W Resistor	1
ZXTN19020DGTA BJT	1
SEN11050 Temperature Sensor	2
5V 2A Power Bank	1
AT Mega32u4 MCU	1
Heating Pads	4

The schematic of the conceptual prototype of the heating system presented in Figure 6.19 below. In this schematic, improved circuit design practices have been applied, including the addition of more terminals for external devices. Since the system needed to be programmed just once, the USB programming device has been removed. Instead, the D- and D+ lines could be utilised for programming the MCU. Capacitors C1, C3, and C5, each rated at 0.1µF, were employed to filter out high-frequency noise on the 5V lines due to their high resonant frequency properties. Capacitors C2 and C4, each rated at 1µF, also served to filter high-frequency noise.

Figure 6.19

A schematic of the conceptual prototype of the heating system



As mentioned earlier, the microcontroller was programmed to process input from the two temperature sensors connected to PORT F4, generated a PWM signal based on this data, and then transmitted this signal to the four heating pads. The terminals T7 and T10 were designated for signal lines, T8 and T11 for power lines, and T9 and T12 for ground lines, all providing connections for the heating pads. Terminals T5 and T6 supplied power to the circuit from a power source, whereas terminals T1, T2, T3, and T4 linked the heating pads to the PCB. Additionally, the circuit featured Q1, a BJT that drove the heating pads.

Another change involved selecting a stronger transistor capable of handling higher currents. The design was further updated by adding thermal vias beneath the output and incorporating a copper pad to enhance the transistor's heat dissipation. Additionally, decoupling capacitors were included to ensure stable power delivery to the circuit's sensitive components.

The developed PCB (see Figures 6.14.) were expected to significantly reduce both size and noise, addressing issues encountered during the testing of the functional prototype with Lilypad temperature sensors. To mitigate these issues in future iterations, more reliable digital temperature sensors, specifically the SEN11050, were selected for the conceptual prototype. These sensors were anticipated to provide more consistent and accurate results. Furthermore, the SEN11050 was specifically developed for outdoor use and is enclosed in a flexible plastic shell with sheathed cables, facilitating easier routing and minimising potential interference with the control board.

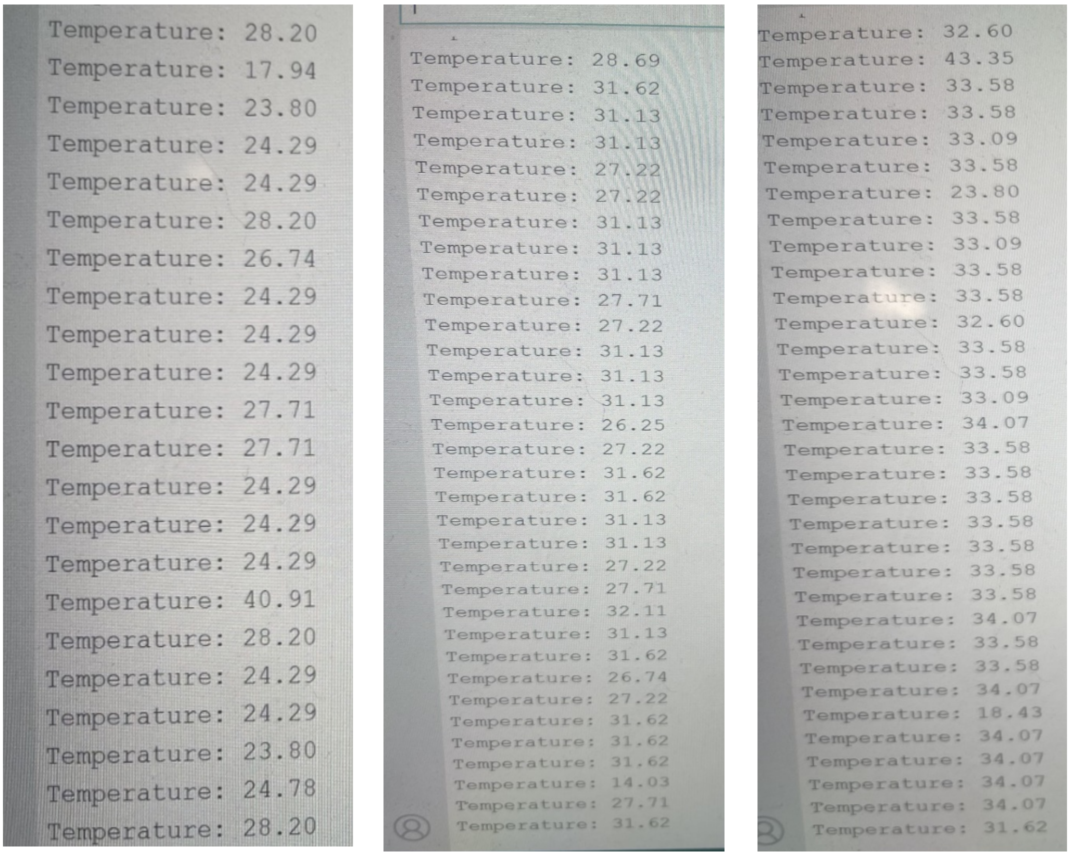
A potential drawback of using conductive yarns and fabrics arises from their tendency to cause shorts if wires cross over each other, unlike traditional insulated wires which can intersect without issue. While careful planning of routing can mitigate this issue, it may also restrict the range of possible applications in which these yarns might be used.

6.3. Software Design and Evaluation

During the creation of the online prototype, the software used to programme and operate the functional prototype was developed using Arduino's proprietary language, a variant of C/C++. For the functional prototype's initial iteration, which included numerous operational modes, the code was structured as a state machine. A significant challenge encountered and resolved during this phase was related to noise interference. The temperature readings presented in Figure 6.20 suggest the presence of electrical noise affecting the temperature sensor as evidenced by impossibly rapid fluctuations away from the mean temperature trend.

Figure 6.*20*

Temperature logs during testing



a) Green mode b) Yellow mode c) Red mode

Considering this context, readings of the temperature sensor were reasonably accurate. Various solutions were investigated to address the unexplained noise, including the replacement of the temperature sensor and modification of the original code. One modification involved introducing a delay in the code to poll the sensor only every two seconds. Although this adjustment mitigated the noise problem, it introduced a new issue: pressing the button failed to transition the programme's state. This was due to the programme pausing during the delay, which prevented any other code from being executed. A solution was ultimately identified by employing the Arduino 'Millis()' function. This function is an Arduino built-in feature which returns the elapsed time since the programme started executing. The solution involved using the Arduino 'Millis()' function to determine if the interval since the last sensor check had met or exceeded the specified polling rate. When this condition was met, the elapsed time was updated and the temperature sensor was queried. This approach addressed the issue by ensuring that the programme did not pause during delays; instead, it continuously looped until the designated polling interval was reached, thus allowing the programme to respond immediately to button presses. Figure 6.21 below presents a piece of code that effectively resolved both the noise issue and the state transition problem.

Figure 6.21

Solution Code Excerpt

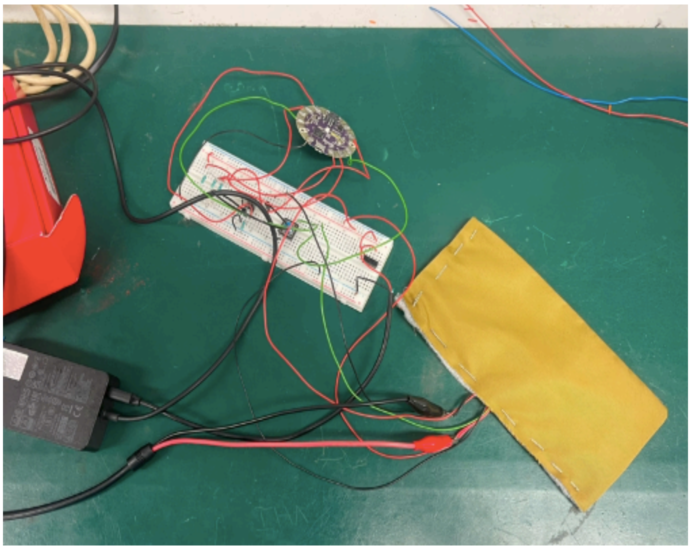
```
timePassed = millis();

if (((timePassed - prevTimePassed) >= pollRate)) {
  prevTimePassed = timePassed;
  temperature = tempSensFunc();
  Serial.println(temperature);
}
```

For the final evaluation of the code, a pocket was created using the textile materials selected for the jacket prototype (see section 5.4) to replicate the actual placement of the heating pad between the jacket's layers (see Figure 6.22). The finalised code for the functional prototype is detailed in Appendix E. As described in Appendix E, variable names were assigned for convenience in managing the code. The declarations for inputs and outputs ensured that the Arduino bootloader could correctly process the data flow. The code featured a control system with a proportional constant of 40, which was used in the control output variable and subsequently impacted the final heater output variable. This heater output was applied to the FET pin, and temperature sensor readings were taken at 200-millisecond intervals. Additionally, a function named "tempSensFunc", located outside the main loop, was responsible for reading the analogue temperature sensor values and converting them to degrees Celsius.

Figure 6.22

Evaluation the final code of the functional prototype

a) Pocket for testing the system prototype



b) Testing of the functional prototype with the heating pads placed in the pocket

For the conceptual prototype utilising the custom PCB, the ATMega 32u4 could not execute Arduino code directly, as it lacked the necessary bootloader. Consequently, the code had to be written in C language, which presented certain challenges compared to the more user-friendly Arduino variant. For instance, C requires the explicit configuration of registers to ensure proper timer functionality, while the Arduino variant can manage these aspects automatically in the background. Developing and executing code for the customised PCB represents a direction for future extensions of the project and could potentially involve a separate research initiative within the IT field. After completing and validating the Arduino code, a flowchart for the C code, illustrated in Figure 6.23, was created to provide guidance.

As shown in Figure 6.23, the C code developed for the prototype started off by incorporating the necessary libraries and defining essential variables, including those associated with PID control. Within the main loop, the average temperature was recorded and processed only if it fell within a plausible range to minimise the effects of erroneous readings. The error was calculated as follows:

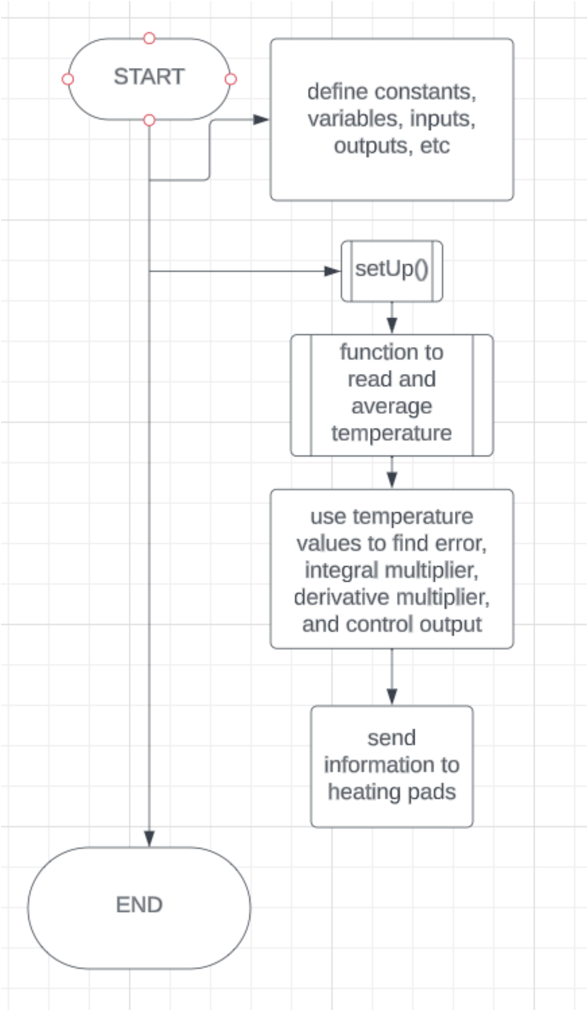
$$Error = Set\ Point - Average\ Value.$$

The derivative was determined by computing the difference between the current and previous errors, and this value was integrated into the following control output equation:

$$Control\ Output\ Value = (Error \times Kp) + (Kd * Derivative\ Value).$$

Figure 6.23

Flowchart for C Code



To maintain the control output value within the range of 0-1023, as specified by the TCCR1B configuration with a 1/1024 prescaler, appropriate conditional statements were employed. The top value for the input capture register was set to the final control output value, and the main loop executed on a one-second interval. For reading the temperature sensors' data, a function which was defined outside of the main loop was employed by utilising the "*requestTemperatures(n)*" and *"getTempCByIndex(n)"* commands, where n represented the number of the sensor. To address potential errors, an if statement verified the connectivity of temperature sensors 1 and 2. An average temperature was then calculated using a straightforward method:

$$Average\ Temperature = \frac{T_1+T_2}{2},$$

This average value was returned by the function. In cases where sensor connections were faulty, a default value was returned to the main loop. This methodology ensured the robust and accurate operation of the system, even in the event of sensor malfunctions.

6.4. Concept for the Integration of the Smart Heating System into the Jacket

The smart heating system consists of an electronic circuit and components assembled and installed into the garment in such a way that ensures safety, functionality, and comfort for the wearer. The primary objective in integrating the hardware into the garment is to identify the optimal placement of components of the smart heating system into the rock-climbing jacket. This is a significant issue as the use of wires in the integrated wearable sensing system should be kept to a minimum while still allowing the jacket to provide additional functionality for users (climbers) during their activities in outdoor environments. Ideally, the placement of the components should be planned at the beginning stages of the development project as part of the proposed constructive lines of clothing to avoid unnecessary seams and thickness.

6.4.1. Identification of Optimal Placement of Components of the Smart Heating System

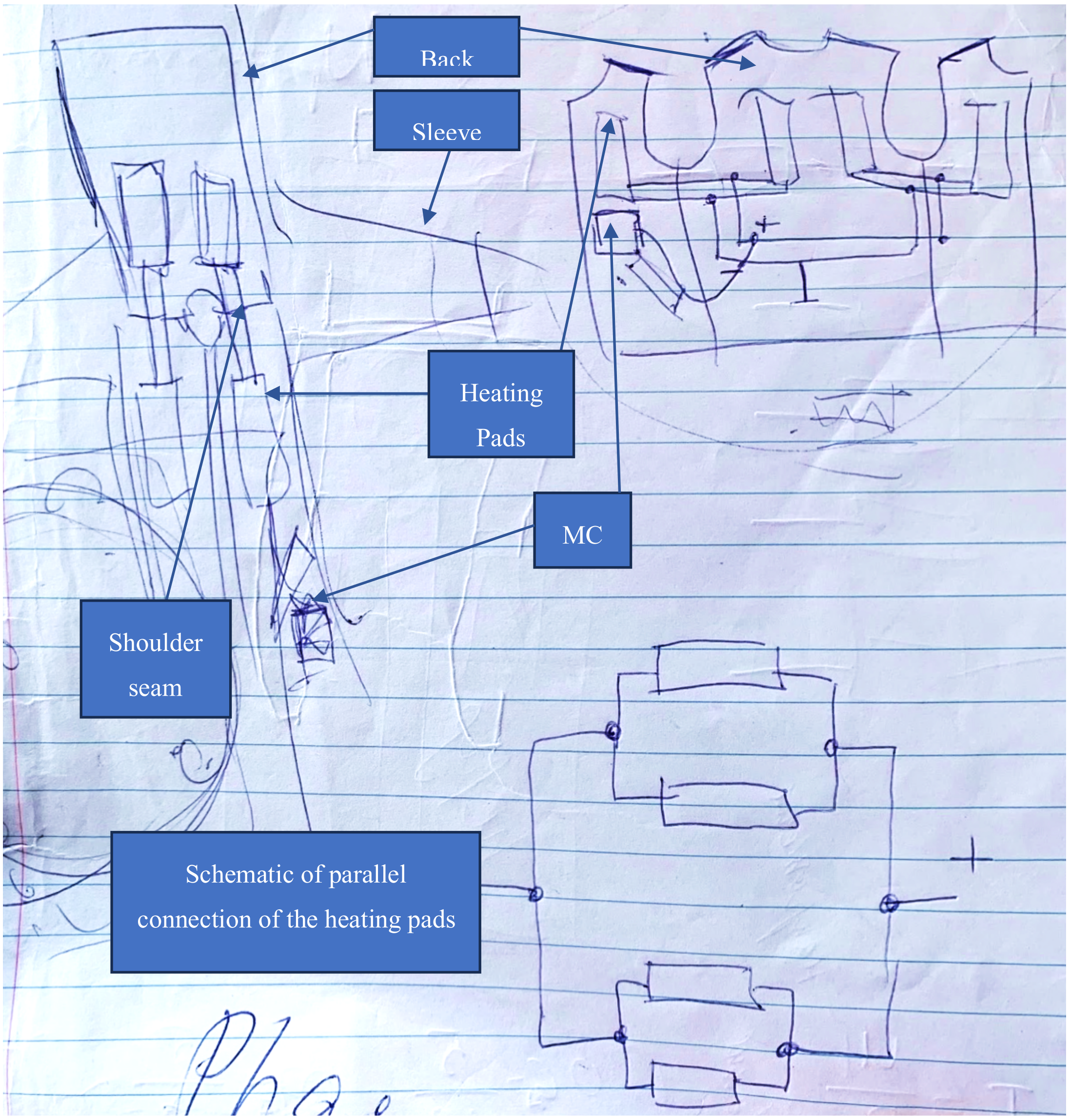
Integrating the hardware components into the jacket required careful consideration of various factors. To find the best solution for integrating the smart heating system module into the jacket, the conceptual prototype was developed. This module consisted of eight components, including four pre-made heating pads, one microcontroller unit, two temperature sensors, and a power bank. Given that the jacket was designed for climbers, it was essential to minimise the use of cables to enhance wearability and comfort. It was also important to ensure that placement of the smart heating system did not interfere with the use of equipment such as ropes, harnesses, or backpacks.

Figure 6.24 shows an initial sketch of possible placements of wires for the parallel connection of the heating pads and other components on the jacket. The first variant of placing wires over the shoulder seam was rejected because of the backpack. After some reflection it became obvious that wearing a backpack would potentially cause discomfort for the wearer if there were any wires on the shoulder seams. It also seemed more likely that an over-shoulder placement would affect the wire's durability because of abrasion. The final version of the jacket design has a seamless shoulder line. Because of the position of the climbing harness, the system components also had to be placed above the waistline.

The effective integration of the heating pads into the jacket also required thorough consideration of their placement. Given the power constraints, it was determined that four heating pads would be optimal as this configuration achieved a manageable power consumption of approximately 10W. These heating elements were strategically positioned to provide maximum heat transfer to the body while ensuring that all components could be wired efficiently.

Figure 6.24

The first initial sketch of components placement on a jacket: process of finding solution



The proposed layout, illustrated in Figure 6.25, included the following placements:

- Four Heating Pads (Red Parts): Two pads are positioned on the back and two on the front, spaced adequately apart to ensure even heat distribution.
- The PCB (Green Parts): The PCB is located on the back of the jacket on the right side near to the side seam to avoid interfering with the climber's movements and the equipment.
- Temperature Sensors (Black parts): The two sensors are placed at a sufficient distance from each other to provide accurate temperature readings needed for effective temperature regulation.
- Power Bank (Blue part): The power bank, which supplies power to the entire circuit, is positioned near the PCB and remains accessible for the climber through the USB connector located in a pocket. This proximity helps to minimize voltage drop due to resistance in the wires, ensuring stable power delivery to the PCB.

Figure 6.25

The components placement on a muslin toile of a jacket: the process of finding the optimal placement

This concept was further developed by incorporating conductive fabric in the form of two lines sewn into the muslin toile of the jacket (see Figure 6.25). The bronze copper fabric was used as the five-volt track, while the greyish conductive material serves as the common ground track for both signal and power ground. Additionally, the position of the customised PCB was defined in the back of the jacket, as illustrated in Figure 6.26. It was proposed that these conductive lines would be sufficient for the safe transmission of the current required to power the temperature sensors. This approach addressed the limitations of conductive thread and fabric, which, even at its thickest, could only handle a maximum current of 100mA—far below the two amps needed for the four heating pads. The larger conductive fabric pieces could accommodate these higher currents safely.

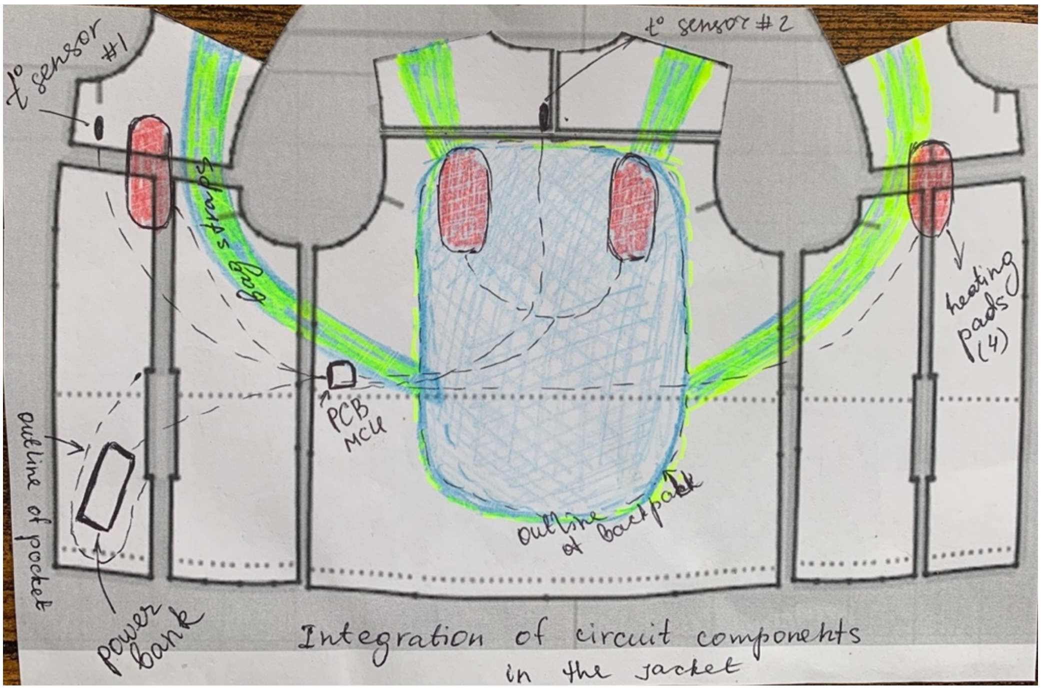
Figure 6.26

The concept of using the conductive fabric lines as wiring

Testing of the conductive fabric revealed an unstable current signal and comparatively high resistance (up to 1.3 ohms) relative to traditional wires (see section 6.2.3). Consequently, wires were utilised for the initial prototype to connect the circuit components. Nonetheless, the potential and limitations of using conductive fabric were explored through the discussion section (see section 7.5). The final conceptual integration of the circuit components into the jacket is depicted in Figure 6.27.

Figure 6.27

The final conceptual solution for the integration the circuit components into the jacket

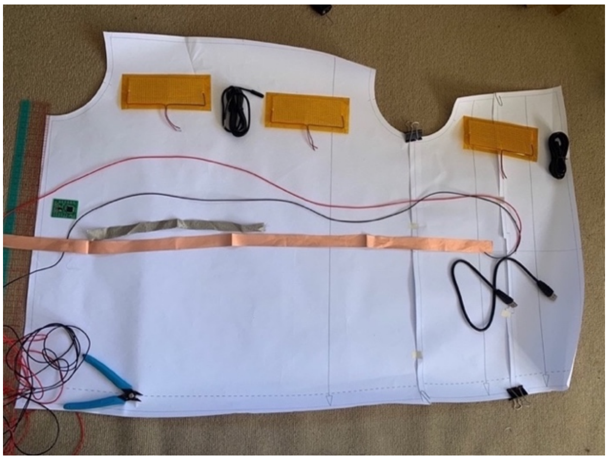


6.4.2. Assembly and Integration of the Conceptual Prototype

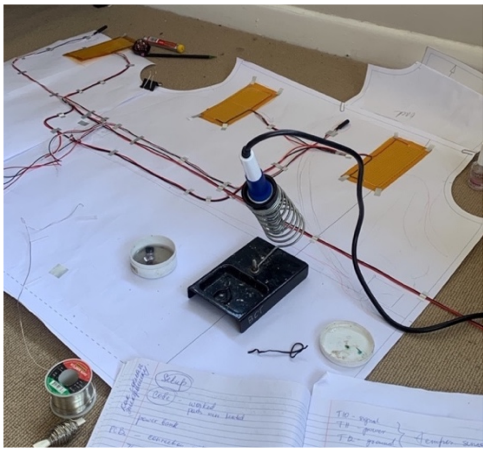
The next step was to assemble all components of the conceptual prototype of the smart heating system. For this purpose, flat paper patterns were used to understand the correct positions of components in their actual sizes and determine the optimal length of wires. One consideration was to make wires less visually obtrusive while increasing the system components' durability. As shown in Figure 6.27 above, the PCB was positioned at the back of the right side near the waist and side lines to reduce the distance between the MCU, sensors, and the USB connector to the power supply, and to minimise any negative impact caused by user activities on the system's durability. Figures 6.28 (a)-(c) show the preparation, assembly (soldering), and fixing the components of the conceptual prototype of the smart heating system. Figure 6.29 presents the completely assembled conceptual prototype ready to be integrated into the outdoor smart jacket.

Figure 6.28

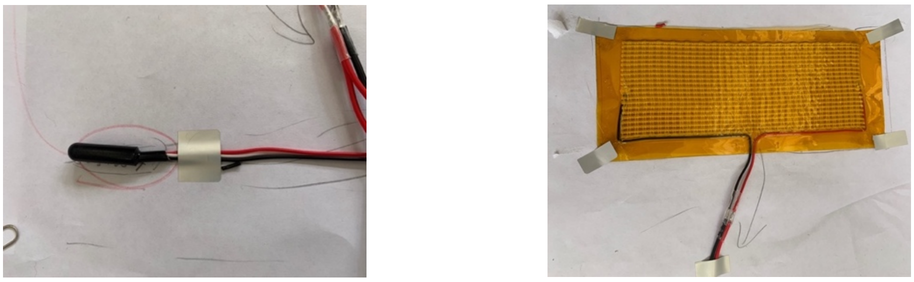
The process of preparation, assembling and fixation of the conceptual prototype components on the flat paper pattern



a) Possible placement of components, preparation (horizontal placement of the heating pads)



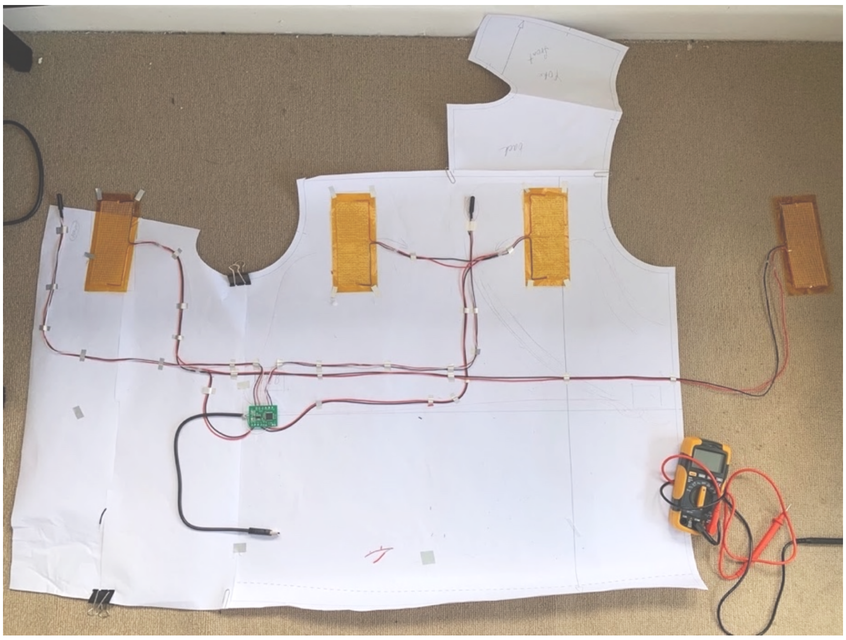
b) Assembling process of components of the conceptual prototype of the heating system



c) Fixing the components (the temperature sensor and the heating pad) by sticker on the paper pattern. The arrow shows direction of wires.

Figure 6.29

The assembled conceptual prototype of the smart heating system fixed on the flat paper pattern



After assembling the outer layer of the jacket made of membrane fabric, the conceptual prototype of the heating system was then fitted into the jacket. All components were carefully fixed inside of jacket using pins on seam allowances or/and small stickers, as shown in Figure 6.30. This was a temporary fixation as for this project, a thin insulation layer was developed as part of the design and material specification stages. It was expected that all components of the smart heating system could be ideally affixed onto this insulation layer by incorporating them alongside the constructive lines and seam lines of the jacket. For this purpose, the insulation layer was created and temporarily attached to the main fabric of the outer layer of the jacket using pins (see Figure 6.31). Then, all components of the system were transferred from the main fabric layer to the insulation layer (see Figure 6.32) and were fixed there (see Figure 6.33 (a) and (b)). Also, to decrease discomfort for the wearer, it was decided to cover all parts of the system with a strip of insulation layer as shown in Figure 6.33 (c) – (f). However, the sensors could not be covered to avoid any incorrect readings. The shoulder lines of the insulation layer were left open for ease of fixing the components of the system on the flat surface. After all components were fixed on this layer, the shoulder lines were jointed.

Figure 6.30

The initial fixing of components of the system on the jacket

a) Front b) Back

Figure 6.31

Fixing an insulation layer on the jacket for transferring the components of the conceptual prototype

a) Front

b) Back

Figure 6.32

Transferring of the components of the system to the insulation layer

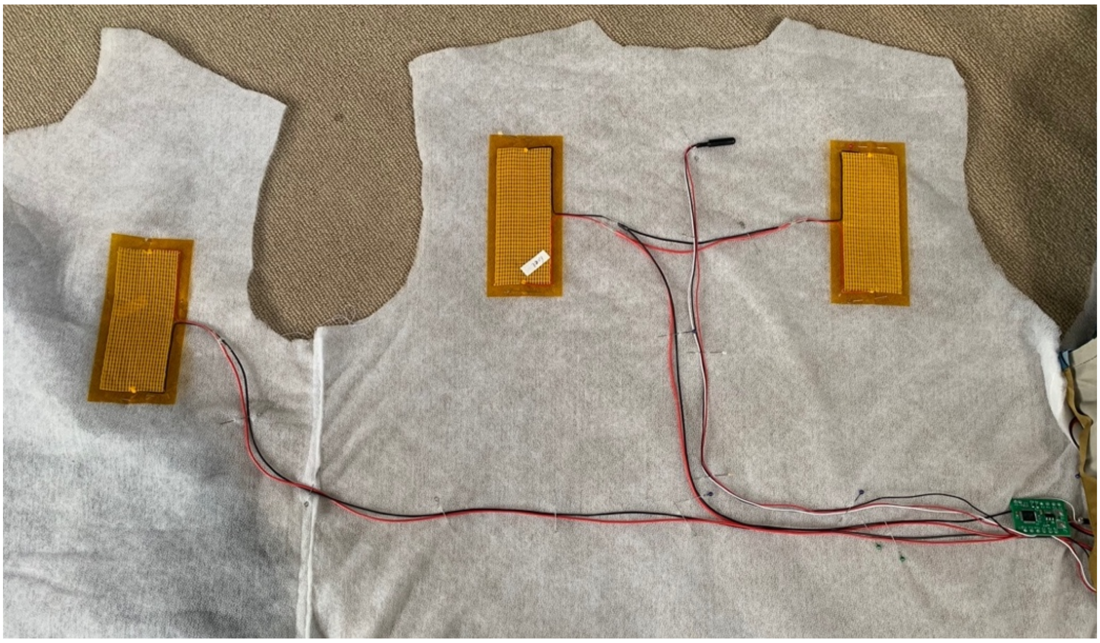
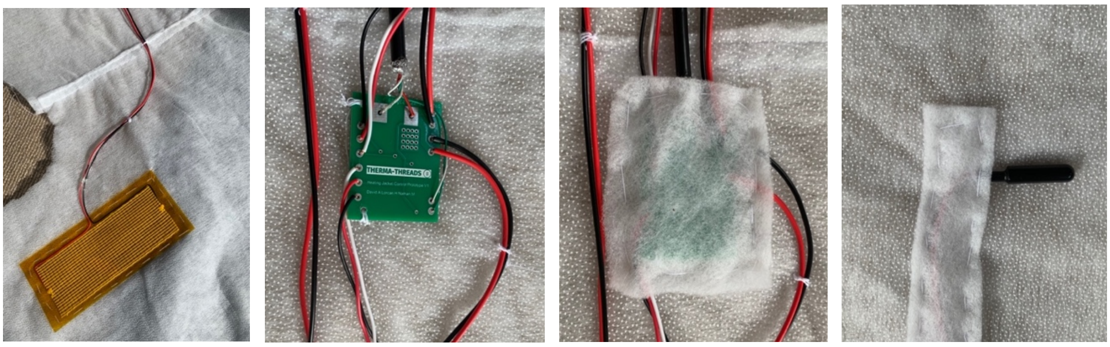
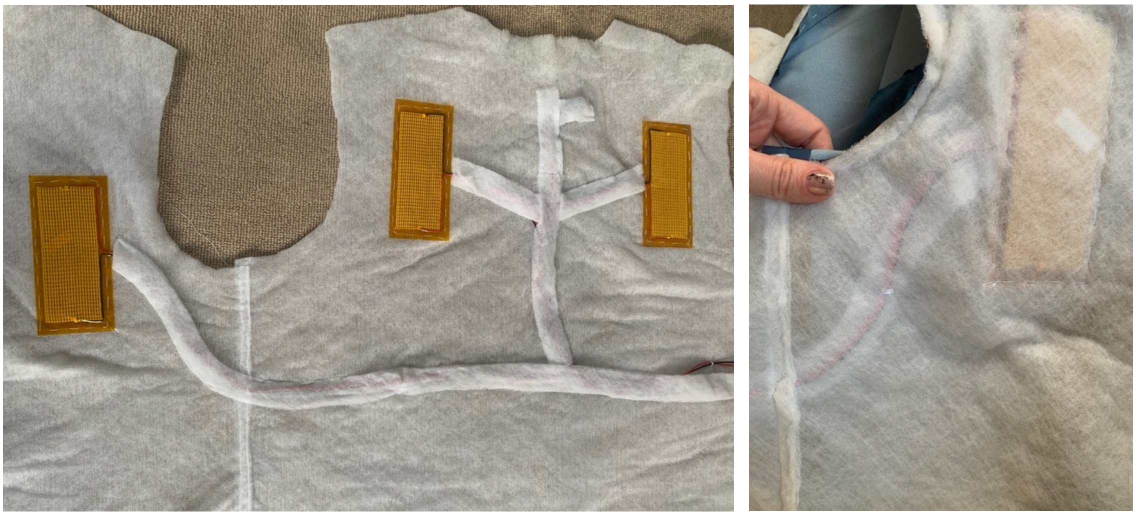


Figure 6.33

Fixing of the system components of the insulation layer



a) Fixing a heating pad | b) Initial fixing PCB | c) Cover PCB using a strip of insulation | d) Cover sensor wires using a strip of insulation



d) Covering wires with a strip of insulation | f) Fixing the covered components of the system to the insulation layer

6.5. Conclusion

This chapter has described the process of finding optimal solutions for the development and integration of a sensing heating system prototype into a rock-climbing jacket. This prototype was developed to automatically regulate the temperature inside the clothing to maintain a stable body temperature for the climber. The process involved consultations and collaborations at various stages with specialists from different fields, such as electronic and electrical engineers, software and hardware product developers, textile engineers, mechanical engineers, with myself as a garment pattern engineer. This project therefore required an interdisciplinary approach.

Strategically, two types of prototypes were developed: functional and conceptual. To achieve this goal, a variety of different component options of the heating system were identified, developed, and tested, along with some alternative materials. Through numerous tests, design iterations, and calculations, more optimal solutions for this project were found.

The functional prototype was created for the purpose of running the system, refining the code for a microcontroller unit, and ensuring the PID controller worked. The prototype effectively collected and processed temperature sensor data through the microcontroller. Despite being at a prototyping stage, the temperature readings were accurate, and the processing was effective. The microcontroller was capable of generating varying PWM signals for the heating pads based on the temperature set in the code. The final functional prototype was assembled on a Veroboard, incorporating a Lilypad Plus USB, a Lilypad temperature sensor, and a single heating pad. In conclusion, the functional prototype was operational and ready for use, although it was not yet in its optimal form.

The conceptual prototype was created with the long-term goal for it to be mass-produced in mind. The function of this prototype was identification of the optimal placement of the components of the wearable smart heating system inside the jacket, considering factors such as minimising discomfort for the wearer, parts of the body that should be kept warm, safe distance between components, wiring connection issues, and placement of the rock-climbing equipment (rope, harness, backpack, etc.). Furthermore, in collaboration with a team of three students from the School of Engineering, Computer and Mathematical Science at AUT, a custom PCB was proposed and developed for this prototype. This custom PCB, mixed with "off-the-shelf" components, was used for the conceptual prototype. Programming this customised PCB represents one of the future directions of this project that may constitute separate research in the field of software development. However, once the Arduino code for the functional prototype was finished and successfully checked, a flow chart for C code for the custom PCB was constructed to provide guidance.

The discussion and conclusion chapters further discuss future directions and possible improvements of the final prototype of the outdoor smart jacket and the use of e-textile materials in such applications (see sections 7.3 -7.10, 8.3, 8.4).

7. DISCUSSION

This chapter discusses the challenges and limitations inherent to this multi-disciplinary field, and the contributions made by this research project. This discussion addresses the contributions of this project to the multi-disciplinary research field of applied technology and intelligent garments. Essentially, the challenges lie in advancing a coherent research inquiry by developing a methodological approach informed by a garment design research perspective that can be adapted and utilised by other researchers in pertinent fields.

The discussion is organised into two main sections: one focuses on aspects related to ergonomic clothing design and pattern engineering, and the other addresses the issues encountered in the development of smart technologies. The first section discusses the problems arising from the lack of standards and requirements for the apparel needs of rock climbers and emphasises the contributions made by this study towards the design of sports clothing through the implementation of new movement tracking technology and 3D fashion design software, which proved to be valuable tools. Additionally, the section discusses the use of complex methodological approaches in the development of clothing integrated with smart systems as well as the use of a systematic approach tailored to the specific stakeholders of this project: rock climbers.

The second section of this chapter discusses the challenges, limitations and potential future advancements in the field of e-textiles and wearable prototypes along with the evolving multidisciplinary approach in this research area towards becoming an interdisciplinary endeavour. This section also examines the limitations associated with the commercial availability of hardware components compatible with textiles and clothing, as well as the challenges in developing such components through interdisciplinary collaboration. Additionally, it highlights power supply issues and suggests future directions in this field. This chapter discusses problems related to the limited number of studies and standards for exploring and testing various characteristics of e-textiles and wearable electronic components integrated into garments, while also reflecting on recent developments in this field. The considerations regarding ventilation and humidity regulation inside the clothing layers are also described in this section.

The discussion chapter concludes with an acknowledgment of sustainability issues that are currently still a part of developing functional innovative clothing and wearable devices. Although this aspect was not a key focus of this project, it is nonetheless an important area to discuss. By addressing the sustainability considerations, advancements in clothing and smart textile technologies can contribute to a more responsible and eco-friendly fashion industry, aligning with global efforts to reduce the environmental impact of the fashion industry and promote ethical practices.

7.1. Lack of Standards and Requirements for the Apparel Needs of Rock Climbers

This section discusses the significant gap that exists in standards and requirements related to rock-climbing clothing and the challenges associated with this problem. This information affected the initial stage of the development of rock-climbing clothing, as standardised regulations could have provided guidance on textile properties and specification, ergonomic design principles, appropriate seam types, environmental considerations, testing protocols, and certification procedures, which are crucial for ensuring safety, performance, and comfort in challenging and variable outdoor environments. A thorough analysis conducted through various standards databases (see section 2.5) revealed a lack of published standards and requirements addressing the apparel needs of rock climbers, including smart wearable technology for climbing. The current standards related to rock-climbing only cover the safety and reliability of climbing-specific gear, definitions of terminology, design, performance and inspection standards, as well as training standards. These standards were analysed to inform the design of the climbing jacket, incorporating parameters from climbing equipment. For instance, information about helmet design and measurements were used to develop a helmet-compatible hood, harness specifications guided the design and placement of pockets, and rope positioning data were utilised to determine the optimal placement for integrating smart heating system components.

The lack of standards in rock-climbing apparel presents several significant challenges. The most critical issue pertains to the safety and reliability of climbing clothing, which is essential for preventing hypothermia in cold mountain environments and ensuring ergonomic design for safe route completion. Standardised guidelines for developing such apparel could regulate material specifications and emphasise their minimum requirement for mechanical characteristics, recommended reinforcement zones, seam types, and other parameters crucial for safety and reliability.

Standards related to ergonomic design and functionality of rock-climbing apparel could establish guidelines for design features and criteria, construction techniques, sizing, fit adjustments, and other parameters that can optimise fit, comfort, and safety of clothing. Furthermore, standards addressing the integration of advanced technologies, such as the smart heating systems developed in this project, would offer regulations for effectively incorporating these technologies into clothing. They would also include testing protocols and sustainability considerations, while providing guidance for users on the proper utilisation of such wearable devices.

Although rock-climbing is a physiologically and psychologically demanding sport and is influenced by various external environmental factors, it has gained considerable global popularity. Recently, sport climbing was included in the Summer Olympic Games, featuring three sub-disciplines: speed climbing, lead climbing, and bouldering. With the sport's growing popularity, there has been a rise in climbing accidents and consultations in emergency departments for climbing-related injuries (Rauch et al., 2019). Some of these injuries could potentially be mitigated through the use of appropriate clothing. This underscores the need for the establishment of comprehensive standards to address the challenges described above.

Besides the lack of standards related to rock-climbing clothing, there is also a gap in the requirements and practical recommendations associated with such clothing. While outdoor apparel manufacturers have made efforts to design rock-climbing clothing with functional features and proprietary technological solutions, these endeavours often fall short of meeting climbers' expectations. This shortfall can be attributed to a lack of comprehensive data regarding specific sport requirements and climbers' needs. As a result, climbers have to make their clothing choices based on their individual requirements, expectations, and personal experiences with existing apparel options, as indicated by the survey (see Chapter 4). Due to these gaps, there exists potential for the development of requirements and practical recommendations related to ergonomic and functional design in rock-climbing apparel, particularly with the integration of smart sensing technologies into such clothing.

In order to contribute to the establishment of standards for rock-climbing apparel, the current research presented a summary of findings from the analysis of commercially available outdoor rock-climbing sportswear (see Chapter 4). Sixteen articles of outdoor rock-climbing sportswear were evaluated in terms of the general characteristics of the item of clothing and the elements of the garment construction with regards to their functions, textile materials, display weight, and price. The key principles in pattern engineering essential for such apparel, namely ensuring optimal fit, mobility, ergonomics, and comfort for climbers, were identified in this study. These findings could guide manufacturers of outdoor apparel to inform decision-making regarding pattern engineering, design solutions, and material specification for various types of high-performance clothing tailored for outdoor climbing. It offers a clearer understanding of the existing clothing ranges for outdoor rock-climbing, including their performance, functionality, and material selection. This information can be utilised in the initial stages of developing outdoor rock-climbing clothing with the potential to improve the design and functionality of such clothing.

7.2. Use of New Technologies in the Design Process of Sports Clothing

In this research project, novel technologies were successfully integrated at various stages. Firstly, an innovative Xsens motion tracking system, specifically the MVN Awinda Straps System, was employed for the assessment of a climber's anthropometric characteristics in dynamic postures. The system provides data on the position, orientation, and kinematic characteristics of each body segment with respect to an earth-fixed reference coordinate system. In this project, the system was utilised to determine climbers' essential body segment motion parameters and angular measurements of primary joint angles while scaling indoor climbing walls. The data obtained was significant during the garment design and pattern development phases, contributing to the creation of functional and ergonomic clothing for climbers.

This appears to have been the first application of such technology in the development process of climbing clothing. The technology enabled the collection of extensive data on body segment coordinates, angular parameters of joint angles, velocity, acceleration, and other variables across three observation sessions. However, due to the limitations described in Chapter 4 particularly the difficulties in obtaining precise values for dynamic stretching parameters, most of the collected data, along with photo and video recordings, were primarily used for qualitative movement assessment. To enhance data accuracy and obtain additional necessary information, this technology was used in conjunction with manual body measurements and CAD software for evaluating the climber's raising parameters. Overall, these measurements were found to be commensurate, meaning they were approximately the same or comparable.

Nevertheless, this data contributes to the field of ergonomic rock-climbing clothing by providing insights into the unique biomechanics and movement patterns associated with rock climbing. It is suggested that these insights be integrated into garment design by incorporating articulated patterning around key joints, such as the knees and elbows, and by adding additional darts and seams to enhance flexibility and expand the range of motion. Seat gussets can provide more movement in the hip and leg area, allowing for a wider range of motion during high leg lifts. Moreover, the incorporation of appropriate ease and dynamic ease allowances in the clothing design ensures that climbers can manoeuvre with freedom and comfort while maintaining requisite levels of flexibility and protection. The outcomes of this study have practical implications for outdoor apparel manufacturers, who can utilise the research findings and recommendations to improve their climbing clothing designs.

A future direction for using this technology in pattern engineering might involve developing a mathematical model that would describe the raising angles of the key joints and establish correlations between body segments and joint angles in static and dynamic positions. Such a model would contribute to the calculation of movement ease allowances for various size ranges and enable the distribution of these dynamic values throughout different areas of the garment. This approach would contribute to the creation of more tailored and optimised climbing clothing designs.

Secondly, this research employed contemporary technologies directly related to clothing design and development processes, which have been widely utilised in the textile and clothing design industry by designers and patternmakers. For this study, the 2D-to-3D concept was successfully implemented using the 2D CAD software programmes Grafis and Corel Draw to develop garment patterns and integrate them into 3D software (see Chapter 5). The 3D virtual fashion design software, CLO 3D and 3DStyle, were utilised as design tools to visualise the jacket design on a 3D digital model in both static and dynamic postures, assess its virtual fitting, and evaluate fabric strain and stress characteristics in dynamic conditions through 3D simulation modes.

These technologies have become increasingly accessible in recent years, enhancing the efficiency, cost-effectiveness, and time management of designers and pattern engineers. With over 20 years of expertise as a pattern engineer and researcher, I assessed both the advantages and limitations of 3D virtual fashion design software in this project. In this discussion, I focus primarily on the 3D software as it represents a more recent advancement in the field. The use of 2D software has been established for many years for creating and managing digital garment patterns and their grading. However, it is worth noting that compatibility between 2D and 3D software is a benefit, as it allows for the seamless integration of flat patterns from 2D CAD programmes into 3D virtual fashion design software.

The first challenge encountered with the use of 3D fashion design software in this project was its complexity in pattern making. This software appears to be primarily designed for evaluating design concepts rather than for creating detailed initial patterns. While it offers options to modify existing pattern bases or develop new patterns, the process can be more time-consuming for users who are not highly experienced with the software. In the researcher's experience, this is because pattern drafting in 3D software resembles the pin draping process on a mannequin. However, this problem can be avoided by integrating flat pattern created or digitised in 2D CAD programmes integrate seamlessly into 3D virtual fashion design software for further processing. This functionality is extremely beneficial for fashion designers who work with pre-made flat patterns, as it streamlines the transition from 2D to 3D design processes.

A major advantage of this tool for designers and pattern engineers is its ability to assess the initial fit and comfort of a designed garment using garment fitting maps. This functionality facilitates the identification of potential areas of discomfort within the patterns, allowing for targeted modifications and adjustments to the flat patterns based on the evaluation outcomes. To explore this capability, the fit and fabric stress characteristics of a designed jacket in static and dynamic body postures were analysed through virtual fitting and real-world observation conducted on an indoor climbing wall. The results were comparable, demonstrating the effectiveness of utilising 3D fashion design technology for the initial evaluation of garment characteristics under both static and dynamic conditions.

A limitation that should be acknowledged is the very limited prior research on the use of this type of information technology in rock climbing apparel. Only a few studies (e.g., Viziteu et al., 2021; Viziteu & Curteza, 2021) have explored the development of climbing clothing, specifically climbing pants, using computerized 3D clothing simulation. Consequently, there is no foundation for understanding a methodology of utilising this software, nor a clear understanding of the problems or advantages associated with using this software for functional rock-climbing clothing.

The research contributes to the advancement of the clothing development process by validating the use of 3D garment virtual software for evaluating garment fit and comfort for a specific category of wearers, in this case rock climbers. The technology's advantages are evident in its capacity to enhance the design process of functional clothing by enabling designers to visualise concepts in real-time, conduct preliminary testing, and assess fit and comfort through virtual try-ons in both static and dynamic scenarios. The research underscores the potential of 3D clothing simulation technologies to aid designers and patternmakers in the creative and experimental aspects of sportswear design. This approach enhances the capabilities of software to transform functional design in both industry and research contexts, which is crucial for the continued academic and professional growth of the industry and for improving fit satisfaction among end users.

7.3. Complex Methodological Approaches in the Development of Smart Clothing: A Tailored, Systematic Approach for Specific Stakeholders

This research project utilised a methodological framework grounded in Human Factors and Ergonomics (HFE), encompassing principles of user-centred design and user experience to guide the development of climbing apparel that aligns with the needs of the end user. As described in Chapter 3, HFE is recognised as a design-driven, systemic, and scientific discipline geared towards well-being and performance (ISO, 2010; Kant, 2018). That chapter also presented examples of functional clothing research and development projects that have successfully adopted the user-centred design approach. Extending this perspective, this study serves as an example of leveraging multiple approaches towards the development of smart garments and the utilisation of e-textiles. Although the individual methods employed in this research are not novel on their own, their combined use offers valuable insights for related work in the fields of smart clothing, design, and e-textiles by offering adaptable and transferable methodologies. Furthermore, the study’s employment of HFE as the epistemic foundation for the development of outdoor smart rock-climbing garment also represents a relatively novel contribution to the field. This contribution could be further strengthened by examining the potential limitations and constraints associated with the methodological approaches employed. Thus, the limitations of HCD and UCD discussed in greater detail in Section 3.4. In practice, the application of HFE approaches and methods within engineering design can be limited by factors such as usability, safety, reliability, and the accessibility of relevant tools, including software, information resources, and the sharing of knowledge constrained by intellectual property concerns (Shorrock & Williams, 2016; Sun et al., 2018a).

In most cases, the development process of clothing integrated with smart systems has been dictated by the principles of physical ergonomics, a specialised area within HFE, with the aim of enhancing safety, efficiency, and comfort. In conceptualising the integration of a wearable smart heating system into a jacket, consideration was given to the optimal placement of circuit components (as described in section 6.4). Factors such as minimising wearer discomfort, identifying body areas requiring warmth, ensuring safe distances between components, addressing wiring connection issues, and accommodating the placement of rock-climbing equipment (such as ropes, harnesses, or a backpack) were taken into account. Additionally, the pattern engineering solutions — such as the incorporation of constructive seam lines and technical openings for USB connectivity — were developed with consideration of technology placement within the jacket. These considerations have facilitated the creation of clothing that integrates wearable electronics seamlessly, ensuring that climbers experience no awareness of wires or other components. The application of complex methodological approaches highlights the multidisciplinary nature of this study and makes a contribution to the fields of smart clothing and e-textiles. The research methodologies developed in the current study can be adapted for similar projects in related fields.

Finally, this study incorporates an individualised approach tailored to the stakeholder, in this case, the rock-climber. The climber was identified as the central user whose needs and experiences guided the development and design of the smart outdoor rock-climbing clothing design proposed in this study. Thus, a model was formulated depicting a simplified system of interactions among the climber, clothing, the climber's capabilities, and climbing conditions (see section 3.1). This model highlights the continuous interaction between these components, which impact the climber's performance and safety. This holistic model elucidates the relationships between system elements and sub-elements, informed by principles of Physical Ergonomics, material selection considerations, and the integration of wearable smart technology. This model can be used to guide designers of outdoor rock-climbing clothing by providing an understanding of the system and highlighting the components and their interconnections that should be considered during the design process.

7.4. Interdisciplinary and Multidisciplinary Approaches to E-textiles and Wearable Electronic Applications

An important area of discussion is the necessity for an interdisciplinary approach to the development of e-textiles and wearable prototypes. Although research in the e-textile field, including my project, has traditionally been multidisciplinary, it should evolve into an interdisciplinary endeavour. The terms "multidisciplinary" and "interdisciplinary" both relate to the engagement of multiple disciplines to varying degrees on the same continuum (Choi & Pak, 2006). Multidisciplinary approaches utilise knowledge from experts in several disciplines while each remains within their boundaries. Interdisciplinarity approaches synthesise, analyse, and harmonise connections between disciplines into a coordinated and cohesive framework.

There are examples of successful applications of these approaches in research projects related to e-textiles. For instance, Kubicek et al. (2022) described the field of textile electrodes and e-textiles as a multidisciplinary approach combining material engineering, biomedical engineering, and chemistry. The authors also highlighted the primary advantages of e-textiles across diverse areas such as communication, clothing, information sciences, healthcare and sport monitoring, magnetic shielding, or the military sector (Kubicek et al., 2022).

The Interdisciplinary Project *INTUITEX* (Brauner et al., 2017) proposed a research framework for development of smart interactive textiles that incorporates multiple interdisciplinary perspectives, including textile technology, interface design, human factors and communication, automation, and integration. During the project, three functional smart textile items were developed, namely a curtain, chair, and jacket, were developed. This project demonstrated that an interdisciplinary consortium of designers and engineers from the areas of textile and electronics using user-centred and participatory design methods along with an iterative product development approach is essential for addressing the challenges and opportunities associated with smart interactive textiles.

Townsend et al. (2017) outlined the development process of a smart textile design methods that emerged from a collaborative, multidisciplinary project involving three university departments: design, chemistry, and electrical engineering. In this study, the authors discussed and analysed the overall project and identified crucial stages necessary for an interdisciplinary collaboration within the realm of textile design practice. They reflect on the outcomes of this collaboration, which facilitated the integration of design principles with scientific knowledge, thereby advancing the field of smart textile design. This research project is an example of moving from a multidisciplinary approach to an interdisciplinary approach.

Similarly, my project also demonstrates its multidisciplinary nature through the involvement of specialists from diverse fields at various stages. These experts contributed to the project through consultations, addressing challenging questions, and collectively building knowledge. Thus, at the outset of the project, consultations with climbers and specialists from the sports and recreational area were conducted to discuss the significance of the project, identify the primary issues with existing clothing options, and establish user needs and preferences. Their insights and opinions were crucial in informing the project's direction and outcomes. Notably, a professional mountain climber with over 20 years of experience highlighted that the process of changing clothing during climbs could lead to falls.

During the testing phase of conductive yarns for potential use as heating elements or wiring (see section 6.2), consultations and assistance were sought from experts at the Textile and Design Lab at AUT. These consultations led to the identification of yarn options that optimally aligned with the project’s objectives and of the need to knit the specimens. The testing procedures for these specimens were conducted with the assistance of a technician from the School of Engineering, Computer, and Mathematical Sciences at AUT. Additionally, three students from this school collaborated with the researcher to design and develop a customised PCB for the conceptual prototype of the heating system and performed some initial testing of the prototypes. Drawing on various disciplinary perspectives and specialist expertise, the researcher integrated knowledge to propose optimal solutions for different considerations. For instance, the choice of conductive yarn as an alternative to wires for connecting components of the system, including the PCB, posed a problem because the yarn did not perform to the same standard as the wire. Had it been possible to use an interdisciplinary approach, the knowledge of integrated specialists could have saved time by avoiding unnecessary testing and directly providing solutions from e-textile options.

Furthermore, consultations were sought from specialists in computer technologies to facilitate the coding necessary for the heating system's operation. A significant challenge arose during the programming of the customised PCB because the team that developed the board did not collaborate with IT specialists during the initial development stages. When the PCB was completed and IT specialists were involved, it became evident that there were discrepancies between the approaches to PCB development. Electronic engineers designed the schematic for the PCB, then printed, programmed, and tested it. In contrast, specialists from computer science preferred to examine each component of the PCB and questioned the choice of components. An interdisciplinary approach could have mitigated such discrepancies by aligning the different approaches and workflows prior to the PCB being made.

Throughout the project, other challenges also emerged when specialists from multiple disciplines collaborated. For instance, a practical challenge involved clarifying tasks and resolving misunderstandings between specialists from different fields. These challenges were attributed to gaps in knowledge, discrepancies in terminology, and occasional miscommunications stemming from the diverse fields and backgrounds of the participants. At different stages of the study, these specialists worked together to reconcile their requirements and perspectives, with particular emphasis given to explaining tasks from the perspective of textile and clothing development. However, these challenges could be mitigated through enhanced collaborative efforts among researchers, who could then develop a more integrated interdisciplinary knowledge base.

An understanding of interdisciplinarity requires a thorough consideration of the ways in which researchers from different disciplinary backgrounds view wearable electronics as research objects and how different disciplines can contribute to the creation of intelligent products and services integrated into products on the basis of different research paradigms (Uotila et al., 2006). For example, while scientists focus on discovering new materials and characterising their properties, engineers utilise these material properties and functionalities to address practical problems (Ruckdashel et al., 2021). Material scientists explore the relationship between material microstructures and properties to advance fundamental knowledge, whereas textile scientists focus on the practical aspects of scaling up production to meet industry needs (Ruckdashel et al., 2021). Adopting a collaborative and interdisciplinary approach would seem essential for the development of e-textile and wearable applications, as it would facilitate a comprehensive understanding of how the system's components interconnect and help mitigate various issues, including those previously described.

To this end, this thesis conceptualised e-textiles and intelligent garments as ideally developed by an interdisciplinary field that integrates ergonomics, design, material and garment engineering, electronics engineering, and information technologies. To the extent possible by one person, the researcher thus acted as an integrator of diverse knowledge, leveraging the benefits arising from this integration to develop smart products. This approach helped to address the challenges identified throughout the project and underscores the inherent advantages of interdisciplinary collaboration.

Thus, as the account of the development process described in this study suggests, an interdisciplinary approach is required during the stage of integrating e-textiles and/or wearable devices into clothing to identify the optimal placement of these components. In this project, a key question was to determine the most effective placement of circuit components within the rock-climbing jacket so as to both minimise wearer's discomfort and enhance functionality and safety. Achieving this requires the adoption of a comprehensive interdisciplinary strategy that integrates expertise from multiple domains. Table 7.1. below summarises the primary considerations for the placement of wearable electronic components in smart clothing and highlights the contributions of specialists from various fields.

Table 7.1

Primary considerations for placement of wearable electronic devices into clothing with area of specialists

Considerations for placement of wearable electronic components in clothing	Explanation	Area of specialists involved
Ergonomics, Comfort, Safety	Ensuring that the placement of components is safe and comfortable for the wearer. Ideally, the wearer should not feel any discomfort because of components. For this reason, the correct size of components is important. Consideration of the wearer activity.	The wearer, electronics engineering, garment engineering, clothing design, e-textile specialists.
Skin Contact	Identifying optimal positions for direct contact sensors or other components with the skin to receive necessary data.	Bio-medical field, electronics engineering, garment engineering, material science, e-textile specialists.
Component Positioning	Determining safe and optimal distances between components to account for factors such as current flow, trace lengths, and other.	Electronics engineering, garment engineering.

Functionality	Providing efficient functionality of the wearable device.	All specialists and the wearer.
Assembly Issues	Addressing challenges related to component assembly, including circuit routing, effective connection of components, protection or reinforcement at connection points, polarity, and potential wireless connections as well as the functionality of device software.	Electronics engineering, information technology, e-textile specialists, garment engineering
Durability	Ensuring the robustness and longevity of both components and their connections.	Electronics engineering, e-textile specialists, textile science, material science.
Integration Issues	Identifying the optimal position of the garment construction elements, lines, seams, pockets, etc. and developing secure fixation components within the clothing to prevent displacement or damage.	Garment engineering, clothing design, electronics engineering
Sustainability issues	Addressing challenges related to the lifecycle and the end of life of materials and components, identifying or developing eco-friendly component options	Textile science, material science, electronics engineering.
Material Types and Textures	Considering the types, textures, and features of materials used in the garment ensuring they are safe to use with electronic components and would not deteriorate or conflict with each other.	Textile science, material science, electronics engineering, chemical engineering, mechanical engineering.
Standardisation	Establishment standards and test procedures associated with e-textile and wearable electronics	Organisations that establish standards, textile science, material science, electronics engineering, chemical engineering, garment engineering.

Table 7.1 presents information about considerations and specialist areas involved in the process of identifying the optimal placement of the wearable devices' components. In this project, the researcher consulted with a few specialists to integrate their specialised knowledge in addressing these considerations. This represented an initial attempt to transition from a multidisciplinary approach to an interdisciplinary one. The aim of such an interdisciplinary approach would be to synthesise and connect the expertise of these specialists through the integration of knowledge, techniques, perspectives, concepts, and methods to advance fundamental understanding and solve problems that extend beyond the scope of a single discipline or area of research practice.

7.5. Challenges Related to Hardware Component Compatibility with Textile and Clothing Applications

Another issue encountered in this study related to the design and availability of electronic components that were available on the market at the time that were compatible with textiles or clothing. Various hardware configurations have been utilised for prototypes, including those for wearable applications, depending on the research focus. Traditionally, Arduino-based hardware is commonly employed in electronic prototyping and research due to its reliability and ease of programming, and this is equally true of wearable smart prototypes, where the Arduino Lilypad series is commonly used. This preference can be attributed to the series' advanced features, such as compatibility with e-textiles, sewability, and, in some cases, washability, as exemplified by the Lilypad USB Plus. For instance, Lee and Baek (2021) utilised Arduino to develop a smart outdoor jacket prototype that monitors users' health and outdoor activities (see Chapter 2, section 2.6). Similarly, Mencarini et al. (2019) employed an Arduino-compatible Bluetooth module (Simblee) to drive and control a vibrotactile wearable prototype aimed at supporting expert climbers' competencies or assisting beginners in acquiring competence (see Chapter 2, section 2.6). In this research project, the functional prototype of the heating system employed a sewable Arduino-compatible electronics microcontroller board, a Lilypad Plus USB, and a Lilypad temperature sensor with an attached heating pad (see Chapter 6). The resulting functional prototype was fully operational and could be integrated into the jacket.

However, many wearable prototype projects that employ Arduino-based hardware often stagnate at the functional prototype stage and do not progress to long-term plans for mass production. This stagnation is partly attributable to the relatively high cost, large size, and unnecessary input/output components associated with some Arduino-compatible PCBs. Additionally, certain components, such as the Lilypad Plus USB PCB, which was once popular in smart wearable prototyping, have been discontinued and are no longer available for purchase.

This project intended to advance the design beyond the initial prototype stage toward potential industrial production. This objective required consultation and collaboration with specialists from various disciplines, including electronic and electrical engineers, software and hardware developers, textile engineers, mechanical engineers, and a garment pattern engineer. This collaborative approach underscores the multidisciplinary nature of the project. Additionally, experienced climbers were consulted to provide valuable insights as needed. To facilitate potential industrial production, a custom PCB was proposed and developed alongside the creation of a flowchart for C code to guide programming (see Chapter 6). The programming of this customised PCB represents a future direction for this project, potentially constituting a separate research area in software development.

The concept of integrating the smart heating system prototype assembled with this custom PCB and other components was developed and presented in the practical part of the project. Optimal placement of these components within the jacket was identified, taking into account factors such as wearer comfort, proximity to key body areas for warmth distribution, safe component spacing, wiring considerations, and compatibility with rock-climbing equipment. This conceptual framework holds promise for adaptation in mass production scenarios.

It is important to discuss some challenges encountered in developing textile and clothing compatible hardware components for this project, which may be helpful to other designers/researchers. Firstly, the approach taken by electronic engineers in designing components often neglects considerations specific to clothing design and/or textile structure. Key concerns include the interconnection of circuit components and secure fixation of the electronics on a textile base. Textile and clothing are flexible structures, and this is a reason why rigid components, such as wires, and their connections, particularly soldering joints, are susceptible to damage during wear due to their frequent exposure to mechanically strenuous conditions. Therefore, it is vital to enhance the durability of connections and to secure and stabilise the fixations of the electronic elements to the textile base for the durability and effectiveness of the finished product.

The utilisation of e-textiles in the form of conductive textiles or conductive yarns may present a conceptual solution to replace traditional wires. An attempt was made in this project to use conductive fabric instead of wires to create high-current tracks for powering temperature sensors and four heating pads, which would offer flexibility in garment design. However, a surface resistance control test revealed higher resistance characteristics (up to 1.3 Ohms) than specified by suppliers, resulting in unstable current signals. This discrepancy led to the conceptual prototype using wires to connect circuit components for this project. Nevertheless, the field of e-textiles is rapidly evolving, with various materials available on the market that may provide stable current transmission between the elements of wearable devices. Additionally, conductive tracks could be created using conductive yarns through knitting or weaving processes, which offers a promising direction for future projects related to integrating wearable electronics into garments. Despite being beyond the scope of the current project, future research could explore if a layer could be developed that is added inside the clothing, situated between the lining and the main fabric, with traditional yarns with knitted or woven conductive tracks.

When textile-based electronic devices are intended for close contact with the human body, it is essential that the materials utilised in fabricating electronic components, such as conductive tracks, batteries, antennas, sensors, and similar elements, be non-toxic and environmentally friendly (Ali et al., 2021). For instance, the Ni/Cu Ripstop Conductive Fabric discussed in Chapter 6 (see Figure 6.10) is unsuitable for direct contact with skin due to the potential of skin allergies caused by nickel content. Other safety and health concerns include the risks of accidental electric shocks, which could be caused by body sweat or ambient moisture, and the effects of prolonged exposure to electromagnetic fields. In addition, salt from body sweat during workouts may corrode metal-plated textile electronics components. These considerations are crucial during the initial stages of wearable device design, which emphasises the limitations that may render certain e-textile applications unfeasible and underscores the necessity of an interdisciplinary approach, including specialists from chemistry, and (bio)medical engineering, in developing such hardware components.

Another consideration that electronic engineers typically overlook is waterproofing circuit elements. This occurs because they primarily design their components for use within stable systems or indoor environments. For wearable electronics proposed to be integrated into outdoor clothing, it is important to create water-resistant components in order to prolong the lifespan of the smart system and, consequently, the clothing itself. One interesting solution to waterproofing e-textiles was presented by Cork et al. (2013), who incorporated off-the-shelf resin encapsulated semi-conductor devices into the core of yarns so that the fabrics could be machine washed and tumble dried.

Related to the issue of waterproofing, durability against environmental degradation is also an important factor that needs to be considered for smart textiles that are intended for outdoor use. Metal-plated textile electrodes may experience a loss of functionality if exposed to air for extended periods, as metals are susceptible to atmospheric corrosion (Iftekhar Shuvo et al., 2021). While certain circuit elements like sensors may come with inherent water-resistant capabilities, others will need custom solutions such as silicone coating or waterproof repellents. While the basic issues have already been identified, more research is needed to advance this field and test the reactions of different types of metals to outdoor conditions. Once again, all these challenges underscore the significance of interdisciplinary collaboration in developing components for garment integration.

Another challenge pertains to the supply chain and the availability of suitable components necessary to design and create entirely new hardware components. While developing a customised PCB, we encountered delays in receiving certain components as shipments to New Zealand can take extra time. Additionally, there are restrictions on importing certain electronic items, such as batteries, which further complicated the development process and is likely to cause problems for commercialising smart clothing in future. For example, for UK and other non-US buyers, the self-heating smart jacket Mercury, described in Chapter 2, does not come with the 10,000mAh battery that Americans receive by default due to international limitations regarding the shipping of batteries. As an alternative, customers are advised to consider solutions such as a USB-A charging powerpack with a 5V, 2A output, which can effectively power this wearable technology (Priday, 2018). While acceptable, such substitutions add complexity to the production and use of such technology across varying geographic regions.

7.6. Power Supply Challenges and Future Directions

Power supply devices represent one of the most significant challenges hindering the commercialisation of e-textile and smart clothing (Park et al., 2018). In the current study, the USB power bank with a capacity of 10,000mAh was employed to power the heating system, chosen for its slim, portable design, compatibility with the microcontroller's operating voltage, and for convenience factors. USB power banks are widely accessible at affordable prices and users simply need to connect it to the jacket. However, based on calculations detailed in Chapter 6, it is anticipated that a 10,000mAh battery will only provide approximately 3.5 hours of operation. Consequently, climbers engaged in longer activities may opt to carry multiple batteries as backups. While this power supply solution is convenient and allows for easy removement or replacement in case of depleted or faulty batteries, it is not considered ideal, as one of the reasons for developing this jacket was to reduce the risk of changing clothing at height, and swapping batteries during a climb may reintroduce some of this risk. Future research into power supply solutions for this project should explore methods for seamlessly integrating a flexible battery with a jacket, ideally with sufficient power for a full day's use.

E-textile applications rely heavily on wearable power supply devices and systems, which are essential to their functionality. Integrating power supplies into textiles carries risks to the well-being of the wearer, as well as considerations related to replacement and flexibility (Ali et al., 2021). For instance, built-in batteries in such systems may be at risk of issues such as battery ignition (Iftekhar Shuvo et al., 2021). Typically, bulky and rigid batteries or capacitors have been used as energy storage solutions for electronic textiles in conventional approaches. Despite significant advancements in reducing the size and weight of these storage devices, making them more portable, they often still require more space than the systems they power (Ali et al., 2021; Iftekhar Shuvo et al., 2021; Park et al., 2018).

The development of power supplies and energy harvesting methodologies for wearable electronics represents a significant area with substantial potential for future advancements. Thus, research has explored energy for wearable electronics that was harvested from different sources, such as solar (Dieffenderfer et al., 2014), human body movements (Park et al., 2018), thermoelectric processes, or electromagnetic waves (Liu et al., 2021). However, these energy sources require additional power management units and energy storage elements to operate effectively, thereby limiting their practicality for wearable applications.

Fabric-based flexible batteries, devoid of rigid electrical components, suggest promising solutions for addressing the power needs of wearable and e-textile applications. These batteries can be directly printed onto fabrics and tailored to meet both mechanical and power specifications of the devices (Ali et al., 2021; Li et al., 2020). For instance, Ali et al. (2021) explored diverse printing techniques and battery chemistries suitable for smart fabrics, with a particular emphasis on those suitable for thick-film deposition to achieve high-energy density textile batteries (Ali et al., 2021).

A study by Park et al. (2018) described highly stretchable and flexible single-strand fiber-based woven-structured triboelectric nanogenerators (TENGs) that convert mechanical energy from human motion into electrical energy. When used as wearable and portable devices, these TENGs were found to be efficient sources of power. This technology was successfully integrated into a shoe where it effectively harvested energy from human motion (Park et al., 2018).

According to the article, this technology is anticipated to find applications in e-textiles and smart clothing due to its scalability and potential for widespread manufacturing.

Overall, there is substantial potential for the development of novel power supply devices that are characterised by flexibility, lightweight construction, miniaturisation, stability, and adaptability for integration into self-powered wearable systems. The primary fabrication strategies for such devices encompass material synthesis, architectural design, device configuration, and system integration to produce flexible power devices (Gao et al., 2021). However, several challenges hinder the advancement of flexible power devices for practical applications. These challenges include the insufficient capacity and energy density of current flexible power devices for long-term use, the mechanical properties of these devices, which need to ensure comparable flexibility across their components and resistance to deformation from external stimuli as well as issues related to biocompatibility, breathability, safety, and sustainability. Future research in this area should address these challenges by focusing on the development of reliable and flexible materials with enhanced electrochemical performance. This can be achieved through advancements in material preparation, device configuration, and system integration for flexible power supply devices (Gao et al., 2021).

7.7. Insufficient Testing Standards in E-Textiles and Wearable Electronic Components

A significant issue in this field is the lack of extensive studies and established standards for testing the various properties of electronic fibres, yarns, fabrics, and wearable electronic components intended to be integrated into smart garments. While developing a smart heating system for this research project as described in detail in Chapter 6, I searched for standardised testing procedures to assess the behaviour of conductive yarns after multiple tensile cycles but encountered a notable gap in available methods. As of 2021, only twenty-two standards related to e-textiles existed, with several still under development. These standards cover testing across five categories: electrical, thermal, mechanical, optical, and environmental factors (Shuvo et al., 2021). Most of these drafts were not published until 2023, highlighting the ongoing need for comprehensive testing frameworks in this rapidly evolving field.

One standard, IPC-8921 (IPC, 2019), was established by the global trade association IPC in 2019 for its members from the electronics industry (Franz et al., 2022). This standard outlines requirements for knitted and woven electronic textiles integrated with conductive yarns, conductive fibres, and/or wires. It includes 20 new terms and definitions specific to e-textiles, as well as provisions for quality assurance and test frequency.

Consequently, specific testing procedures in this project employed expedient methods and also adapted traditional textile standards methods to e-textiles, utilising existing testing facilities at AUT such as the Texture Analyser TA.XTplus. In this study, the electrical resistance of conductive yarn after numerous tensile cycles was tested using a combined and modified approach involving two standard strip methods, BS EN 62047-22-2014 (BSI, 2014) and BS EN ISO 13934-1-2013 (ISO, 2013) as discussed in section 6.2.2.

Test methods, protocols and procedures for smart textiles are necessary to ensure product safety, efficiency, and durability. These issues can be mitigated through rigorous quality control and the application of standardised testing methods (Iftekhar Shuvo et al., 2021). Due to the lack of dedicated standard test methods, e-textiles manufacturers face challenges in controlling product quality. This limitation hinders their ability to scale up and fully realise the potential of their innovative e-textile technologies and products.

The issue was discussed by the Occupational Safety and Health Administration (U.S. Department of Labor, n.d.) in relation to smart personal protective equipment (PPE), emphasising the necessity for compliance with smart PPE regulations for proper certification. Thierbach (2020) argued that testing PPE and its electronic components separately is inadequate, underscoring the importance and need for manufacturing guidelines specifying how smart PPE should be tested and which methods should be employed. The absence of standardised testing procedures poses a significant barrier, discouraging many manufacturers from investing in the development of smart PPE.

Smart clothing, including smart PPE clothing, is an emergent area that requires the development of appropriate product standards and testing methods, in particular for combinations of textiles and electronics, that can be used to ensure that all related risks are checked in a proper manner (Thierbach, 2020). The development and adoption of product-oriented test methods by the manufacturing industry presents a future direction in this field. Such advancements will enhance the design process, contributing to the creation of more efficient, safer, and durable smart and e-textile products (Iftekhar Shuvo et al., 2021). Standardisation of e-textiles components would provide much-needed scalability and cost control mechanisms for e-textiles designers and manufacturers, which would improve the overall market viability (Shi et al., 2023). Furthermore, it is essential to implement standards that offer guidance on using safe, biodegradable, and disposable electronic materials in textiles. This is particularly important for certain e-textile devices, such as textile batteries, which may necessitate the use of potentially hazardous materials to achieve optimal electrical performance (Komolafe et al., 2021).

Furthermore, the establishment of standards providing guidance on the integration of electronic materials into e-textiles that are safe, biodegradable and disposable is essential. For certain e-textile devices, such as textile batteries, which may necessitate the use of materials which are potentially hazardous, it is particularly important to achieve optimal electrical performance (Komolafe et al., 2021). The establishment of standards and test procedures that include sustainable criteria in relation to e-textiles would increase the potential for commercialising electronic yarns, fibres, and fabrics as well as the integration of them into wearable and flexible e-use in the areas of human health monitoring and many other smart devices (Dulal et al., 2022).

7.8. Limitations of Prototype Testing and Future Steps

There were several noticeable limitations in this study related to the testing of the finished jacket with the integrated heating system by potential users. Thus, the jacket was only tested by one user and only in an indoor setting. The assessment of the general fit, comfort, and ergonomics of the finished jacket was limited by there being only one jacket produced, tailored to one particular climber. This is defensible given the scope of the project and the resources available, and that the individual had extensive climbing experience, but, nonetheless, it poses limitations to the study. The jacket was evaluated both by the researcher and by the rock-climber. However, only the one climber, who was interviewed following a brief climbing session, participated in this assessment.

Although this climber can be considered a professional with extensive climbing experience, it would be beneficial to assess the jacket with a larger group of climbers to obtain a broader range of opinions. It is possible that this climber's technique differed from other climbers, and the jacket might perform differently for others. Ideally, this type of clothing should be assessed by a variety of climbers, male and female, with different body types who are engaging in a variety of climbing techniques. However, expanding the testing of the jacket with various climbers would necessitate the creation of a larger number of prototypes in different sizes and for both genders. This process would include developing a jacket specifically tailored for a female range and performing pattern grading for both male and female jackets to extend the size range. Additionally, the length of the wires used to connect components of the smart heating system would have to be customised according to the size of the jacket. Another consideration would be the determination of the optimal temperature level for the heating pads depending on gender. Although theoretical insights from the literature review guided this parameter, consultation with a specialist from the biomedical field was not sought during the project to validate this information. Should the project advance to mass production, the involvement of such specialists would be essential to ensure the accuracy and safety of the heating system. This development phase would require additional specialists and resources, including increased funding and time, to effectively support the creation and testing of these prototypes.

A further limitation of the user prototype testing is related to the fact that the jacket was only tested during a climbing session conducted on an indoor climbing wall due to limitations prescribed in the Ethics approval given for conducting this research, even though the jacket was designed for outdoor use. This limitation prevented testing the jacket in a real mountain environment, thereby restricting the evaluation of its thermal characteristics and the performance of the heating system in cold conditions. Consequently, only laboratory tests of the heating system were conducted. This limitation could be mitigated by expanding the testing setting to include a wider variety of outdoor environments.

7.9. Ventilation and Humidity Considerations

Ventilation and humidity regulation is an aspect of rock-climbing clothing that was considered in depth in this study. This focus was justified by the findings of the survey analysis of climbers' needs (see Chapter 4) and the recognised significance of maintaining an appropriate microclimate within the clothing layers (see section 2.4). A common solution proposed by outdoor clothing manufacturers for rock-climbing is the incorporation of functional vents through zipped openings positioned along the side seams. This design solution was identified during analysis of existing clothing presented in Chapter 4 and Appendix D. However, experienced rock climbers have indicated infrequent or negligible utilisation when rock-climbing, although they did not specify why not. For this reason, this popular solution for ventilation was excluded from the design of an ergonomic rock-climbing jacket.

A more sophisticated solution for adaptive ventilating structures in a fabric, using biomimicry, was presented by Chapman (2013). This adaptable ventilation was based on the structure of a pinecone (Chapman, 2013). A pine consists of three layers, each with a significantly different hygroscopic expansion coefficient (K. Song et al., 2015). In a wet state, the scales of the pinecone remain closed. As humidity decreases, typically during spring, the scales bend away from each other, causing the pinecone to open and release the seeds. In the same way, a multilayer coating is applied to a fabric, with U-shaped perforations punched through both the fabric and the coating (see Figure 7.1).

In a wet state, the scales of the pinecone remain closed. As humidity decreases, typically during spring, the scales bend away from each other, causing the pinecone to open and release the seeds. In the same way, a multilayer coating is applied to a fabric, with U-shaped perforations punched through both the fabric and the coating (see Figure 7.1). When the material becomes wet, such as through perspiration, the perforation blades bend, thereby enhancing ventilation. When the material dries out, the blades close, reducing ventilation.

Figure 7.1 (Image removed due to copyright restrictions)

Adaptive ventilation based on pinecones

Note. Copyright 2013, by Woodhead Publishing Limited

A similar concept was presented Zhong et al. (2017), who suggested the use of humidity sensitive smart polymer materials to create two types of Nafion-based smart clothing structures triggered by humidity change. These structures are capable of rapidly and reversibly altering their porosity or thermal insulation in response to an individual's perspiration levels. A design that mimics sweating pores, utilising an array of flaps on a Nafion sheet, has demonstrated responsiveness to humidity gradients by automatically opening or closing to regulate airflow through the pores. This mechanism was shown to effectively manage both humidity and temperature (Zhong et al., 2017). Such structures, which emulate human skin, function adaptively and repeatedly.

At the outset of the project, consideration was given to incorporating two modules into the jacket capable of regulating temperature and humidity levels, similar to the projects described above. For this reason, the initial prototype of the heating system employed a digital temperature and humidity sensor (refer to Chapter 6, section 6.3). However, integrating both modules into the jacket was likely to create a conflict between the two systems. If humidity levels were to increase, causing the pores to open automatically and allowing cold air to infiltrate the jacket, the heating system would continuously heat up, resulting in improper functioning. Consequently, as temperature increases, the wearer may sweat, resulting in higher humidity levels on the inner surface of the textile (Zhong et al., 2017). To address this concern in the jacket design, ventilation issues were addressed through the careful selection of materials, particularly the use of a membrane fabric as the main textile material for the outer layer (see section 5.4). This fabric is breathable and facilitates moisture transfer effectively.

The incorporation of a smart system that can regulate humidity and temperature levels simultaneously would be one of the primary directions for the future development of similar clothing systems.

7.10. Sustainability Considerations

Sustainability is a multifaceted concept involving the integration of better usage of materials, reducing overall carbon footprints and balancing the use of renewable resources and biodegradable products with an efficient recycling/remanufacturing economy (Dulal et al., 2022). In the context of developing functional, innovative clothing and wearable devices, it has become essential to address sustainability considerations concerning environmental, social, and economic impacts. These issues should be integrated from the initial stages of the design process. This current section provides an overview of key sustainability considerations relevant to this research project and the broader context of smart clothing development.

7.10.1. Material and Electronic Component Selection

The first consideration in any new design pertains to the selection of sustainable textile materials and sustainable electronic materials and components. Significant progress has been made in materials science towards the development of sustainable fibres that can replace synthetic fibres produced through highly polluting and carbon-intensive processes. The criteria for fibre sustainability include low water and energy consumption, biodegradability, recyclability, the use of renewable resources, strict chemical control, the absence of genetically modified organisms (GMOs), and the prevention of soil erosion (Dulal et al., 2022). At present, there is growing international interest in the development of sustainable bio-based polymer fibres that meet most of these criteria. According to BS EN 16575:2014 (European Standard, 2014), the term "bio-based" refers to products wholly or partly derived from biomass, such as plants, trees, or animals (it is noted that the biomass may have undergone physical, chemical, or biological treatment) (Tavanaie, 2021). Moreover, significant progress has also been made in the development of sustainable biopolymer fibres modified with graphene or other conductive 2D materials (Dulal et al., 2022). Despite this rapid development, there remains a challenge in directly comparing the performances of one type of electronic fibres/yarns/fabrics with another due to the absence of consistent technical testing procedures and standards, as mentioned in section 7.7, and the need for environmentally conscious, factually consistent, and simple evaluation standards (Dulal et al., 2022).

This study presented findings on the material selection for existing outdoor rock-climbing sportswear currently available on the market, as detailed in the Chapter 4. The analysis revealed that synthetic fibres are more prevalent than natural fibre options in outdoor rock-climbing clothing. Specifically, the most common outer fabric is nylon or polyester, or a blend of these with elastane. Fabrics comprising natural fibres, primarily cotton, combined with synthetic fibres, are typically used for rock-climbing pants but are rarely used for jackets. Although naturally produced fibres like cotton are biodegradable (Mohsin et al., 2013), they may have significant environmental impacts when produced at industrial scale. Textiles made of blended natural and synthetic fibres are also recognised as being more difficult to recycle given current methods of textile recycling (Peterson, 2015). Manufacturers predominantly use synthetic insulation fabrics or sometimes a combination of synthetic fibres and goose down. Overall, the analysis suggests that manufacturers prioritise characteristics such as light-weightness, durability, waterproofing, low cost, and vibrant coloration over sustainability in their fabric selection as these properties are not commonly found in naturally occurring, sustainable materials. Furthermore, only limited research exists on the interaction between sustainable fabrics and electronic components and there is a lack of established standards in this area.

For this project, a polymer-based woven polyester membrane fabric called Taslan was chosen (see section 5.4) that exhibited notable strengths, including robustness and durability, coupled with rapid drying capabilities and efficient moisture-wicking and stain-resistant properties. These characteristics are expected to extend the garment's lifecycle, thereby contributing to its sustainability by promoting longer wear and use. Moreover, for the insulation layer, a synthetic lightweight material that comprises 40% recycled polyester and 60% polyester was selected. The incorporation of recycled polyester fibres in textiles helps to mitigate potential negative environmental impacts, thereby enhancing the overall sustainability of the garment.

Wearable electronics would not be feasible without electronic components, such as electrodes, connectors, and interconnectors (Dulal et al., 2022). These components are typically soldered onto a printed circuit board (PCB) to create an electronic circuit designed for specific functions. The attachment of circuitry to textiles also involves the use of materials such as solder, protective coatings, plastics, and paints (Dulal et al., 2022). However, these materials can release toxic substances, posing potential hazards to both humans and the environment. To address these concerns, green technology has been developed for the production of printed circuit boards, including lead-free soldering methods (Li et al., 2018). An even more sustainable and environmentally friendly alternative is the use of biodegradable electronic materials. These materials are engineered to fully degrade and physically dissipate under environmental conditions, thereby reducing their ecological impact (Li et al., 2018). However, further research is needed in this area as wearable electronics incorporating biodegradable materials must be significantly improved to meet required electrical performance standards while ensuring effective biodegradation.

7.10.2 Sustainable Manufacturing Processes

The sustainability of wearable electronics hinges not only on the sustainability of its individual components but also on the manufacturing and fabrication processes used. A sustainable manufacturing process must integrate energy-efficient technologies and practices to significantly reduce greenhouse gas emissions and optimise resource utilisation. This includes the adoption of renewable energy sources, water-saving practices, waste reduction, and the refinement of production techniques to minimise energy consumption, water pollution, and material waste.

To extend this principle to wearable devices, all components—textile substrates, insulators (dielectrics), conductors, and semiconductors—must be produced using sustainable methods and designed to be recyclable and/or biodegradable (Dulal et al., 2022). There is still considerable scope for improvement in wearable e-textile design through enhanced fabrication or manufacturing technology that can be cost-effective, environmentally friendly, and provide better performance. For example, an eco-friendly strategy proposed by Dulal et al. (2022) involves reducing the number of polymer materials used in e-textile manufacturing. In this context, electrospinning is suggested as a viable alternative technique for producing biodegradable polymeric nanofibre membranes suitable for flexible and wearable electronics applications. Moreover, these resource-intensive products should be designed to retain their inherent value throughout their entire lifecycle, ensuring that wearable e-textiles do not lose their functional or material worth at the end of their usage.

7.10.3. Wearable Electronics Lifespan and End-of-Life Management

The integration of electronics into clothing presents several challenges related to retaining textile breathability, flexibility, maintaining appearance, and washability. Integrated devices and materials must be robust enough to last the lifetime of their intended application while delivering reliable electrical performance comparable to traditional equivalent devices (Komolafe et al., 2021). This enhances their durability, functionality, and longevity.

To achieve the transformative potential of wearable e-textiles, innovations in materials are essential for facilitating effective user adoption and fostering a sustainable circular economy. In this context, Shi et al. (2023) proposed a new 4R e-textile design concept: repair, recycle, replacement, and reduction.

Repair. Shi et al. (2023) proposed the division between “fibre level” and “fabric-level” repairs. According to this distinction, effective “fibre level” repairs involve resewing, reweaving, reknitting, and self-healing of electronic fibres, while bulk “fabric-level” repairs utilise other methods such as recoating, reprinting, and respraying of active materials. The critical considerations here relate to fault detection, monitoring and prediction of fault symptoms, and maintenance. Due to their seamless integration into smart textiles, routine monitoring and maintenance of electronic components can be extremely difficult. Additionally, any attempt to repair defective components may permanently damage the smart textile products (Mouton, 2021). To enable these strategies for effective repair, it is essential to ensure that e-textile materials are chosen for mechanical robustness and electrical versatility, and that adequate adhesion and post-repair performance are maximised (Shi et al., 2023).

In maintaining wearable electronics that function as portable computing devices for real-time data analytics, it is crucial to regularly update electronic components, firmware, networking protocols, and software. Challenges in performing these updates can significantly compromise the lifespan of the e-textile product (Mouton, 2021).

Recycle. Recyclability is the capability of a product to be reused at the end of its multiple lifetimes to reduce waste, pollution, and resource use (Dulal et al., 2022). In the near term, by categorising and separating e-textile components into the base textile and the electronic modules, respectively, the base textile can be recycled as regular clothing and the electronic components as regular e-waste streams (Shi et al., 2023). However, this approach becomes more challenging with encapsulated electronics, such as those described by Cork et al. (2013), which incorporate off-the-shelf resin-encapsulated semiconductor devices into the core of yarns. Extracting components from such e-textiles is complex, time-consuming, and costly. Furthermore, the disassembly of various electronic components needs to be considered to fully recycle wearable electronics at the end of their useful life (Tseng et al., 2013).

Replacement. The concept of replacement focuses on creating functional fibres using renewable, earth-abundant materials or even living biohybrids that minimise environmental impacts on disposal (Shi et al., 2023). Despite bio-based fibres providing a renewable source of fibre platforms for e-textile production, they typically lack inherent electronic functions, nano- and micro-structured active coatings, and functionalisation strategies commonly employed in e-textiles. Addressing these limitations would be essential to develop viable alternatives for synthetic encapsulation in the near future.

Reduction. According to Shi et al. (2023), reduction can be interpreted in two ways:

• reduction of the total emissions and energy consumption during e-textile production and deployment;

• reduction of the total amount of material used in e-textiles to achieve and maintain a specified function, especially in cases where repair, recycling, and replacement strategies might involve carbon/energy-intensive processes.

To address the first point, current processing methods for e-textiles are largely analogous to those used for traditional textiles. These methods are both water- and energy-intensive and generate significant amounts of toxic chemical waste that necessitates effluent treatment (Shi et al., 2023). To mitigate the environmental impact of e-textile manufacturing, it is crucial to innovate in fibre and textile fabrication technologies and optimise existing processing techniques. Employing low-energy, efficient sensors and electronic components in smart clothing can help reduce the environmental impact associated with their operation. However, the integration of sensors and batteries, which are often inseparable from the application, poses challenges for repair, replacement, and safe disposal, potentially resulting in hazardous waste (Mouton, 2021).

In response to this challenge, my project has adopted a USB-attachable power bank for powering the entire circuit. This power supply is not only cost-effective but also easily removable and replaceable, simplifying disposal at the end of its life cycle. Ensuring that smart textile waste does not introduce new health and environmental risks during disposal is crucial. The ability to easily remove or replace the USB power bank in the event of depleted or faulty batteries enhances the longevity of the garment, contributing to a more sustainable lifecycle. Additionally, the use of removable electronic components in this jacket would help reduce microplastic pollution in water streams during the washing of e-textiles, along with preserving the life of the electronic components.

The second point is particularly relevant for e-textiles that function as biological/chemical sensors or transducers in direct contact with biofluids or pollutants. These contaminated single-use or transient wearable e-textile interfaces are designed to be disposable for health and safety requirements and thus warrant a materials reduction strategy (Shi et al., 2023).

7.10.4. Consumer Education

An essential aspect of promoting sustainability in wearable electronics involves educating consumers about the environmental and social impacts of their clothing choices. This awareness can foster more sustainable purchasing behaviour and encourage the adoption of eco-friendly practices. As wearable electronics integrated with textiles transition from bespoke creations to mass-produced items, concerns related to laundering, disposal, and electronic waste will become increasingly prominent (Dulal et al., 2022). Therefore, it is crucial to provide users with comprehensive guidance on proper garment care and maintenance at home as well as promoting repair, component replacement, and upcycling can help extend the lifecycle of garments and reduce waste and thereby minimise the jacket's environmental impact.

Additionally, there are cultural and privacy concerns associated with the use of smart clothing in the workplace. The situation becomes particularly sensitive when data from wearables, such as smart clothing, is shared with third parties like employers, as it may be perceived as an invasion of privacy (Mouton, 2021). To address these issues, it is necessary to provide employees with complete information about data usage, obtain their consent, and ensure that practices align with principles of social sustainability and workers' rights.

To conclude this section, the smart wearable electronics market holds considerable potential for integrating sustainable materials. It is anticipated that wearable textiles with innovative designs and functionalities will become a staple in our daily lives in the future. To mitigate the environmental impacts associated with wearable electronic applications, addressing sustainability challenges from the early stages of mass production is crucial. By tackling these sustainability considerations, advancements in clothing and smart clothing technologies can contribute to a more responsible and eco-friendly fashion industry, aligning with global efforts to reduce environmental impact and promote ethical practices. This project supports sustainability by extending the garment's lifespan through improved functionality and ergonomic design, and by carefully selecting materials, such as insulation fabric containing 40% recycled polyester. Additionally, the use of a removable and replaceable USB power bank for powering the jacket's circuit simplifies both washing and disposal, thereby enhancing the garment's overall sustainability.

Future improvements for this jacket and similar smart clothing initiatives could benefit from adhering to the 4R e-textile design concept: repair, recycle, replacement, and reduction (Shi et al., 2023). To facilitate the washing of garments, and the replacement and repair of electronic components, it is advantageous to design these components to be easily removable. This can be achieved by integrating the electronics into a separate layer of the garment and fabricating this layer to be detachable. Such an approach would also streamline the process of separating electronics for subsequent disposal. Moreover, if users choose to discontinue the use of smart functions or if the electronic components become irreparable, removing this separate layer would allow the jacket to function as a conventional garment, thereby extending its lifespan. Such improvements can enhance the sustainability of smart clothing by enabling easier maintenance and recycling and by allowing the garment to be repurposed as a general item, thus further extending its usability.

7.11. Other Research Limitations

This section presents a detailed discussion on the research limitations in relation to specific aspects of the project. A notable limitation of this study pertained to the scoping review, specifically the scarcity of prior published research on rock climbing apparel. Few studies addressing rock climbing clothing, particularly rock-climbing pants, were identified. Consequently, there was a lack of foundational understanding regarding methodological approaches, prevalent research problems, analogous research projects, challenges, and the use of new technologies for developing this category of clothing. Additionally, there was a limited data on rock climbers' needs and preferences, and lack of established standards and requirements for their apparel as discussed in detail in section 7.3. However, the scoping review was restricted to to peer-reviewed and publicly accessible publications, which might have excluded significant research retained in corporate environments. This limitation was particularly relevant to the current market status of smart clothing, as some relevant studies, technical documentation, and user testing responses were likely not available. Therefore, the analysis of existing commercial products was based on information provided by manufacturers or sellers and on a visual analysis of images concerning pattern engineering solutions. Since the completion of this research, other relevant articles and standards may have been published. Although I have checked the current publications and standards in this field, there remains a possibility that significant information may have been overlooked.

Due to the limited information available on methodological approaches identified in the literature scoping, the entire chapter was devoted to detailing the methodological framework, including the approaches, methods, techniques, and tools employed in this research. At the end of Chapter 3, limitations associated with the use of HCD and UCD approaches were acknowledged (see section 3.4).

A key primary source of information for this study was the survey conducted at the start (see sections 3.2.3 and 4.1); however, the survey, too, had some limitations. The survey included open-ended questions, which elicited subjective responses from the climbers. Consequently, the study relied on self-reported data from participants, which was accepted at face value and cannot be independently verified. Self-reported data from participants may be subject to biases, including selective memory regarding certain climbing techniques and potential exaggeration or embellishment of reported information.

Another limitation pertains to the number of participants involved in the survey and their gender distribution. During the phase of recruiting professional climbers for the survey, I reached out to organisations and rock-climbing clubs that provided lists of hundreds of potential participants. Despite numerous recruitment efforts via email, only eight responses were received. One climber initially completed a consent form but did not participate in the survey, even after a follow-up reminder. It appeared that professional climbers were either disinterested in participating in the project related to technological improvement of clothing or unwilling to invest time in completing the questionnaire. Regarding gender, only one female climber out of seven participants took part in the survey. This gender disparity is reflective of the sport's greater popularity among males. Notably, the only female participant expressed disapproval of integrating smart components into rock climbing clothing, although she did not provide a rationale for her opinion.

The criteria for selecting types of clothing and popular brands for analysis were based on primary data obtained from a survey of experienced climbers. However, due to the limited number of respondents, some popular brands of outdoor rock-climbing apparel may not have been included. Additionally, since the completion of this analysis, new clothing solutions, advancements in textile materials, and the emergence of new brands in outdoor rock-climbing apparel may have occurred.

During an observation session, an innovative motion tracking system, specifically the Xsens system technology, was utilised. However, limitations and challenges associated with using this technology in the context of developing rock-climbing apparel were identified. This information was presented in Chapter 4 (see section 4.3.1).

The topic of developing smart clothing - encompassing the selection, creation, and assembly of electronics, the programming of heating systems, and their integration into garments - was novel to the researcher, whose expertise lies in pattern making and garment design. Although considerable time was spent in researching the topic and with consultations with experts from related fields, it still means that some of technical challenges could remain on a broad level and have not been discussed in detail or resolved completely.

The limitations associated with the development of both the conceptual and functional prototypes of the heating system primarily pertained to hardware components. The first limitation involved the constraints imposed by the availability of hardware components compatible with textiles or clothing. This issue was discussed in detail above (see section 7.5), and it included challenges related to the supply chain and restrictions on the shipping of certain items. The second limitation pertained to advancements in information technology and hardware components. Since the development of the smart heating system, new components with enhanced functionalities may have been introduced, such as prefabricated PCBs, advanced temperature sensors, and innovations in e-textiles. Additionally, there had been developments in power supply technology, which were also covered in section 7.6. Furthermore, some limitations of using e-textile and wearable electronic components were associated with a lack of testing standards as thoroughly described in section 7.7.

An aspect not within the scope of this research project, but pertinent to the discussion of limitations, is the commercialisation of innovative smart products, such as the developed jacket. The commercialisation of such products encounters several challenges. Key challenges include their higher cost compared to traditional garments and manufacturers' reluctance to invest in the development of manufacturing lines for large-scale production. Although the higher prime cost of the jacket may be justified by its extended functionality, consumers might prefer simpler and more affordable options. Additionally, the manufacturers face constraints related to the potential risks in creating smart clothing due to the lack of testing standards and certifications in place as discussed in section 7.7. The uncertainty of market acceptance for smart clothing further deters manufacturers from committing resources to scale production. As noted by Michaelson (2015), this reluctance represents a significant barrier to advancing products beyond the prototype phase. Scaling up production requires substantial initial investment, which can be highly risky if the associated challenges are not thoroughly addressed.

7.12. Summary

This chapter presented a discussion on the primary considerations, challenges, and contributions of the project within the design field of e-textiles and smart wearables. Additionally, it addresses relevant research limitations and potential future research directions. Several discussion points were thematically organised around research aspects, including ergonomic clothing design and pattern engineering, the issues encountered in the development of smart technologies, limitations in prototype testing and future directions. Sustainability issues in the context of developing functional innovative clothing and wearable devices were also acknowledged in this chapter, as an important discussion point despite this aspect not being a key focus of this project.

The first discussion point focused on a significant gap in standards and requirements for rock-climbing clothing. This type of information is important during the initial development stages, as standardised regulations could provide guidance on textile properties, ergonomic design principles, appropriate seam types, environmental considerations, testing protocols, and certification procedures. These elements are vital for ensuring safety, performance, and comfort in challenging outdoor environments. The discussion emphasised the need for the establishment of comprehensive standards to address the significant challenges posed by the absence of existing standards in rock-climbing apparel.

The second discussion point explored the advantages, challenges, and limitations associated with the novel technologies integrated at various stages of the research project. The innovative Xsens motion tracking system was utilised to assess climbers' anthropometric characteristics in dynamic postures. The successful implementation of the 2D-to-3D concept as a design tool enabled the visualisation of the jacket design on a 3D digital model in both static and dynamic postures, the digitalisation and modification of flat patterns, virtual fitting assessment, and the evaluation of fabric strain and stress characteristics in dynamic conditions through 3D simulation. This approach enhances the capabilities of software to transform functional design in both industry and research contexts, which is useful for the ongoing academic and professional development of the industry and for improving fit satisfaction among end users.

The next section discussed the application of complex methodological approaches, which highlights the multidisciplinary nature of this study and contributes to the fields of smart clothing and e-textiles. Moreover, the study incorporated an individualised approach tailored to the specific stakeholder, in this case, the rock-climber. These research approaches can be adapted to relevant research projects.

The second part of this chapter discussed the challenges, limitations and potential future advancements in the field of e-textile and wearable prototypes. This part started by examining the significance of interdisciplinarity and multidisciplinary approaches in the development and application of e-textile and smart wearable prototypes. This discussion underscored the transition from a predominantly multidisciplinary framework towards a more integrated interdisciplinary approach in this research area.

Another discussion point addressed the limitations associated with the design and commercial availability of hardware components compatible with textiles and clothing applications. This section also explored the challenges encountered in developing such components through interdisciplinary collaboration. These insights are particularly relevant for other designers and researchers working on similar projects. Additionally, the discussion extended to concerns regarding power supply and outlined potential future directions in this field.

A significant topic covered in this chapter involves the limited number of studies and standards pertaining to the exploration and testing of various characteristics of e-textiles and wearable electronic components integrated into garments. The establishment of comprehensive standards and testing procedures represents a future direction in this field. Such standards would facilitate a design process that is safer, more efficient, and more durable, thereby enhancing the potential for the commercialisation of electronic fibres, yarns, and fabrics.

A noticeable discussion point highlighted the limited testing of a finished jacket and heating system prototype, noting that evaluations were primarily conducted in an indoor setting with a single climber. Strategies to address these limitations and future steps for broader testing were discussed, including the requirement for additional specialists, resources as well as increased funding and time. Additionally, the chapter explored considerations for ventilation and humidity regulation within clothing layers and the challenges of simultaneously integrating the ventilation/humidity control and heating systems in rock-climbing apparel.

Finally, the chapter provided an overview of key sustainability considerations relevant to this research project and the broader context of developing functional innovative clothing and wearable devices. Although this aspect was not a key focus of this project, it is an important area to discuss. By addressing the sustainability considerations, advancements in clothing and smart textile technologies can contribute to a more responsible and eco-friendly fashion industry, aligning with global efforts to reduce environmental impact and promote ethical practices. Future directions toward sustainability could benefit from adhering to the 4R e-textile design concept that focuses on: repair, recycle, replacement, and reduction.

CHAPTER 8. CONCLUSION

In this chapter, the outcomes and findings of this research are considered in relation to the project aims, objectives, and research questions. The potential implications of the findings to the field of clothing design research and practices, and the contribution to knowledge are presented. The impacts and insights about the research limitations, identified in the previous chapter, are considered and future research opportunities and directions are discussed.

8.1. Reflections on the Research Aim and Questions of the Study

This thesis presents an original inquiry that set out to develop smart clothing specifically designed for climbers. The aim was to enhance the functionality and safety of conventional outdoor rock-climbing apparel by incorporating an autoregulatory temperature control system. The integration of such a heating system into clothing allowed for a shift from a traditional multi-layer clothing approach used to manage climber's body temperature fluctuations during rock climbing in variable high-altitude, snowy, and windy environments. This traditional layering approach, while effective, requires carrying multiple layers and poses risks due to the difficulty of changing clothing in potentially dangerous conditions, often while secured to safety ropes that must be removed or adjusted in order to do so. While smart heated clothing is becoming popular, most products on the market are designed for suburban environments and everyday use. Although a few smart jackets have been adapted for outdoor sports, none have been specifically tailored for rock climbing.

The study was organised around the primary research question posed. This question sought to explore how the functionality of outdoor rock-climbing apparel can be enhanced. To answer this question, the key challenges that rock climbers encounter with current apparel options and traditional layering approaches were first identified. This inquiry, addressed through surveys and interviews with rock climbers, aimed to understand their experiences with climbing apparel and to identify their needs and potential areas for design intervention. An analysis of their feedback contributed to the final design of the jacket, providing insights into which aspects of the clothing needed enhancement, which sensors needed to be integrated, and guiding the selection of materials, colour solutions, pocket placement, hood configuration, and other design components that were important for the development of rock-climbing apparel and extending its functionality. Climbers identified the most problematic areas of their current clothing in terms of abrasion and durability issues. These findings were summarised, and the recommendations were provided for improving clothing design, the integration of smart technologies, and reinforcing the areas identified to enhance durability and longevity. This information can be useful to other designers and manufacturers of outdoor rock-climbing apparel.

Two secondary questions asked how functionality, safety, and comfort can be enhanced through employing an ergonomic approach to the clothing design and through incorporation of smart wearable technologies into climbing apparel. Answers to these questions were elicited through the processes of design development, garment manufacture, and final evaluation of the jacket. The principles of physical ergonomics were incorporated in the design process of the clothing along with other considerations related to sport-specific factors. These included the high amplitude of movements during climbing activities, an issue which was addressed during the pattern engineering stage. Additional considerations included the wearing of special climbing equipment for safety reasons and a range of environmental factors. In identifying and taking account of the various factors that could influence the functionality, safety, fit, and comfort of climbing apparel from the initial stages of the development phase, the study sought to identify the optimal design and ergonomic solutions. Engaging the end user—the climber—in the development process from the outset, helped to mitigate potential issues at later stages. The incorporation of smart technologies extended functionality, safety, and comfort through the consideration of key factors such as minimising wearer discomfort, identifying body areas requiring warmth, and optimal temperature level, ensuring safe distances between components, addressing wiring connection issues, and accommodating the placement of rock-climbing equipment. This integration fulfilled the aim of the project as a proof of concept.

8.2. Contributions

This research project is practice-based and resulted in a practical design outcome, a functional, ergonomic smart outdoor jacket for rock climbing, that integrated climbers' activities, needs, and preferences. While only one prototype was produced and tested, and this is acknowledged as a limitation, this thesis nonetheless contributes to knowledge in several ways. It advances explicit knowledge in the field of the enhancement of outdoor rock-climbing apparel, the development of wearable electronic applications, and contributes to knowledge related to the creation of the artefact itself. The research presented contributes valuable insight toward understanding the need for interdisciplinary and user-centred approaches in the design and development of integrated clothing systems, such as specilised application of outdoor rock-climbing. Given the highly commercial nature of this area, there is little documented or published. This research therefore makes a valuable contribution by providing insights and knowledge that are not widely available in the existing literature.

Firstly, it advances explicit knowledge in the field of outdoor rock-climbing apparel by enhancing the understanding of ergonomic clothing design integrated with wearable technologies and offering recommendations for contemporary solutions in garment design and material selection. It also justifies the use of novel information technologies at various stages of rock-climbing clothing development, such as the Xsens motion tracking system and 3D fashion design software. The successful implementation of the 2D-to-3D concept as a design tool, and the visualisation and virtual clothing assessment in 3D simulation mode, demonstrated how this approach capitalises on the capabilities of software to transform functional design into practical applications in both industry and research contexts.

Secondly, the research underscores the methodological approaches employed for development of both ergonomic rock-climbing clothing and e-textiles and smart wearables. These research approaches grounded in HFE and highlighted the multidisciplinary character of this study. While the methods used in the research are not novel in themselves, how they have come together provides insights for related research projects in the fields of smart clothing, design and e-textiles by presenting adaptable and transferable methodologies. Additionally, it underscores the interdisciplinary nature of e-textiles and smart wearables, advocating for a transition from a predominantly multidisciplinary framework to a more integrated interdisciplinary approach (see section 7.4. and table 7.1.), and discussing the broader interdisciplinary implications for this research area.

The practical contribution in knowledge related to the creation of a functional outdoor rock-climbing jacket. Thus, a functional prototype of a smart heating system was created in this research project, and a conceptual solution for the integration of this system into a jacket was proposed that considered the demands of the ergonomic design, rock-climbing activities, and associated equipment. This practical outcome can be adapted by designers and manufacturers to enhance functionality of the outdoor sport clothing.

This study acknowledges several challenges and limitations encountered at various stages of the project. The discussion of these challenges, potential solutions, and future directions has also contributed to the advancement of explicit knowledge in the field of smart outdoor rock-climbing apparel. These contributions have the potential to benefit researchers and designers of smart clothing.

8.3. Future directions

This functional and design study encountered challenges directly related to the research process and identified limitations across the field that other researchers might explore further. This project involved prototyping, which is a process that reveals various recommendations for potential improvements and likely future scenarios. Several directions for the improvement of smart outdoor rock-climbing garment were identified throughout the stages of this project and are discussed below. Additionally, this section addresses the limitations encountered in this project by situating them within broader contexts that require future attention.

A significant gap identified in both the literature review, and the project is the absence of standards, testing procedures, and requirements for outdoor climbing apparel, as well as for e-textiles and wearable electronic components that are integrated into garments. This issue, discussed in the previous chapter (see sections 7.1 and 7.7), presents potential opportunities for future advancement in this field. The establishment of standards and standardised regulations for outdoor rock-climbing apparel could provide essential guidance on various aspects of clothing development, including design features, sizing, material specifications, environmental considerations, and other parameters crucial for safety and reliability. Extending these standards to smart outdoor rock-climbing clothing could involve incorporating testing protocols, sustainability considerations, end-user guidance, and certification processes. Implementing comprehensive standards and testing procedures for e-textiles would facilitate a design process that is safer, more efficient, and more durable, thereby enhancing the potential for the commercialisation of electronic fibres, yarns, and fabrics and their broader use in wearable applications. Establishing standards and regulations that address sustainability considerations for functional, innovative clothing and wearable devices could significantly contribute to a more responsible and eco-friendly fashion industry. This aligns with global efforts to mitigate environmental impact and promote ethical practices. The 4R e-textile design concept—repair, recycle, replacement, and reduction (Shi et al., 2023)—discussed in Section 7.10, offers a promising future direction for advancing sustainability in this field.

Another potential future advancement for smart clothing and wearable applications is reflected in the limitations identified with commercial availability and design of hardware components and textile electronics for wearable devices. The initial future direction for the developed jacket involves enhancing the hardware components and connections of the heating system. The first recommendation is the implementation of a protective and waterproofing solution for the customised circuit board through a process known as potting. This process can protect the core of electronic devices from damage. Potting involves immersing or coating a PCB or electronic component with a protective liquid or gel-like substance material, such as epoxy, polyurethane or silicone, which are also referred to as potting compounds (FS Technology, n.d.). For the PCB developed for the current project, a possible solution would be to cover it with a non-conductive epoxy. This would protect the circuit from moisture while ensuring its proper functionality.

The next future direction relates to developing customised textile-based solutions to address the problem of limited availability of electronic component options. The developed electronic fabric systems must adhere to practical standards, ensuring functionality, aesthetics, and comfort, given the variations in fibrous electronics (Pu et al., 2023). Additionally, it is essential to account for the integration of connections between textile electronic components within the fabric. However, these solutions would necessitate an extended development and testing period and the associated costs would increase accordingly. Thus, the potential advancement for the created jacket involves a comprehensive redesign of the heating system. Rather than utilising and connecting multiple pre-made heating pads, it is feasible to employ heating elements constructed from conductive yarn or thread. These elements could be integrated with a non-conductive fabric base through various methods such as embroidery, sewing, knitting, weaving, or printing. As mentioned in Section 7.10, a future improvement for the jacket could involve creating a detachable layer that incorporates the electronics, which would also align the design with sustainability goals. This layer could integrate the heating elements directly, potentially offering significantly improved heating performance and safer connections, though it might also substantially increase power consumption. Another proposed improvement for the heating system involves programming the front and back pair of heating elements separately. This approach would enable more precise responses by allowing for individualised reading and processing of data from sensors. Further research is required to assess the feasibility of these approaches, but it represents a promising direction for advancing the original concept.

Another area for potential advancement pertains to the challenges associated with connecting and integrating hardware in wearable applications. It is necessary to build reliable, environmentally stable, and flexible interconnections between electronic components and fabric circuits while ensuring adequate electrical connectivity (Pu et al., 2023). Future directions in this area at higher level could focus on addressing the complexities associated with the integration of textiles and electronics. Standard electronic components integrated with textile can be damaged under strain/stress of fabric. Each electronic component must be precisely adapted and integrated with the fabric structure to maintain a balance between preserving the garment's natural feel and achieving advanced electronic performance (Pu et al., 2023). Approaches to smart textile fabrication that are able to perform complex computing with high reliability were presented by de Mulatier et al. (2018). The authors introduced the use of flexible gradient structures and hybrid substrates that are both flexible and stretchable in interface design to enhance device durability and achieve superior computational performance. However, these advancements resulted in a decrease in wearing comfort, indicating that further development of this technology is required (de Mulatier et al., 2018).

The potential future improvement for the developed rock-climbing jacket, and by extension similar augmented clothing solutions, involves the use of conductive thread or fabric instead of wires. The utilisation of less cables would reduce the system's thickness and weight while preserving its washability. Employing conductive thread or fabric for connecting temperature sensors to the control board rather than using waterproof cables could enhance the overall product and simplify repairs in the event of a connection failure between the temperature sensor and the control board. The simplification of the repair process—achievable with just a needle and conductive thread as opposed to the more complex procedure required for repairing a broken cable—aligns with the 4R e-textile design sustainability concept (see section 7.10). In the current project, a conceptual solution involving the use of conductive fabric lines as wiring was proposed (see section 6.5). Unfortunately, this approach proved unsuccessful as the current produced was unstable and insufficient for powering the four heating pads. Thus, further investigation into the use of conductive threads and fabrics as viable solutions is necessary.

Extending functionality of smart clothing through the development and integration of multiple wearable devises represents substantial potential for future advancements. Thus, the literature review referenced a project by Lee and Baek (2021) which focused on developing a multifunctional wearable system integrated with a smartphone to enhance the capabilities of existing smart outdoor apparel. The potential enhancement for the current project could involve modification of the entire heating system into a temperature and humidity managing system that incorporates air movement within the clothing. This can be achieved by integrating additional hardware components, for example, a portable fan, additional humidity sensors, or a self-powered supply device. The integration of the self-powered supply devices and energy harvesting methods for wearable electronics represents another promising advancement for smart clothing in line with the discussion in section 7.6. For instance, the functionality of the *Life Tech Jacket*, described in the literature review (see section 2.6), is enhanced by the inclusion of a wearable wind turbine generator capable of powering a GPS and other mobile devices.

The area requiring further comprehensive research pertains to the multidisciplinary and interdisciplinary approaches involved in the development and application of e-textile and smart wearable prototypes. These approaches and associated issues were elaborated upon in section 7.4. The field of e-textiles and wearable devices is recognised as intrinsically interdisciplinary (Ismar et al., 2020; Pu et al., 2023; Ruckdashel et al., 2022). Although there is a growing body of literature on the formation and management of multidisciplinary teams in emerging, interdisciplinary domains such as medicine (Coulter et al., 2022), and despite the acknowledgment of challenges faced by researchers in the smart garment sector when working in multidisciplinary teams, there is a notable absence of guidelines or models to address these challenges. The discussion section 7.4 emphasised the need to transition from a predominantly multidisciplinary framework to a more integrated interdisciplinary approach in this research area. This highlights a clear need for further investigation.

8.4. Project Potential

This multidisciplinary functional and design research project was a successful attempt at creating smart clothing for rock-climbing, combining my expertise in pattern engineering with the contributions of other specialists from different fields, including electronics, computer technology, textile science, and materials science, and involving an end-user (a rock climber) throughout the development process. This thesis presents a comprehensive study focused on enhancing the functionality of outdoor rock-climbing apparel through ergonomic design and the integration of smart technologies, with a particular emphasis on improvements in fit, comfort, and safety.

The research project explored various aspects of developing smart clothing and prototyping wearable electronics, advancing knowledge in this field and offering valuable insights into the limitations and challenges encountered throughout different stages of the design process. Contemporary solutions and recommendations for garment design and material selection were proposed in this study. Furthermore, it contributes to garment development and design methodology by incorporating information technologies such as the Xsens motion tracking system and virtual fashion design software into the design process. These contributions have the potential to benefit manufacturers of outdoor sports clothing. Ultimately, this approach could be extended to a range of sports and activities, including multi-day hiking, trekking, polar expeditions, and search and rescue operations, thereby underscoring the broader applicability of innovations in garment technology that have emerged from this study.

Ultimately, it is hoped that this project can contribute to the production of clothing that will enable people to engage in outdoor activities, particularly rock-climbing, safely and in comfort. There will always be people for whom the dangers and discomfort are part of the appeal and who will take a minimalist approach that suits their needs. However, other climbers are likely to prefer to wear a single garment which keeps them protected from the elements and at an optimal temperature without having to worry about carrying additional gear or engaging in the dangerous operation of changing clothing at heights and disconnecting from safety ropes while doing so. Garments like these would allow them to focus on climbing, and enjoying their chosen activity without worrying about personal comfort. If such products could be produced at an appropriate price level, it is likely that they would find a wide market.

REFERENCES

ACCT. Association for Challenge Course Technology. (n.d.). *ANSI/ACCT Standards | Current Edition*. Retrieved January 21, 2024, from https://www.acctinfo.org/products/ansi-acct-03-2019-print-member-en

Adafruit. (n.d.). *DHT11, DHT22 and AM2302 Sensors. Overview*. Retrieved April 29, 2024, from https://learn.adafruit.com/dht/overview#

Adkisson, H. (2022, May 19). *The Art of the Conceptual Prototype*. https://blinkux.com/ideas/art-conceptual-prototype

Afanas'eva, R. F., Burmistrova, O. V., & Burmistrov, V. M. (2006). *Hygienic Requirements for Thermal Insulation Personal protection Kit from cold in different climatic regions and Methods for its assessment. Methodical recommendations.* (MP 2.2.8.2127-06). https://files.stroyinf.ru/Data2/1/4293847/4293847831.htm

Ainslie, P. N. (2003). Physiology of accidental hypothermia in the mountains: a forgotten story. *British Journal of Sports Medicine*, *37*(6), 548–550. https://doi.org/10.1136/bjsm.37.6.548

Ali, A. E., Jeoti, V., & Stojanović, G. M. (2021). Fabric based printed-distributed battery for wearable e-textiles: a review. *Science and Technology of Advanced Materials*, *22*(1), 772–793. https://doi.org/10.1080/14686996.2021.1962203

Anderson, M., & Price, D. (1991). *Hypothermia* (2nd ed.). New Zealand Mountain Safety Council Inc. https://issuu.com/nzmountainsafetycouncil/docs/hypothermia_manual_24_watermark

Aosong Electronics Co., L. (n.d.). *Digital-output relative humidity & temperature sensor/module DHT22 (DHT22 also named as AM2302)*. Retrieved April 29, 2024, from https://www.sparkfun.com/datasheets/Sensors/Temperature/DHT22.pdf

Arbab, A. A., Memon, A. A., Sun, K. C., Choi, J. Y., Mengal, N., Sahito, I. A., & Jeong, S. H. (2019). Fabrication of conductive and printable nano carbon ink for wearable electronic and heating fabrics. *Journal of Colloid and Interface Science*, *539*, 95–106. https://doi.org/10.1016/j.jcis.2018.12.050

Armadillo. (n.d.). *Why Armadillo Merino®?* Retrieved March 1, 2024, from https://armadillomerino.com

Asadi, M. (2022). *Graphene : a vision to the future of smart E-Textile application* [University of Borås]. https://urn.kb.se/resolve?urn=urn:nbn:se:hb:diva-27721

Ascentionism. (n.d.). *Is Ice Climbing Dangerous? Main Hazards and How to Stay Safe*. Ascentionism. Retrieved September 15, 2023, from https://ascentionism.com/is-ice-climbing-dangerous-main-hazards-and-how-to-stay-safe/

AS/NZS. (2020). *Personal Equipment for Work at Height, Part 1: Manufacturing requirements for full body combination and lower body harnesses* (AS/NZS 1891.1:2020). https://www.standards.govt.nz/shop/asnzs-1891-12020

Aspiring Safety. (n.d.). *Climbing harness standards*. Retrieved January 22, 2024, from https://www.aspiring.co.nz/harness-ppe-standards/

Axelrod, Y. K., & Diringer, M. N. (2008). Temperature Management in Acute Neurologic Disorders. *Neurologic Clinics*, *26*(2), 585–603. https://doi.org/10.1016/j.ncl.2008.02.005

Bahadir, S. K., & Sahin, U. K. (2018). A Wearable Heating System with a Controllable e-Textile-Based Thermal Panel. In *Wearable Technologies*. InTech. https://doi.org/10.5772/intechopen.76192

Baukh, O. (2023, January 12). *Ultimate Guide to Product Development in Fashion*. https://techpacker.com/blog/design/the-ultimate-guide-to-product-development-in-fashion/

Becker, K. (2018, December 28). *The best heated jackets*. https://www.digitaltrends.com/outdoors/best-heated-jackets/

Better health channel. (n.d.). *Hypothermia*. Retrieved January 15, 2024, from https://www.betterhealth.vic.gov.au/health/healthyliving/hypothermia

Bishop, P. A., Balilonis, G., Davis, J. K., & Zhang, Y. (2013). Ergonomics and Comfort in Protective and Sport Clothing: A Brief Review. *Journal of Ergonomics*. https://www.longdom.org/open-access/ergonomics-and-comfort-in-protective-and-sport-clothing-a-brief-review-20706.html

Blessthisstuff. (n.d.). *Life Tech Jacket/by Kolon Sport*. Retrieved February 12, 2024, from https://www.blessthisstuff.com/stuff/wear/coats-jackets/life-tech-jacket-by-kolon-sport/

Boorady, L. M. (2011). Functional clothing— Principles of fit. Indian Journal of Fibre & Textile Research , 36, 344–347.

Borges, L. M., Rente, A., Velez, F. J., Salvado, L. R., Lebres, A. S., Oliveira, J. M., Araujo, P., & Ferro, J. (2008). Overview of progress in Smart-Clothing project for health monitoring and sport applications. *2008 First International Symposium on Applied Sciences on Biomedical and Communication Technologies*, 1–6. https://doi.org/10.1109/ISABEL.2008.4712605

Borthwick, M., Tomitsch, M., & Gaughwin, M. (2022). From human-centred to life-centred design: Considering environmental and ethical concerns in the design of interactive products. *Journal of Responsible Technology*, *10*, 100032. https://doi.org/10.1016/j.jrt.2022.100032

Brauner, P., van Heek, J., Schaar, A. K., Ziefle, M., Hamdan, N. A., Ossmann, L., Heller, F., Borchers, J., Scheulen, K., Gries, T., Kraft, H., Fromm, H., Franke, M., Wentz, C., Wagner, M., Dicke, M., Möllering, C., & Adenau, F. (2017). *Towards Accepted Smart Interactive Textiles* (pp. 279–298). https://doi.org/10.1007/978-3-319-58481-2_22

Bright, C. M. (2014). *A History of Rock Climbing Gear Technology and Standards.* http://scholarworks.uark.edu/meeguht/41

Brink, I. U., Kornev, N. V., Ostankov, N. M., Sirotkin, A. U., Sten'kina, M. P., & Cherunova, I. V. (2019). *Jacket with automated system of thermoregulation.* (Patent 194096 U1). BVN Engineering. https://elibrary.ru/item.asp?id=41460195

Brown, D. J. A., Brugger, H., Boyd, J., & Paal, P. (2012). Accidental Hypothermia. *New England Journal of Medicine*, *367*(20), 1930–1938. https://doi.org/10.1056/NEJMra1114208

BSI. (2014). *Semiconductor devices. Micro-electromechanical devices - Electromechanical tensile test method for conductive thin films on flexible substrates* (BS EN 62047-22:2014). https://www.standards.govt.nz/shop/bs-en-62047-222014

Buckingham, L. (2008, July 19). *Climbing vs bouldering*. The Guardian. https://www.theguardian.com/lifeandstyle/2008/jul/19/healthandwellbeing

Budde, R., Kautz, K., Kuhlenkamp, K., & Züllighoven, H. (1990). What is prototyping? *Information Technology & People*, *6*(2/3), 89–95. https://doi.org/10.1108/EUM0000000003546

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., & Wood, K. (2017). Design prototyping methods: state of the art in strategies, techniques, and guidelines. *Design Science*, *3*, e13. https://doi.org/10.1017/dsj.2017.10

Camotrek. (2020, April 7). *All about waterproof breathable fabrics.* https://camotrek.com/blogs/news/waterproof-breathable-fabrics/

Campbell, S., Greenwood, M., Prior, S., Shearer, T., Walkem, K., Young, S., Bywaters, D., & Walker, K. (2020). Purposive sampling: complex or simple? Research case examples. *Journal of Research in Nursing*, *25*(8), 652–661. https://doi.org/10.1177/1744987120927206

CEN. (2012). *Mountaineering equipment - Helmets for mountaineers - Safety requirements and test methods* (BS EN 12492:2012). https://www.standards.govt.nz/shop/bs-en-124922012

CEN. (2019). *Mountaineering equipment - Harnesses - Safety requirements and test methods* (EN 12277:2016+A1:2019). https://standards.iteh.ai/catalog/standards/sist/de34d3c4-f713-463f-a8c0-9d0547e2022d/sist-en-12277-2016a1-2019

Chammas, A., Quaresma, M., & Mont'Alvão, C. (2015). A Closer Look on the User Centred Design. *Procedia Manufacturing*, *3*, 5397–5404. https://doi.org/10.1016/j.promfg.2015.07.656

Chapman, J. (2022, October 28). *Want to Get Better at Trad Climbing? Go Aid Climbing*. Climbing. https://www.climbing.com/skills/get-better-at-trad-climbing-go-aid-climbing/

Chapman, R. A. (Ed.). (2013). *Smart Textiles for Protection*. Woodhead Publishing.

Chen, C., & Huang, Y. (2015). *Electrically-Heated Clothing/Pants with Controller* (Patent 20150312965A1). Phihong Technology Co Ltd. https://www.patentguru.com/US2015312965A1

Cherrington, M., Airehrour, D., Lu, J., Xu, Q., Cameron-Brown, D., & Dunn, I. (2020). Features of Human-Centred Algorithm Design. *2020 30th International Telecommunication Networks and Applications Conference (ITNAC)*, 1–6. https://doi.org/10.1109/ITNAC50341.2020.9315169

Choi, B. C. K., & Pak, A. W. P. (2006). Multidisciplinarity, interdisciplinarity and transdisciplinarity in health research, services, education and policy: 1. Definitions, objectives, and evidence of effectiveness. *Clinical and Investigative Medicine. Medecine Clinique et Experimentale*, *29*(6), 35–64.

Ciesielska, M., Boström, K. W., & Öhlander, M. (2018). Observation Methods. In *Qualitative Methodologies in Organization Studies* (pp. 33–52). Springer International Publishing. https://doi.org/10.1007/978-3-319-65442-3_2

Cloud, R., Cao, W., & Song, G. (2013). Functional finishes to improve the comfort and protection of apparel. *Advances in the Dyeing and Finishing of Technical Textiles.*, 258–279.

Coalter, F., Dimeo, P., Morrow, S., & Taylor, J. (2010). The benefits of mountaineering and mountaineering related activities: A review of literature. *A Report to the Mountaineering Council of Scotland*. https://dspace.stir.ac.uk/bitstream/1893/12273/1/Dimeo_2010_The_Benefits_of_Mountaineering.pdf

Coppolillo, R., & Chauvin, M. (2022, April 4). *A Simple Way To Limit Tangles And Chaos In A Party Of Three*. https://www.climbing.com/skills/trad-climbing-skills-rope-management-three-party/?scope=anon

Cork, C., Dias, T., Acti, T., Ratnayaka, A., Mbise, E., Anastasopoulos, I., & Piper, A. (2013, September 5). The next generation of electronic textiles. *The 1st International Conference on Digital Technologies for the Textile Industries*. https://www.academia.edu/6750189/The_next_generation_of_electronic_textiles

Coulter, J., Magee, J., & Nugent, C. (2022). E-Textiles: A Soft Touch Barometer for Female Students to Self-Manage Their Stress. *Journal of Textile Design Research and Practice*, *10*(3), 243–273. https://doi.org/10.1080/20511787.2022.2128033

Cruickshank, L., & Trivedi, N. (2017). Beyond Human-Centred Design: Supporting a New Materiality in the Internet of Things, or How to Design When a Toaster is One of Your Users. *The Design Journal*, *20*(5), 561–576. https://doi.org/10.1080/14606925.2017.1349381

Dallas semiconductor. (n.d.). *DS18B20. Programmable Resolution 1-Wire® Digital Thermometer*. Retrieved April 29, 2024, from http://cdn.sparkfun.com/datasheets/Sensors/Temp/DS18B20.pdf

Das, A., & Alagirusamy, R. (2010). *Science in Clothing Comfort*. Woodhead Publishing India.

de Mulatier, S., Nasreldin, M., Delattre, R., Ramuz, M., & Djenizian, T. (2018). Electronic Circuits Integration in Textiles for Data Processing in Wearable Technologies. *Advanced Materials Technologies*, *3*(10). https://doi.org/10.1002/admt.201700320

Dell', R. A., Afanas'eva, R. F., & Chubarova, Z. S. (1991). *Hygienic of clothing: textbook for universities* (2nd ed.). Legprombitizdat.

Di Domenico, I., Hoffmann, S. M., & Collins, P. K. (2022). The Role of Sports Clothing in Thermoregulation, Comfort, and Performance During Exercise in the Heat: A Narrative Review. *Sports Medicine - Open*, *8*(1), 58. https://doi.org/10.1186/s40798-022-00449-4

DiAngelis, S. (n.d.). *Learn: Styles of Rock Climbing*. Retrieved September 15, 2023, from https://mojagear.com/styles-of-rock-climbing-beginners/

Dieffenderfer, J. P., Beppler, E., Novak, T., Whitmire, E., Jayakumar, R., Randall, C., Weiguo Qu, Rajagopalan, R., & Bozkurt, A. (2014). Solar powered wrist worn acquisition system for continuous photoplethysmogram monitoring. *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 3142–3145. https://doi.org/10.1109/EMBC.2014.6944289

Donahue, T., & Luebben, C. (Eds.). (2014). *Rock Climbing. Mastering Basic Skills* (2nd ed.). Mountaineers Books.

Dulal, M., Afroj, S., Ahn, J., Cho, Y., Carr, C., Kim, I.-D., & Karim, N. (2022). Toward Sustainable Wearable Electronic Textiles. *ACS Nano*, *16*(12), 19755–19788. https://doi.org/10.1021/acsnano.2c07723

eBioMedicine. (2023). Forever chemicals: the persistent effects of perfluoroalkyl and polyfluoroalkyl substances on human health. *EBioMedicine*, *95*, 104806. https://doi.org/10.1016/j.ebiom.2023.104806

Eppinger, E., Slomkowski, A., Behrendt, T., Rotzler, S., & Marwede, M. (2023). Design for Recycling of E-Textiles: Current Issues of Recycling of Products Combining Electronics and Textiles and Implications for a Circular Design Approach. In *Recycling Strategy and Challenges*

Associated with Waste Management Towards Sustaining the World. IntechOpen. https://doi.org/10.5772/intechopen.107527

Ermakova, I. A. (2006). *The hygienic of garment*. Vladivostok State University of Economics and Service.

Escalade Rock Climbing Gym. (n.d.). *Climbing 101*. Retrieved August 14, 2024, from https://www.escaladegym.com/climbing-101-1

Eshenaur Spolarich, A. (2023). Sampling Methods: A guide for researchers. *Journal of Dental Hygiene*, *97*(4), 73–77.

Etikan, I. (2017). Sampling and Sampling Methods. *Biometrics & Biostatistics International Journal*, *5*(6). https://doi.org/10.15406/bbij.2017.05.00149

European Standard. (2014). Bio-based products. Vocabulary (BS EN 16575:2014). In *BSI Standards Limited 2014*.

Ezzy, A. C., Hagstrom, A. D., Shorter, K. A., & Gray, A. J. (2018). Anthropometric, strength, climbing and training characteristics that predict outdoor rock climbing performance. *Journal of Australian Strength & Conditioning.*, *26*(4), 7–15.

Fang, S., Wang, R., Ni, H., Liu, H., & Liu, L. (2022). A review of flexible electric heating element and electric heating garments. *Journal of Industrial Textiles*, *51*(1_suppl), 101S-136S. https://doi.org/10.1177/1528083720968278

Ferraro, V., & Ugur, S. (2011). Designing wearable technologies through a user centered approach. *Proceedings of the 2011 Conference on Designing Pleasurable Products and Interfaces*, 1–8. https://doi.org/10.1145/2347504.2347510

Franz, R., Rotzer, S., Rai, P., & Koncar, V. (2022, March 29). *New IPC Standards Help Engineers Weave Through the World of E-Textiles*. Electronic Design. https://www.electronicdesign.com/markets/automation/article/21236759/new-ipc-standards-help-engineers-weave-through-the-world-of-e-textiles

FS Technology. (n.d.). *A Comprehensive Guide to Potting PCB Boards*. Retrieved August 27, 2024, from https://www.fs-pcba.com/a-comprehensive-guide-to-potting-pcb-boards/

Gamma Jacket. (2023, March 15). *GAMMA: All-Season 100% Graphene Infused Heated Jacket*. https://www.kickstarter.com/projects/weargraphene/gamma-all-season-graphene-infused-heated-jacket

Gamma Jacket: Wear Graphene. (n.d.). *The Ultimate Utility Jacket for the Modern Adventurer*. Retrieved February 3, 2024, from https://weargraphene.com/

Gao, J., Shang, K., Ding, Y., & Wen, Z. (2021). Material and configuration design strategies towards flexible and wearable power supply devices: a review. *Journal of Materials Chemistry A*, *9*(14), 8950–8965. https://doi.org/10.1039/D0TA11260G

Ginszt, M., Saito, M., Zięba, E., Majcher, P., & Kikuchi, N. (2023). Body Composition, Anthropometric Parameters, and Strength-Endurance Characteristics of Sport Climbers: A Systematic Review. *Journal of Strength and Conditioning Research*, *37*(6), 1339–1348. https://doi.org/10.1519/JSC.0000000000004464

Girling, R., & Palaveeva, E. (2017, March 11). *Beyond The Cult Of Human-Centered Design.* Fast Company. https://www.fastcompany.com/90149212/beyond-the-cult-of-human-centered-design

GOBI Heat. (n.d.). *Shift Mens Heated Snowboard Jacket*. Retrieved February 5, 2024, from https://gobiheat.com/products/shift-mens-5-zone-heated-snowboard-jacket

Gonçalves, C., Ferreira da Silva, A., Gomes, J., & Simoes, R. (2018). Wearable E-Textile Technologies: A Review on Sensors, Actuators and Control Elements. *Inventions*, *3*(1), 14. https://doi.org/10.3390/inventions3010014

Gupta, D. (2011). Design and engineering of functional clothing. *Indian Journal of Fibre & Textile Research*, *36*, 327–335.

Hamish, M. (2017, October 18). *WHY ARMADILLO MERINO®.* https://blog.armadillomerino.com/blog/armatech-101-why-armadillo-merino

Henkel, R. (2023). *ISPO Award Winner 2023: GOREWEAR Concurve GORE-TEX Jacket. Responsible Performance Three-Layer Jacket With Kinetic Garment Design*. https://www-ispo-com.cdn.ampproject.org/c/s/www.ispo.com/en/promotion/ispo-award-winner-gorewear-concurve-gore-tex-jacket?amp

HexArmor. (2022, June 6). *Climbing-style safety helmet standards you need to know*. https://www.hexarmor.com/posts/climbing-style-safety-helmet-standards-you-need-to-know

Hitti, N. (2018, February 28). *Self-heating smart jacket responds to changes in temperature*. https://www.dezeen.com/2018/02/28/ministry-of-supply-self-heating-smart-jacket-responds-temperature-changes-technology/

Ho, C. P., Fan, J., Newton, E., & Au, R. (2011). Improving thermal comfort in apparel. In G. Song (Ed.), *Improving comfort in clothing* (1st ed., pp. 165–181). Woodhead Publishing Limited.

Horiba, Y., Tokutake, A., & Inui, S. (2020). Prediction of clothing mobility using a musculoskeletal simulator. International Journal of Clothing Science and Technology, 32(1), 132–147. https://doi-org.ezproxy.aut.ac.nz/10.1108/IJCST-03-2018-0041

Houde, S., & Hill, C. (1997). What do Prototypes Prototype? In *Handbook of Human-Computer Interaction* (pp. 367–381). Elsevier. https://doi.org/10.1016/B978-044481862-1.50082-0

Huck, J., Maganga, O., & Kim, Y. (1997). Protective overalls: evaluation of garment design and fit. *International Journal of Clothing Science and Technology*, *9*(1), 45–61. https://doi.org/10.1108/09556229710157876

IEA, I. E. A. (n.d.). *What Is Ergonomics (HFE)?* Retrieved July 24, 2023, from https://iea.cc/about/what-is-ergonomics/

Iftekhar Shuvo, I., Decaens, J., Lachapelle, D., & I. Dolez, P. (2021). Smart Textiles Testing: A Roadmap to Standardized Test Methods for Safety and Quality-Control. In *Textiles for Functional Applications*. IntechOpen. https://doi.org/10.5772/intechopen.96500

Igarashi, T. L., Fernandes, T. L., Hernandez, A. J., Keutenedjian Mady, C. E., & Albuquerque, C. (2022). Behavior of skin temperature during incremental cycling and running indoor exercises. *Heliyon*, *8*(10), e10889. https://doi.org/10.1016/j.heliyon.2022.e10889

Ilanchezhiyan, P., Zakirov, A. S., Kumar, G. M., Yuldashev, Sh. U., Cho, H. D., Kang, T. W., & Mamadalimov, A. T. (2015). Highly efficient CNT functionalized cotton fabrics for flexible/wearable heating applications. *RSC Advances*, *5*(14), 10697–10702. https://doi.org/10.1039/C4RA10667A

Imbesi, S., & Scataglini, S. (2021). A User Centered Methodology for the Design of Smart Apparel for Older Users. *Sensors*, *21*(8), 2804. https://doi.org/10.3390/s21082804

International Federation of Sport Climbing. (n.d.). *OLYMPIC GAMES TOKYO 2020*. Retrieved November 7, 2022, from https://www.ifsc-climbing.org/index.php/olympic-games

International Grade Comparison Chart. (1999). The American Alpine Journal (AAJ) . https://publications.americanalpineclub.org/articles/13201212386/International-Grade-Comparison-Chart

IPC. (2019). *Requirements for Woven and Knitted Electronic Textiles (E-Textiles) Integrated with Conductive Fibers, Conductive Yarns and/or Wires* (IPC-8921). https://shop.ipc.org/ipc-8921/ipc-8921-standard-only/Revision-0/english

Ismar, E., Kurşun Bahadir, S., Kalaoglu, F., & Koncar, V. (2020). Futuristic Clothes: Electronic Textiles and Wearable Technologies. *Global Challenges*, *4*(7). https://doi.org/10.1002/gch2.201900092

ISO. (1989). *Garment construction and anthropometric surveys - Body dimensions* (ISO 8559:1989 (en)). https://www.iso.org/obp/ui/#iso:std:iso:8559:ed-1:v1:en

ISO. (2010). *Ergonomics Of Human-System Interaction – Part 210: Human-Centred Design For Interactive Systems* (ISO 9241-210). https://www.iso.org/standard/77520.html

ISO. (2013). *Textiles — Tensile properties of fabrics — Part 1: Determination of maximum force and elongation at maximum force using the strip method* (ISO 13934-1:2013). https://www.iso.org/standard/60676.html#:~:text=ISO%2013934%2D1%3A2013%20specifies,fabrics%20using%20a%20strip%20method.

ISO. (2016). *Ergonomics principles in the design of work systems* (ISO 6385:2016). https://www.iso.org/standard/63785.html

ISO. (2017). *Basic human body measurements for technological design Part 1: Body measurement definitions and landmarks* (ISO 7250-1:2017). https://www.iso.org/standard/65246.html

Jacko, J. A. (Ed.). (2012). *The Human–Computer Interaction Handbook*. CRC Press. https://doi.org/10.1201/b11963

Jayasinghe, K., & Seram, N. (2017). THE ERGONOMIC FACTORS: A STUDY ON ACTIVE WEAR. *2nd International Conference on Apparel Textiles and Fashion Design*.

Jeong, Y., & Hong, K. (2015). Subjective Wearing Assessment and Clothing Pressure depending on the Pattern Reduction Rate of Developed Cycle Pants Using the 3D Human Scan Data. *Korean Journal of Human Ecology*, *24*(2), 255–266. https://doi.org/10.5934/kjhe.2015.24.2.255

Johnston, M., & Koo, H. (2017). Apparel design for female rock climbers: satisfactions and preferences. *International Journal of Fashion Design, Technology and Education*, *10*(3), 300–307. https://doi.org/10.1080/17543266.2016.1223755

Kamalha, E., Zeng, Y., Mwasiagi, J. I., & Kyatuheire, S. (2013). The Comfort Dimension; a Review of Perception in Clothing. *Journal of Sensory Studies*, *28*(6), 423–444. https://doi.org/10.1111/joss.12070

Kant, V. (2018). Muddling between science and engineering: an epistemic strategy for developing human factors and ergonomics as a hybrid discipline. *Theoretical Issues in Ergonomics Science*, *19*(5), 606–635. https://doi.org/10.1080/1463922X.2017.1414334

Khaluta, K. (2015). *Jacket with automated electronic internal temperature control system* (Patent 153913U1). https://patents.google.com/patent/RU153913U1/ru

Kim, H., Lee, S., & Kim, H. (2019). Electrical Heating Performance of Electro-Conductive Para-aramid Knit Manufactured by Dip-Coating in a Graphene/Waterborne Polyurethane Composite. *Scientific Reports*, *9*(1), 1511. https://doi.org/10.1038/s41598-018-37455-0

Kirby, T. (n.d.). *Rock Climbing Terms: Styles and Techniques*. American Alpine Institute. Retrieved September 15, 2023, from https://www.alpineinstitute.com/articles/expert-tips/rock-climbing-terms-styles-and-techniques/

Klepp, I. G., Laitala, K., & Wiedemann, S. (2020). Clothing Lifespans: What Should Be Measured and How. *Sustainability*, *12*(15), 6219. https://doi.org/10.3390/su12156219

Köhler, A. R., Hilty, L. M., & Bakker, C. (2011). Prospective Impacts of Electronic Textiles on Recycling and Disposal. *Journal of Industrial Ecology*, *15*(4), 496–511. https://doi.org/10.1111/j.1530-9290.2011.00358.x

Komolafe, A. (2016). *Reliability and interconnections for printed circuits on fabrics* [Doctoral Thesis]. University of Southampton.

Komolafe, A., Zaghari, B., Torah, R., Weddell, A. S., Khanbareh, H., Tsikriteas, Z. M., Vousden, M., Wagih, M., Jurado, U. T., Shi, J., Yong, S., Arumugam, S., Li, Y., Yang, K., Savelli, G., White, N. M., & Beeby, S. (2021). E-Textile Technology Review–From Materials to Application. *IEEE Access*, *9*, 97152–97179. https://doi.org/10.1109/ACCESS.2021.3094303

Korotkova, I. V. (2012). *Hygiene of clothing. Lecture notes.* (pp. 1–43). MSUTU named after K.G. Razumovsky.

Krug, D. (2023, January 29). *The History of Rock Climbing*. Climb Denver. https://denverclimbingcompany.com/the-history-of-rock-climbing/

Kubicek, J., Fiedorova, K., Vilimek, D., Cerny, M., Penhaker, M., Janura, M., & Rosicky, J. (2022). Recent Trends, Construction, and Applications of Smart Textiles and Clothing for Monitoring of Health Activity: A Comprehensive Multidisciplinary Review. *IEEE Reviews in Biomedical Engineering*, *15*, 36–60. https://doi.org/10.1109/RBME.2020.3043623

Kubley, A., Chitranshi, M., Hou, X., & Schulz, M. (2021). Manufacturing and Characterization of Customizable Flexible Carbon Nanotube Fabrics for Smart Wearable Applications. *Textiles*, *1*(3), 534–546. https://doi.org/10.3390/textiles1030028

Kuzmichev, V., & Yan, J. (2022). The Application of Digital Twins in the Field of Fashion. In *Digital Twins: Basics and Applications* (pp. 45–57). Springer International Publishing. https://doi.org/10.1007/978-3-031-11401-4_6

LaBat, K. L., & DeLong, M. R. (1990). Body Cathexis and Satisfaction with Fit of Apparel. *Clothing and Textiles Research Journal*, *8*(2), 43–48. https://doi.org/10.1177/0887302X9000800206

Ladha, C., Hammerla, N. Y., Olivier, P., & Plötz, T. (2013). ClimbAX. *Proceedings of the 2013 ACM International Joint Conference on Pervasive and Ubiquitous Computing*, 235–244. https://doi.org/10.1145/2493432.2493492

Laitala, K., & Klepp, I. G. (2020). What Affects Garment Lifespans? International Clothing Practices Based on a Wardrobe Survey in China, Germany, Japan, the UK, and the USA. *Sustainability*, *12*(21), 9151. https://doi.org/10.3390/su12219151

Langford, N. J. (2005). Carbon Dioxide Poisoning. *Toxicological Reviews*, *24*(4), 229–235. https://doi.org/10.2165/00139709-200524040-00003

Ledbury, J. (2018). Design and product development in high-performance apparel. In *High-Performance Apparel* (pp. 175–189). Elsevier. https://doi.org/10.1016/B978-0-08-100904-8.00009-2

Lee, H., & Baek, K. (2021). Developing a smart multifunctional outdoor jacket with wearable sensing technology for user health and safety. *Multimedia Tools and Applications*, *80*(21–23), 32273–32310. https://doi.org/10.1007/s11042-021-11166-7

Lepak-Kuc, S., Podsiadły, B., Skalski, A., Janczak, D., Jakubowska, M., & Lekawa-Raus, A. (2019). Highly Conductive Carbon Nanotube-Thermoplastic Polyurethane Nanocomposite for Smart Clothing Applications and Beyond. *Nanomaterials*, *9*(9), 1287. https://doi.org/10.3390/nano9091287

LessEMF. (n.d.). *Fabric&Textiles*. Retrieved April 9, 2024, from https://lessemf.com/product/pure-copper-polyester-taffeta/

Li, R., Wang, L., Kong, D., & Yin, L. (2018). Recent progress on biodegradable materials and transient electronics. *Bioactive Materials*, *3*(3), 322–333. https://doi.org/10.1016/j.bioactmat.2017.12.001

Li, Y., Yong, S., Hillier, N., Arumugam, S., & Beeby, S. (2020). Screen Printed Flexible Water Activated Battery on Woven Cotton Textile as a Power Supply for E-Textile Applications. *IEEE Access*, *8*, 206958–206965. https://doi.org/10.1109/ACCESS.2020.3038157

Linxweiler, E., & Maude, M. (Eds.). (2017). Mountaineering. Basic Safety System. In *Mountaineering: The Freedom of the Hills* (9th ed., pp. 134–154). Mountaineers Books.

Liu, K., Wang, J., Zhu, C., & Hong, Y. (2016). Development of upper cycling clothes using 3D-to-2D flattening technology and evaluation of dynamic wear comfort from the aspect of clothing pressure. *International Journal of Clothing Science and Technology*, *28*(6), 736–749. https://doi.org/10.1108/IJCST-02-2016-0016

Liu, K., Zeng, X., Bruniaux, P., Wang, J., Kamalha, E., & Tao, X. (2017). Fit evaluation of virtual garment try-on by learning from digital pressure data. *Knowledge-Based Systems*, *133*, 174–182. https://doi.org/10.1016/j.knosys.2017.07.007

Loomia Technologies Inc. (n.d.). *Do E-Textiles Contribute to Electronic Waste?* . Retrieved January 4, 2024, from https://www.loomia.com/blog/etextiles-electronic-waste

Madhu. (2018, November 8). *Difference Between Graphene and Carbon Fiber*. https://www.differencebetween.com/difference-between-graphene-and-carbon-fiber/

Magiera, A., & Roczniok, R. (2018). The climbing preferences of advanced rock climbers. *Human Movement*, *14*(3), 254–264. https://doi.org/10.2478/humo-2013-0031

Maguire, M. (2001). Methods to support human-centred design. *International Journal of Human-Computer Studies*, *55*(4), 587–634. https://doi.org/10.1006/ijhc.2001.0503

Markee, N. L., & Pedersen, E. I. (1991). The conceptualization of comfort with regard to clothing . *Critical Linkages in Textiles and Clothing Subject Matter: Theory, Method and Practice [ITAA Special Publication #4-2]*, 81–93.

McCann, J., & Bryson, D. (2009). *Smart Clothes and Wearable Technology*.

Mcleod, S. (2023, July 31). *Likert Scale Questionnaire: Examples & Analysis*. Simply Psycology. https://www.simplypsychology.org/likert-scale.html

Meena, J. S., Choi, S. Bin, Jung, S.-B., & Kim, J.-W. (2023). Electronic textiles: New age of wearable technology for healthcare and fitness solutions. *Materials Today Bio*, *19*, 100565. https://doi.org/10.1016/j.mtbio.2023.100565

Mencarini, E., Leonardi, C., Cappelletti, A., Giovanelli, D., De Angeli, A., & Zancanaro, M. (2019). Co-designing wearable devices for sports: The case study of sport climbing. *International Journal of Human-Computer Studies*, *124*, 26–43. https://doi.org/10.1016/j.ijhcs.2018.10.005

Mermier, C. M., Janot, J. M., Parker, D. L., & Swan, J. G. (2000). Physiological and anthropometric determinants of sport climbing performance. *Br J Sports Med*, *34*, 359–366.

Michaelson, D. (2015). *Assessing functional needs of rock climbing pants (Master's thesis)* [Master's thesis]. Auburn University.

Michaelson, D., Teel, K. P., & Chattaraman, V. (2018). Assessing Rock Climbers' Functional Needs in Climbing Pants. *Clothing and Textiles Research Journal*, *36*(4), 235–250. https://doi.org/10.1177/0887302X18783580

Microchip. (n.d.). *ATMEGA32U4-AU*. Retrieved April 8, 2024, from https://www.microchipdirect.com/product/ATMEGA32U4-AU?samples=true

Microchip. (2014, March 25). *Low-Power Linear Active ThermistorTM ICs. MCP9700/9700A*. https://cdn.sparkfun.com/datasheets/E-Textiles/Lilypad/38512_SPCN.pdf

Milwaukee. (n.d.). *Heated jackets*. Retrieved February 7, 2024, from https://www.milwaukeetool.co.nz/workwear/heated-gear/heated-jackets/

Mithun, Ahamed. M., Mithun, Ahamed. M., & Yafooz, Wael. M. S. (2018). Extended User Centered Design (UCD) Process in the Aspect of Human Computer Interaction. *2018*

International Conference on Smart Computing and Electronic Enterprise (ICSCEE), 1–6. https://doi.org/10.1109/ICSCEE.2018.8538388

Mohsin, M., Rasheed, A., Farooq, A., Ashraf, M., & Shah, A. (2013). Environment friendly finishing of sulphur, vat, direct and reactive dyed cotton fabric. *Journal of Cleaner Production*, *53*, 341–347. https://doi.org/10.1016/j.jclepro.2013.04.018

Mokhlespour Esfahani, M. I., & Nussbaum, M. A. (2018). Preferred Placement and Usability of a Smart Textile System vs. Inertial Measurement Units for Activity Monitoring. *Sensors*, *18*(8), 2501. https://doi.org/10.3390/s18082501

Motlogelwa, S. (2018). Comfort and durability in high-performance clothing. In *High-Performance Apparel* (pp. 209–219). Elsevier. https://doi.org/10.1016/B978-0-08-100904-8.00012-2

Mountain Passions. (n.d.). *All About Ice-Climbing*. Retrieved September 15, 2023, from https://www.mountainpassions.com/winter/winter-activities/ice-climbing/

Mountaineers. (2003). *Mountaineering: The Freedom of the Hills* (S. M. Cox & K. Fulsaas, Eds.; 7th ed.). Mountaineers Books.

Moustakas, C. (1990). *Heuristic research : design, methodology, and applications*. SAGE Publications, Inc. https://doi.org/10.4135/9781412995641

Mouton, A. (2021). *Challenges in producing smart clothing for professional wear: a scoping review* [Master's thesis]. Satakunta University of Applied Science.

Mukhopadhyay, P. (2023). *Ergonomics in Fashion Design*. Springer Nature Singapore. https://doi.org/10.1007/978-981-19-4534-2

Naesgaard, O. P., Storholmen, T. C. B., Wiggen, O. N., & Reitan, J. (2017). A user-centred design process of new cold-protective clothing for offshore petroleum workers operating in the Barents Sea. *INDUSTRIAL HEALTH*, *55*(6), 564–574. https://doi.org/10.2486/indhealth.2017-0127

National Institute of Environmental Health Sciences. (n.d.). *Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS)*. Retrieved July 6, 2024, from https://www.niehs.nih.gov/health/topics/agents/pfc

Neves, É. P. das, Brigatto, A. C., & Paschoarelli, L. C. (2015). Fashion and Ergonomic Design: Aspects that Influence the Perception of Clothing Usability. *Procedia Manufacturing*, *3*, 6133–6139. https://doi.org/10.1016/j.promfg.2015.07.769

New Zealand Alpine Club. (n.d.). *About the Club*. Retrieved March 24, 2022, from https://alpineclub.org.nz/about-club

Nielsen, J. (1994, November 1). *How to Conduct a Heuristic Evaluation*. https://www.nngroup.com/articles/how-to-conduct-a-heuristic-evaluation/

Niinimäki, K., & Armstrong, C. (2013). From pleasure in use to preservation of meaningful memories: a closer look at the sustainability of clothing via longevity and attachment. *International Journal of Fashion Design, Technology and Education*, *6*(3), 190–199. https://doi.org/10.1080/17543266.2013.825737

NIKWAX Outdoor Innovation. (n.d.). *Fluorocarbons (PFCs)*. Retrieved July 6, 2024, from https://www.nikwax.com/en-gb/environment/fluorocarbons/#:~:text=PFCs%20are%20a%20group%20of,(of%20thousands)%20of%20PFC.

NIWA. (n.d.). *Map Alpine*. Retrieved August 7, 2024, from https://niwa.co.nz/map-alpine

Novikova, A., Joseph, F., & Cleveland, D. (2023). Rock-climbing apparel: an analysis of current clothing options and future strategies for the design of rock-climbing clothing. *International Journal of Fashion Design, Technology and Education*, 1–9. https://doi.org/10.1080/17543266.2023.2261023

NZ History. (n.d.). *Hillary and Tenzing reach summit of Everest*. New Zealand Government . Retrieved August 28, 2024, from https://nzhistory.govt.nz/edmund-hillary-and-tensing-norgay-reach-summit-of-everest#:~:text=29%20May%201953&text=A%20beekeeper%20from%20New%20Zealand,of%20the%20world's%20highest%20peak.

ORORO Heated Apparel. (n.d.). *Men's Heated Jacket in Black & Gold*. Retrieved February 5, 2024, from https://www.ororowear.com/products/ororo-sports-heated-jacket-black-gold?variant=41759098044598

Papachristou, E., & Anastassiu, H. T. (2022). Application of 3D Virtual Prototyping Technology to the Integration of Wearable Antennas into Fashion Garments. *Technologies*, *10*(3), 62. https://doi.org/10.3390/technologies10030062

Park, J., Kim, D., Choi, A. Y., & Kim, Y. T. (2018). Flexible single-strand fiber-based woven-structured triboelectric nanogenerator for self-powered electronics. *APL Materials*, *6*(10), 101106. https://doi.org/10.1063/1.5048553

Parra, M. (2018, June 04). What is Mountaineering? Equipment, Best Season, Top Spots. https://www.explore-share.com/blog/what-is-mountaineering/)

Peng, Y., & Cui, Y. (2020). Advanced Textiles for Personal Thermal Management and Energy. *Joule*, *4*(4), 724–742. https://doi.org/10.1016/j.joule.2020.02.011

Peterson, A. (2015). *Towards Recycling of Textile Fibers. Separation and Characterization of Textile Fibers and Blends* [Master'sThesis, Chalmers University of

Technology]. https://odr.chalmers.se/server/api/core/bitstreams/7be6fa02-fccf-42c9-957d-88865ccc04ec/content

Polartec®. (n.d.). *Polartec® Alpha® ACTIVE INSULATION* . Retrieved November 7, 2022, from https://www.polartec.com/fabrics/insulation/alpha

Priday, R. (2018, February 23). *The Alexa-powered Mercury jacket can heat itself and listens to your voice commands*. https://www.wired.co.uk/article/ministry-of-supply-kickstarter-mercury-jacket-self-heating

Pu, J., Ma, K., Luo, Y., Tang, S., Liu, T., Liu, J., Leung, M., Yang, J., Hui, R., Xiong, Y., & Tao, X. (2023). Textile electronics for wearable applications. *International Journal of Extreme Manufacturing*, *5*(4), 042007. https://doi.org/10.1088/2631-7990/ace66a

Putnam, C., Reiner, A., Ryou, E., Caputo, M., Cheng, J., Allen, M., & Singamaneni, R. (2016). Human-Centered Design in Practice. *Journal of Technical Writing and Communication*, *46*(4), 446–470. https://doi.org/10.1177/0047281616653491

Raji, R. K., Luo, Q., & Liu, H. (2021). Ergonomics in fashion engineering and design – Pertinent issues. *Work*, *68*(1), 87–96. https://doi.org/10.3233/WOR-203274

Rauch, S., Wallner, B., Ströhle, M., Dal Cappello, T., & Brodmann Maeder, M. (2019). Climbing Accidents—Prospective Data Analysis from the International Alpine Trauma Registry and Systematic Review of the Literature. *International Journal of Environmental Research and Public Health*, *17*(1), 203. https://doi.org/10.3390/ijerph17010203

Research and Markets. (2021, March 26). *Global Smart Clothing Markets, 2019-2020 & Forecast to 2027: Rising Trend of Smart Wearable Fabrics in Healthcare, Sports and Fitness Industries*. https://www.prnewswire.com/news-releases/global-smart-clothing-markets-2019-2020--forecast-to-2027-rising-trend-of-smart-wearable-fabrics-in-healthcare-sports-and-fitness-industries-301256827.html

Rogale, D., Firšt Rogale, S., Knezić, Ž., Jukl, N., & Majstorović, G. (2023). Measurement Methods of the Thermal Resistance of Materials Used in Clothing. *Materials*, *16*(10), 3842. https://doi.org/10.3390/ma16103842

Ruckdashel, R. R., Khadse, N., & Park, J. H. (2022). Smart E-Textiles: Overview of Components and Outlook. *Sensors*, *22*(16), 6055. https://doi.org/10.3390/s22166055

Ruckdashel, R. R., Venkataraman, D., & Park, J. H. (2021). Smart textiles: A toolkit to fashion the future. *Journal of Applied Physics*, *129*(13). https://doi.org/10.1063/5.0024006

Sadi, Md. S., Yang, M., Luo, L., Cheng, D., Cai, G., & Wang, X. (2019). Direct screen printing of single-faced conductive cotton fabrics for strain sensing, electrical heating and color changing. *Cellulose*, *26*(10), 6179–6188. https://doi.org/10.1007/s10570-019-02526-6

Safety Academy. Lab Rock. (n.d.). *On the rock face.* Safety Academy Lab Rock. Retrieved September 15, 2023, from https://www.ortovox.com/uk/safety-academy-lab-rock/chapter-3-belay-stations-and-belay-techniques

Schepers, M., Giuberti, M., & Bellusci, G. (2018). *Xsens MVN: Consistent Tracking of Human Motion Using Inertial Sensing.*

Seifert, L., Wolf, P., & Schweizer, A. (Eds.). (2017). *The science of climbing and mountaineering*. Routledge.

Senthilkumar M, Anbumani N, & Hayavadana J. (2011). Elastane fabrics – A tool for stretch applications in sports . *Indian Journal of Fibre and Textile Research*, *36*, 300–307.

Seonyoung, Y. (2024, April 21). *Revolutionizing Textile And Apparel Manufacturing Through Digitization*. Textile World. https://www.textileworld.com/textile-world/knitting-apparel/2024/04/revolutionizing-textile-and-apparel-manufacturing-through-digitization/

Shanley, L. A., Slaten, B. L., & Shanley, P. S. (1993). Military protective clothing: Implications for clothing and textiles curriculum and research. *Clothing and Textiles Research Journal*, *11*(3), 55–59. https://journals.sagepub.com/doi/pdf/10.1177/0887302X9301100308?casa_token=9a4OJjIv1doAAAAA:xr7w60amleuUHjpHbVpk_NSTkPv3UDltWupa2eO64LM2IExQ3SLE9Zs4oz0VylsK4BIvgfuj5DrP

Shathi, M. A., Chen, M., Khoso, N. A., Rahman, M. T., & Bhattacharjee, B. (2020). Graphene coated textile based highly flexible and washable sports bra for human health monitoring. *Materials & Design*, *193*, 108792. https://doi.org/10.1016/j.matdes.2020.108792

Sheel, A. W. (2004). Physiology of sport rock climbing. *British Journal of Sports Medicine*, *38*(3), 355–359. https://doi.org/10.1136/bjsm.2003.008169

Shepherd, N. (2014). *Climbing manual: The essential guide to rock climbing.* Haynes Publishing.

Shi, H. H., Pan, Y., Xu, L., Feng, X., Wang, W., Potluri, P., Hu, L., Hasan, T., & Huang, Y. Y. S. (2023). Sustainable electronic textiles towards scalable commercialization. *Nature Materials*, *22*(11), 1294–1303. https://doi.org/10.1038/s41563-023-01615-z

Shieldex. (n.d.). *Shieldex® 235/36 HCB*. Retrieved April 9, 2024, from https://www.shieldex.de/en/products/shieldex-235-36-hcb-2/

Shorrock, S. T., & Williams, C. A. (2016). Human factors and ergonomics methods in practice: three fundamental constraints. Theoretical Issues in Ergonomics Science, 17(5–6), 468–482. https://doi.org/10.1080/1463922X.2016.1155240

Smith, L. O. (2006). Alpine Climbing: Injuries and Illness. *Physical Medicine and Rehabilitation Clinics of North America*, *17*(3), 633–644. https://doi.org/10.1016/j.pmr.2006.05.003

Soleil, K. H. H. (2012). *Helmet Use Among Outdoor Recreational Rock Climbers Across Disciplines: Factors of Use and Non-use. Master's Thesis* [University of Tennessee]. https://trace.tennessee.edu/cgi/viewcontent.cgi?article=2391&context=utk_gradthes

Song, H. K., & Ashdown, S. P. (2015). Investigation of the Validity of 3-D Virtual Fitting for Pants. *Clothing and Textiles Research Journal*, *33*(4), 314–330. https://doi.org/10.1177/0887302X15592472

Song, K., Yeom, E., Seo, S.-J., Kim, K., Kim, H., Lim, J.-H., & Joon Lee, S. (2015). Journey of water in pine cones. *Scientific Reports*, *5*(1), 9963. https://doi.org/10.1038/srep09963

Sparkfun. (n.d.-a). *Heating Pad Hand Warmer Blanket*. Retrieved August 9, 2024, from https://learn.sparkfun.com/tutorials/heating-pad-hand-warmer-blanket/all

Sparkfun. (n.d.-b). *LilyPad USB Plus Hookup Guide*. Retrieved March 12, 2024, from https://learn.sparkfun.com/tutorials/lilypad-usb-plus-hookup-guide/all

Sparkfun. (n.d.-c). *Heating Pad - 5x15cm*. Retrieved September 27, 2024, from https://www.sparkfun.com/products/11289

Sports Techie. (n.d.). *Kolon Sport Life Tech Extreme Environment Smart Jacket System Designed By Seymourpowell*. Retrieved February 12, 2024, from https://sportstechie.net/kolon-sport-life-tech-extreme-environment-smart-jacket-system-designed-by-seymourpowell/

Stanton, N. A., Young, M. S., & Harvey, C. (2014). *Guide to Methodology in Ergonomics*. CRC Press. https://doi.org/10.1201/b17061

Sun, X., Houssin, R., Renaud, J., & Gardoni, M. (2018-a). A review of methodologies for integrating human factors and ergonomics in engineering design. International Journal of Production Research, 57(15–16), 4961–4976. https://doi.org/10.1080/00207543.2018.1492161

Sun, X., Houssin, R., Renaud, J., & Gardoni, M. (2018-b). Towards a human factors and ergonomics integration framework in the early product design phase: Function-Task-Behaviour. *International Journal of Production Research*, *56*(14), 4941–4953. https://doi.org/10.1080/00207543.2018.1437287

Tabor, J., Chatterjee, K., & Ghosh, T. K. (2020). Smart Textile-Based Personal Thermal Comfort Systems: Current Status and Potential Solutions. *Advanced Materials Technologies*, *5*(5). https://doi.org/10.1002/admt.201901155

Takanori. (2024, March 24). *PFC-Free & PFAS-Free: Why Sustainable Consumers are Demanding Eco-Friendly Alternatives*. Drooproof. Soranoshita Co.

https://en.droproof.com/column/the-rise-of-pfc-free-why-sustainable-consumers-are-demanding-eco-friendly-alternatives#:~:text=PFCs%2C%20commonly%20used%20in%20the,consumers%20seek%20greener%2C%20safer%20options.

Tavanaie, M. A. (2021). Engineered biodegradable melt-spun fibers. In *Engineered Polymeric Fibrous Materials* (pp. 191–232). Elsevier. https://doi.org/10.1016/B978-0-12-824381-7.00014-7

The Crag. Aotearoa/New Zealand. (n.d.). *Rock climbing*. Retrieved March 11, 2022, from https://www.thecrag.com/climbing/new-zealand

Thierbach, M. (2020). Smart personal protective equipment: intelligent protection for the future. *European Agency for Safety and Health at Work (EU-OSHA)*. https://osha.europa.eu/sites/default/files/Smart_personal_protective_equipment_intelligent_protection_of_the_future.pdf

Tian, M., Hao, Y., Qu, L., Zhu, S., Zhang, X., & Chen, S. (2019). Enhanced electrothermal efficiency of flexible graphene fabric Joule heaters with the aid of graphene oxide. *Materials Letters*, *234*, 101–104. https://doi.org/10.1016/j.matlet.2018.09.078

Tosi, F. (2020a). *Ergonomics and Design* (pp. 3–29). https://doi.org/10.1007/978-3-030-33562-5_1

Tosi, F. (2020b). *From User-Centred Design to Human-Centred Design and the User Experience* (pp. 47–59). https://doi.org/10.1007/978-3-030-33562-5_3

Townsend, R. C., Karttunen, A. J., Karppinen, M., & Mikkonen, J. (2017). The Cross-section of a Multi-disciplinary Project in View of Smart Textile Design Practice. *Journal of Textile Design Research and Practice*, *5*(2), 175–207. https://doi.org/10.1080/20511787.2018.1449076

Tseng, M.-L., Chiu, (Anthony) Shun Fung, Tan, R. R., & Siriban-Manalang, A. B. (2013). Sustainable consumption and production for Asia: sustainability through green design and practice. *Journal of Cleaner Production*, *40*, 1–5. https://doi.org/10.1016/j.jclepro.2012.07.015

TsNIIShP. (1988). *The unified methodology for constructing men's clothes of the member countries of the Council of Economic Mutual Assistance (capacious CEV)* (Vol. 3).

TsNIIShP. (2006). *Technical Standards. Outerwear of coat-suit assortment. General specifications* (GOST 25295-2003). https://internet-law.ru/gosts/gost/2745/

Tyson, A., & Loomis, M. (2006). *Climbing Self Rescue: Improvising Solutions for Serious Situations (Mountaineers Outdoor Expert)*. Mountaineers Books.

UIAA. (2018). *Helmets. Climbing and Mountaineering Equipment* (UIAA 106). https://theuiaa.org/documents/safety/Recommendations_Standard_106_BMC.pdf

UIAA. (2024). *UIAA Safety Standards*. https://www.theuiaa.org/safety/safety-standards/

Uotila, M., Mattila, H., & Hänninen, O. (2006). Methods and models for intelligent garment design. In *Intelligent textiles and clothing* (pp. 5–18).

U.S. Department of Labor. (n.d.). *Occupational Safety and Health Administration*. Retrieved September 8, 2024, from https://www.osha.gov

VDiff Climbing. (2020). *Big Wall and Aid Climbing: How to Climb the Big Stone*.

Viziteu, D.-R., & Curteza, A. (2021). Development of climbing clothes using computerized 3D clothing simulation. *Art and Design*, *2*, 9–19. https://doi.org/10.30857/2617-0272.2021.2.1

Viziteu, D.-R., Curteza, A., & Avadanei, M. (2021). Ergonomic principles to design clothing for rock climbers. *Technical-Scientific Conference of Undergraduate*, 529–532. http://repository.utm.md/bitstream/handle/5014/16469/Conf_TehStiint_UTM_StudMastDoct_2021_V_2_p529_532.pdf?sequence=1&isAllowed=y

Vredenburg, K. (1999). Increasing ease of use. *Communications of the ACM*, *42*(5), 67–71. https://doi.org/10.1145/301353.301419

Wakkary, R. (2021). *Things we could design: For more than human-centered worlds.* The MIT Press.

Wang, R., Xu, Z., Zhuang, J., Liu, Z., Peng, L., Li, Z., Liu, Y., Gao, W., & Gao, C. (2017). Highly Stretchable Graphene Fibers with Ultrafast Electrothermal Response for Low-Voltage Wearable Heaters. *Advanced Electronic Materials*, *3*(2). https://doi.org/10.1002/aelm.201600425

Watkins, S. M., & Dunne, L. E. (2015). *Functional Clothing Design: From Sportswear to Spacesuits*. Bloomsbury Publishing Inc. https://doi.org/10.5040/9781501303715

Wayatt, G. (2005). *Alpine skills.* . New Zealand Mountain Safety Council.

What is a Functional Prototype? (2023, March 2). Design 2 Market. https://www.design2market.co.uk/academy/what-is-a-functional-prototype/#:~:text=A%20functional%20prototype%20is%20the,validate%20design%20marketability%20before%20production.

Wittman, M. (n.d.). *What Is Aid Climbing? — A Beginner's Guide on How to Get Started*. Retrieved September 15, 2023, from https://mojagear.com/what-is-aid-climbing-beginner-guide-how-to-get-started/

Worksafe. (2020, October 21). *Health and safety duties for businesses that import and supply PPE*. https://www.worksafe.govt.nz/topic-and-industry/personal-protective-equipment-ppe/health-and-safety-duties-for-businesses-that-import-and-supply-ppe/

Xsens Technologies B.V. (2020). *Xsens. MVN User Manual*. https://www.movella.com/support/software-documentation

Yang, K., McErlain-Naylor, S. A., Isaia, B., Callaway, A., & Beeby, S. (2024). E-Textiles for Sports and Fitness Sensing: Current State, Challenges, and Future Opportunities. *Sensors*, *24*(4), 1058. https://doi.org/10.3390/s24041058

Zaman, S. uz, Tao, X., Cochrane, C., & Koncar, V. (2021). Smart E-Textile Systems: A Review for Healthcare Applications. *Electronics*, *11*(1), 99. https://doi.org/10.3390/electronics11010099

Zhang, X. (2021). Computational modelling of biomechanics for an artificial hip joint. In *Computational Modelling of Biomechanics and Biotribology in the Musculoskeletal System* (pp. 517–546). Elsevier. https://doi.org/10.1016/B978-0-12-819531-4.00020-1

Zhong, Y., Zhang, F., Wang, M., Gardner, C. J., Kim, G., Liu, Y., Leng, J., Jin, S., & Chen, R. (2017). Reversible Humidity Sensitive Clothing for Personal Thermoregulation. *Scientific Reports*, *7*(1), 44208. https://doi.org/10.1038/srep44208

APPENDIX A. Ethics Approval Letter

Auckland University of Technology Ethics Committee (AUTEC)

TE WĀNANGA ARONUI O TĀMAKI MAKAU RAU

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

5 July 2021

Frances Joseph
Faculty of Design and Creative Technologies

Dear Frances

Re Ethics Application: **21/171 Development of Functional/Ergonomic Rock Climbing Clothes for Different Climate Zones and Evaluation of Integration of Smart Sensing Technology**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved for three years until 5 July 2024.

Non-Standard Conditions of Approval

1. Replace the word 'concern' with the word 'consent' in the bullet point in the Consent Form seeking consent to re-contact participants.
2. Inclusion of the AUT logo on the advertisement for participants.

Non-standard conditions must be completed before commencing your study. Non-standard conditions do not need to be submitted to or reviewed by AUTEC before commencing your study.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.

AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: nzd2032@autuni.ac.nz;novikovavsues@gmail.com; Donna Cleveland; ksheerin@aut.ac.nz

Auckland University of Technology Ethics Committee (AUTEC)

Auckland University of Technology
D-88, Private Bag 92006, Auckland 1142, NZ
T: +64 9 921 9999 ext. 8316
E: ethics@aut.ac.nz
www.aut.ac.nz/researchethics

26 April 2022

Frances Joseph
Faculty of Design and Creative Technologies

Dear Frances

Re Ethics Application: **21/171 Development of Functional/Ergonomic Rock Climbing Clothes for Different Climate Zones and Evaluation of Integration of Smart Sensing Technology**

Thank you for providing evidence as requested, which satisfies the points raised by the Auckland University of Technology Ethics Committee (AUTEC).

Your ethics application has been approved in stages for three years until 26 April 2025.

Standard Conditions of Approval

1. The research is to be undertaken in accordance with the Auckland University of Technology Code of Conduct for Research and as approved by AUTEC in this application.
2. A progress report is due annually on the anniversary of the approval date, using the EA2 form.
3. A final report is due at the expiration of the approval period, or, upon completion of project, using the EA3 form.
4. Any amendments to the project must be approved by AUTEC prior to being implemented. Amendments can be requested using the EA2 form.
5. Any serious or unexpected adverse events must be reported to AUTEC Secretariat as a matter of priority.
6. Any unforeseen events that might affect continued ethical acceptability of the project should also be reported to the AUTEC Secretariat as a matter of priority.
7. It is your responsibility to ensure that the spelling and grammar of documents being provided to participants or external organisations is of a high standard and that all the dates on the documents are updated.
8. AUTEC grants ethical approval only. You are responsible for obtaining management approval for access for your research from any institution or organisation at which your research is being conducted and you need to meet all ethical, legal, public health, and locality obligations or requirements for the jurisdictions in which the research is being undertaken.

Please quote the application number and title on all future correspondence related to this project.

For any enquiries please contact ethics@aut.ac.nz. The forms mentioned above are available online through http://www.aut.ac.nz/research/researchethics

(This is a computer-generated letter for which no signature is required)

The AUTEC Secretariat
Auckland University of Technology Ethics Committee

Cc: nzd2032@autuni.ac.nz;novikovavsues@gmail.com; Donna Cleveland; kelly.sheerin@aut.ac.nz

APPENDIX B. Detailed Calculations of the Combined Thickness of the Layers of the Climbing Jacket

This appendix describes the method for calculating the combined thickness of all layers of the climbing jacket, based on the required thermal resistance of clothing taking into account a human's energy consumption and the time of their exposure to given meteorological conditions, ambient temperature, wind speed, and breathability of clothing (Afanas'eva et al., 2006; Dell' et al., 1991). The method is based on the equation of the body's heat balance, which is achieved by combining the effects of the formation of heat in the body (heat production) and its release (heat transfer).

1. **Calculating the heat deficit of the human body**

The heat deficit in the human body D, in joules per hour, is calculated by the formula:

$$D= [C \cdot P \cdot (0,7 \cdot t_m+0,3 \cdot t_k)]/24, \text{ (B1)}$$

where C is the specific heat capacity of the human body;
P is the weight of the human body, in kg;
t_m is the average weighted body temperature, in °C;
t_k is the average weighted skin temperature, in °C;
24 is the number of hours in a day.

The data for the climber used in the current study were:
C = 0.89°C
P = 80 kg
t_m = 37.2 °C
t_k = 30 °C

The resulting heat deficit for the climber is D = 103.952 joules/hour = 0.0249 Kcal/hour

2. **Calculating the radiative-convective heat loss**

The radiative-convective heat loss $Q_{p\text{-}k}$, watt, is calculated by the formula:

$$Q_{р\text{-}к} = 0,72 \cdot M + 0,03 \cdot M_o + 0,8 \cdot D/\tau - Q_{дых}, \text{ (B2)}$$

where M is the amount of heat production, in kcal/hour (Table B1);
M_o is the amount of basal metabolism, in watts (Table B2);
τ is the time spent outdoors, in hours;
$Q_{дых}$ is the heat loss due to heating of the exhaled air, in watts (Table B3).

Table B1. *The amount of human heat production for selected activities*

Activity	Human's heat production (kcal/hour)
complete calm, deep sleep	70
quiet lying in bed	70
sitting	75-80
standing	80
light physical work	120-170
moderate physical work	170-220
hard physical work	From 220
walking on a flat road at a speed of 3 km/hour	150-170

walking on a flat road at a speed of 5 km/hour	230-270
bicycle racing	790
swimming competition	870
mountaineering	670-970
reading quietly	90-100
reading aloud	105
work in a scientific laboratory	120-140

Table B2. *The amount of basal metabolism by gender and age, in watts*

Age, years	Man	Woman
3	69.9	63.4
5	65.5	61.6
8	58.3	56.3
10	54.2	51.5
12	50.9	47.2
15	48.6	42.8
20	44.7	39.9
25	43.1	39.5
30	42.3	39.7
35	41.4	39.0
40	41.3	37.9
50	39.3	37.1
60	38.5	36.4
70	37.7	35.7

Table B3. *The heat loss due to heating of the exhaled air, in watts*

Temperature, °C	+10	+5	0	-5	-10	-15	-20	-25	-30	-35
Heat loss, watts	5.8	7.2	8.6	10	11.6	14.0	15.6	16.9	18.2	19.6

Data for calculating:
M = 750 kcal/hour
M_o = 41.3 watts;
τ = 4 hours;
$Q_{дых(1)}$ = 14.0 watts (for temperature -15 °C)
$Q_{дых(2)}$ = 8.6 watts (for temperature 0°C)

$Q_{р-к\ (1)}$ = 527.244 watts (for temperature -15 °C)
$Q_{р-к\ (2)}$ = 532.644 watts (for temperature 0 °C)

3. **Calculating the heat flux density**

The density of heat flux is a measure of the amount of heat passing through a unit area per unit time. The heat flux density q, watts/m² is calculated by the formula:

$$q = Q_{p\text{-}k}/S_o, \quad (B3)$$

where S_o is the surface area of the human body, m²
Data for calculating:
S_o - the surface area of the male body with height – 180cm and weight – 80 kg in average = 1.87 m²

$q_{(1)}$ = 281.949 watts/m² (for temperature -15 °C)
$q_{(2)}$ = 284.836 watts/m² (for temperature 0 °C)

4. Calculating the thermal resistance of clothing

The thermal resistance of clothing R_{sum}, (m²·°C)/watts, is calculated by the formula:

$$R_{sum} = (t_к - t_в)/q, \quad (B\ 4)$$

Where $t_к$ - is the average weighted skin temperature, °C;
$t_в$ - air temperature, °C
Data for calculating:
$t_k = 30$ °C
$t_{в(1)} = -15$ °C
$t_{в(2)} = 0$ °C

$R_{sum(1)}$ = 0.159 (m²·°C)/watt (for temperature -15 °C)
$R_{sum(2)}$ = 0.105 (m²·°C)/watt (for temperature 0 °C)

5. The correction for wind effects on the total thermal resistance of clothing

The correction for wind to the total thermal resistance of clothing Δ, % is calculated by the formula:

$$\Delta = (0.07 \cdot A_p + 2.0) \cdot Vwind + 5.0, \quad (B5)$$

where A_p is the air permeability of the combined clothing layers, dm³/(m²·s) (Table B4).
Vwind – Wind speed, m/s

Table B4. *The air permeability of the combined clothing layers*

Wind speed, m/c	Under 2	2-4	Above 4
The air permeability of the combined clothing layers, dm³/(m²·s)	7÷60	7÷20	7÷10

Considering the significance of clothing air permeability at different wind speeds, it follows that, at wind speeds above 4 m/s, materials providing an air permeability of the combined clothing layers of 7-10 dm³/(m²·s) should be used. So, Ap = 9 dm³/(m²·s)
Vwind = 5m/s

Δ = 5.526%

6. The required thermal resistance, including the wind speed

The required thermal resistance, (m²·°C)/watts, is calculated by the formula:

$$R_{req} = (R_{sum} \cdot 100)/(100 - \Delta), \quad (B6)$$

$R_{req(1)}$ = 0.168 (m²·°C)/watts (for temperature -15 °C)
$R_{req(2)}$ = 0.111 (m²·°C)/watts (for temperature 0 °C)

7. The thickness of the combined layers of the climbing jacket

The thickness of the combined layers of the clothing δ_n, meters, is calculated by the formula

$$\delta_n = R_{req} \cdot \lambda_e, \quad (B7)$$

where λ_e is the equivalent thermal conductivity coefficient of textile materials, watts/(m²·°C).

$\lambda_e = 0.041$ watts/(m²·°C)

$\delta_{n(1)}$ = 0,0069m (for temperature -15 °C)
$\delta_{n(2)}$ = 0,0046m (for temperature 0 °C)

8. The thickness of the combined layers of the clothing for specific parts of the human body

The thickness of the layers of the clothing for different parts of the human body is calculated by the formula:

$$\delta_{n'} = K \cdot \delta n \quad (B8)$$

where K is the coefficient of insulation efficiency (see table B5).

Table B5. *The coefficient of insulation efficiency*

Parts of the human body	The coefficient of insulation efficiency, K
torso	1.26
arms and shoulders	1.13
thigh	1.15
shin	0.90
head	0.5

Table B6. *The resulting thickness of the combined layers of the clothing for specific parts of the human body, in meters*

Parts of the climber's body	Thickness of the combined layers of the jacket for temperature -15 °C	Thickness of the combined layers of the jacket for temperature 0 °C
torso	0.0087	0.0058
arms and shoulders	0.0078	0.0052
head	0.0035	0.0023

9. The thickness of the air gaps between the layers of clothing

The thickness of the air gaps $\delta_{air\ gap}$, in meters, is calculated by the formula:

$$\delta_{air\ gap} = R_{air\ gap} \cdot \lambda_{air\ gap}, \quad (B9)$$

where $R_{air\ gap}$ - thermal resistance of air gaps

$$R_{air\ gap} = (0.38 \div 0.8) \cdot R_{req}, \ (m^2 \cdot °C)/watts, \quad (B10)$$

$R_{air\ gap\ (1)}$ = 0.084 (m²·°C)/watts (for temperature -15 °C)
$R_{air\ gap\ (2)}$ = 0.055 (m²·°C)/watts (for temperature 0 °C)

$\lambda_{air\ gap}$ - coefficient of thermal conductivity of air gaps, watts/(m²·°C).
$\lambda_{air\ gap}$ = 0.023 watts/(m·°C)

$\delta_{air\ gap\ (1)}$ = 0.0019 meters (for temperature -15 °C)
$\delta_{air\ gap\ (1)}$ = 0.0013 meters (for temperature 0 °C)

10. The thickness of the combined layers of materials forming the clothing

The thickness of the all layers of materials forming the clothing δ_m, meters, is calculated by the formula

$$\delta_m = \delta_{n'} - \delta_{air\ gap} \quad (B11)$$

$\delta_{m(1)}$= 0.005 meters (for temperature -15 °C)
$\delta_{m(2)}$= 0.0033 meters (for temperature 0 °C)

Each layer of materials forming the clothing (the main fabric, lining, insulation and interfacing) has a different coefficient of thermal conductivity (λ) and thermal resistance (R). In relation to this, selection of all materials forming the clothing must meet the following requirement:

$$R_{req} = R'_{req} \quad (B12)$$

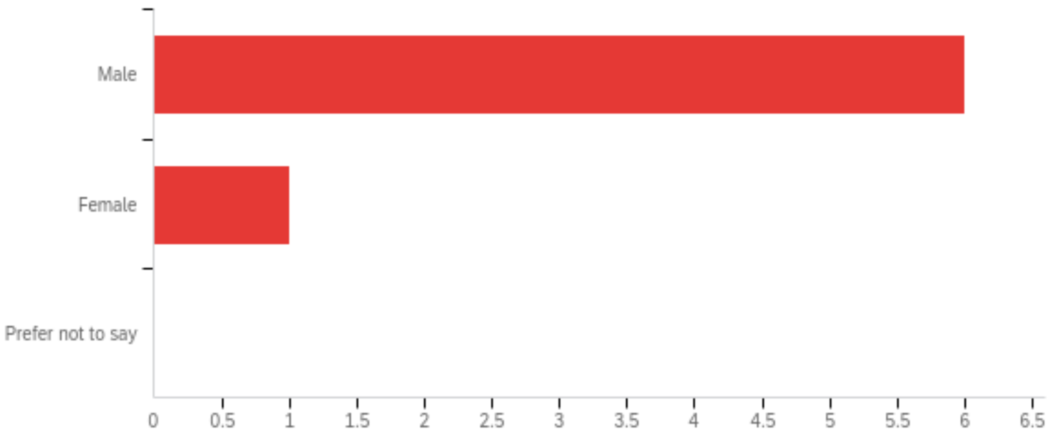
$$R'_{req} = \sum R_{i\ m} + \sum R_{i\ air\ gap} \quad (B13)$$

Where $\sum R_{i\ m}$ - thermal resistance of each layer of materials forming the clothing, ($m^2 \cdot$°C)/watts;
$\sum R_{i\ air\ gap}$ - thermal resistance of air gaps, ($m^2 \cdot$°C)/watts;

The calculated thickness of the combined layers of materials forming the jacket was verified using equation B12. For both temperature conditions of -15 °C and 0 °C, the request $R_{req} = R'_{req}$ was fulfilled, indicating an acceptable deviation and confirming that the thickness of materials forming the clothing were selected correctly, ensuring that the clothing offers the required level of thermal properties and wind resistance.

APPENDIX C. Report for a Questionnaire “Rock Climber's Clothes - Satisfaction, Preferences, Requests and Needs”

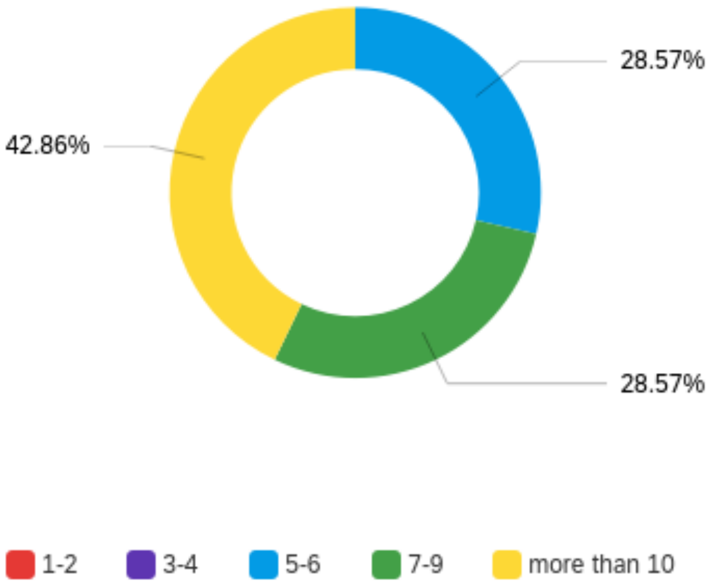
Q1 - What is your gender?



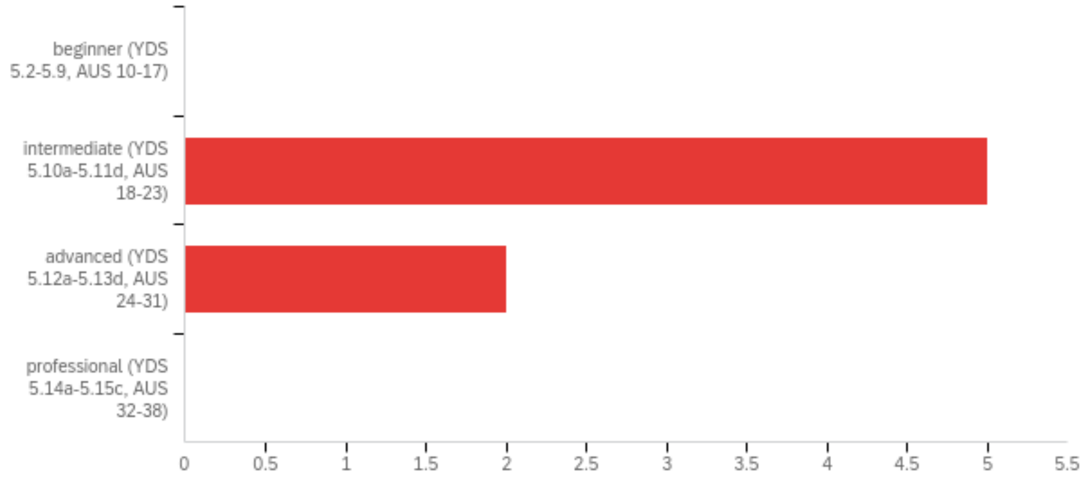
#	Answer	%	Count
1	Male	85.71%	6
2	Female	14.29%	1
3	Prefer not to say	0.00%	0
	Total	100%	7

Q3 - Haw many years have you been rock climbing?

#	Answer	%	Count
1	1-2	0.00%	0
2	3-4	0.00%	0
3	5-6	28.57%	2
4	7-9	28.57%	2
5	more than 10	42.86%	3
	Total	100%	7

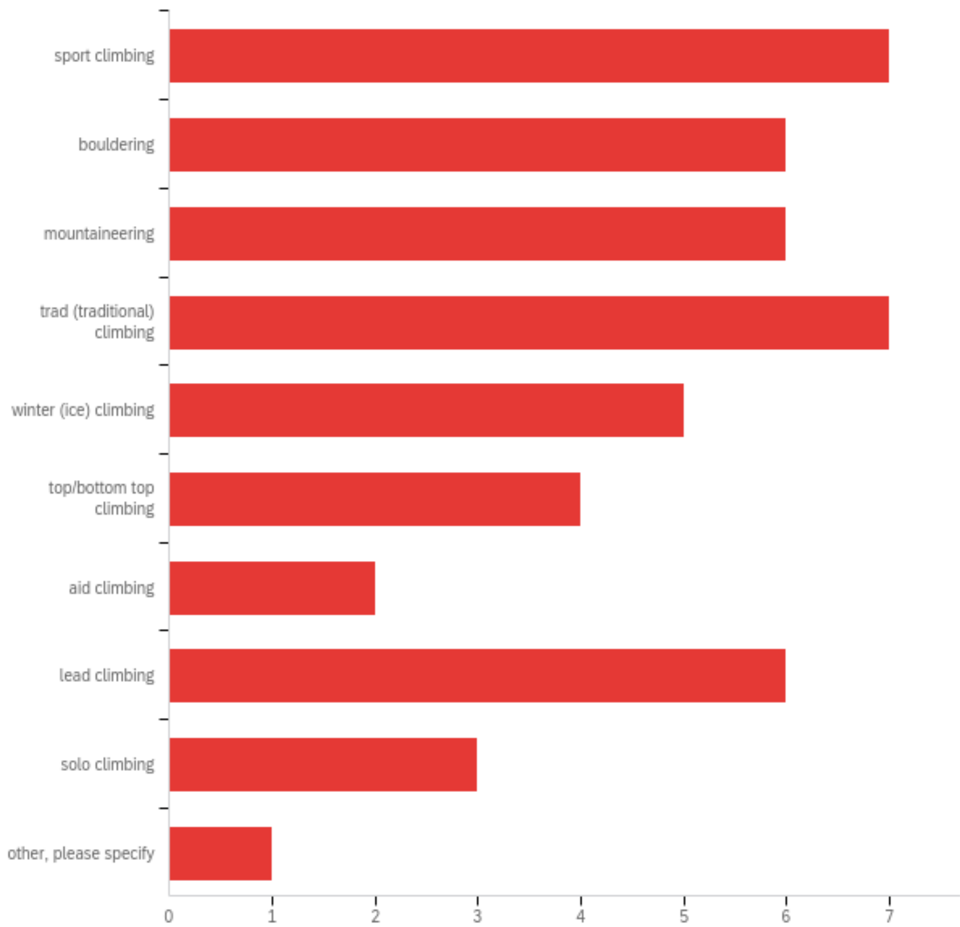


Q4 - What is your experience level in rock climbing?



#	Answer	%	Count
1	beginner (YDS 5.2-5.9, AUS 10-17)	0.00%	0
2	intermediate (YDS 5.10a-5.11d, AUS 18-23)	71.43%	5
3	advanced (YDS 5.12a-5.13d, AUS 24-31)	28.57%	2
4	professional (YDS 5.14a-5.15c, AUS 32-38)	0.00%	0
	Total	100%	7

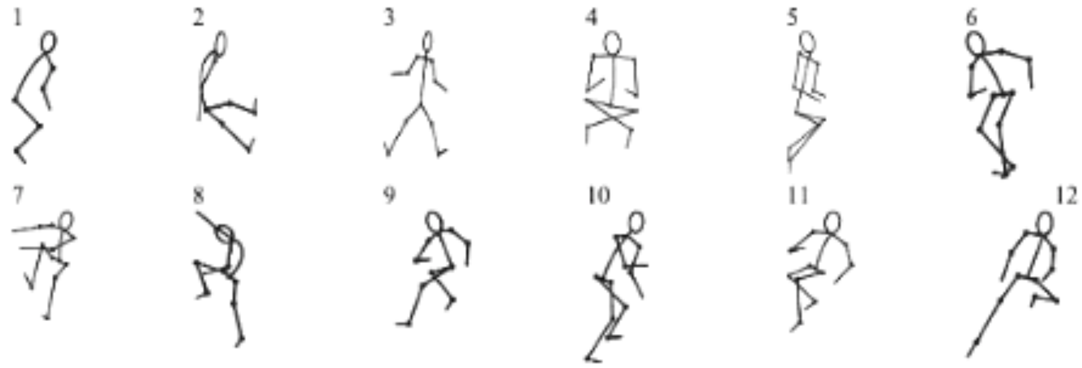
Q5 - What styles of rock climbing have you experienced? (You can choose more than one option)

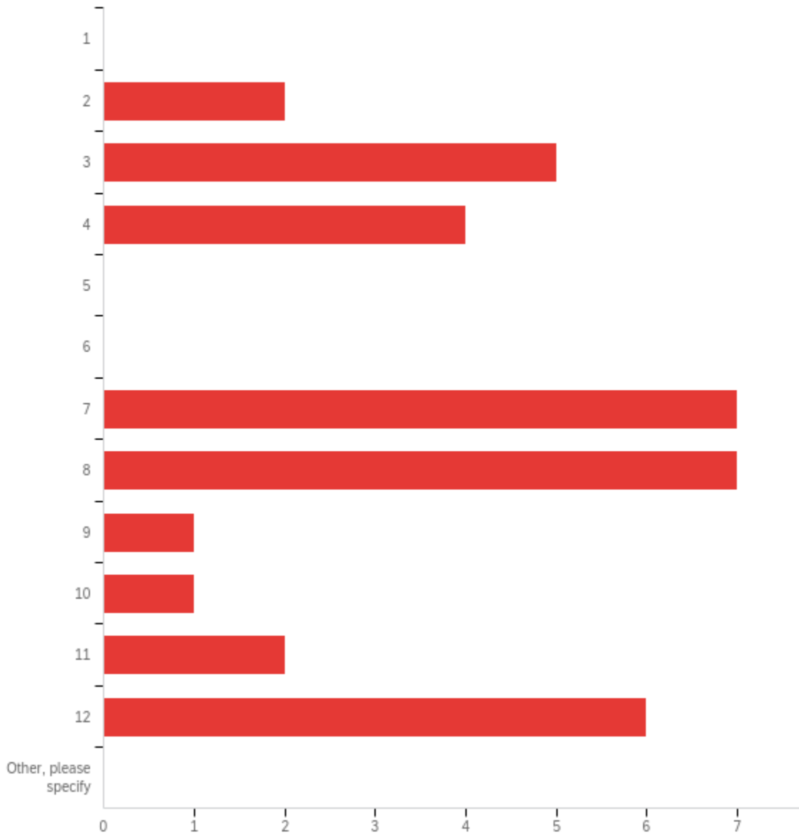


#	Answer	%	Count
1	sport climbing	14.89%	7
2	bouldering	12.77%	6
3	mountaineering	12.77%	6
4	trad (traditional) climbing	14.89%	7
5	winter (ice) climbing	10.64%	5
6	top/bottom top climbing	8.51%	4
7	aid climbing	4.26%	2
8	lead climbing	12.77%	6
9	solo climbing	6.38%	3
10	other, please specify	2.13%	1
	Total	100%	47

Q5_10_TEXT - other, please specify.
Alpine Rigging for Cinema Projects and Multi day endurance events

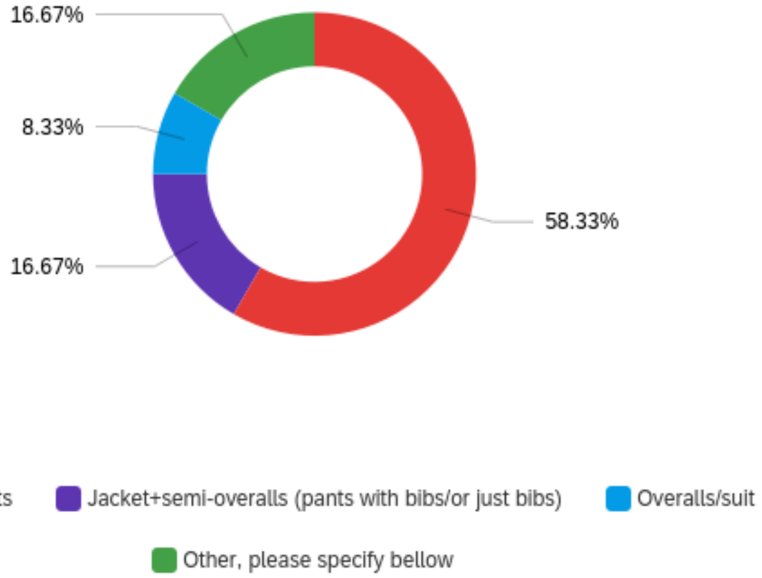
Q6 - What are the positions or movements you experience most while climbing? You can choose to rank as many poses as relevant





#	Answer	%	Count
1	1	0.00%	0
2	2	5.71%	2
3	3	14.29%	5
4	4	11.43%	4
5	5	0.00%	0
6	6	0.00%	0
7	7	20.00%	7
8	8	20.00%	7
9	9	2.86%	1
10	10	2.86%	1
11	11	5.71%	2
12	12	17.14%	6
13	Other, please specify	0.00%	0
	Total	100%	35

Q7 - What type of clothes do you prefer for outdoor climbing? (You can choose more than one option)



#	Answer	%	Count
1	jacket + pants	58.33%	7
2	Jacket+semi-overalls (pants with bibs/or just bibs)	16.67%	2
3	Overalls/suit	8.33%	1
4	Other, please specify bellow	16.67%	2
	Total	100%	12

Q7_4_TEXT - Other, please specify bellow

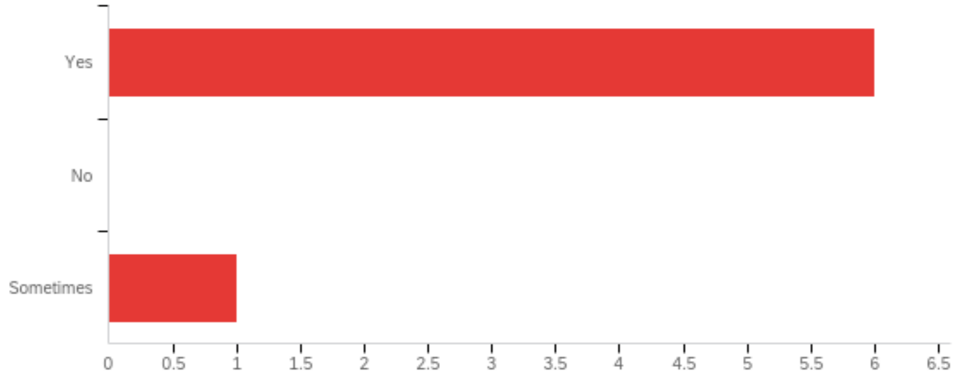
shorts

t-shirt and tights

Q8 - What brand(s) and type(s) (or style/design) of rock-climbing clothing do you prefer to wear while performing rock climbing especially trad climbing, mountaineering, or winter (ice) climbing?

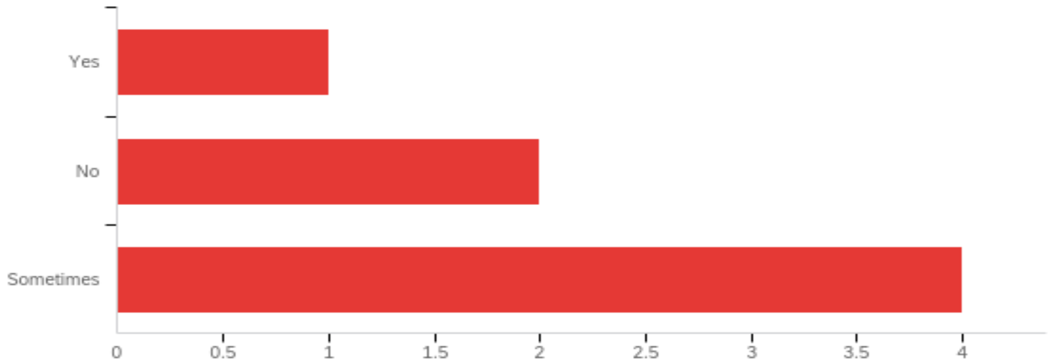
Arcteryx, Black Diamand, Patagonia, E9
sivera, black diamond
I prefer to wear heavier industrial grade clothing that is often a hybrid of professional clothing such as ski patrol pants and specific clothing pieces that suit the climb and conditions. E.G old Norse wear Black woolen singlet (good for autumn trad climbing)
arcteryx, north face, prana,
Sivera, Marmot, Kalborn
Macpac gear for mountaineering, Lycra pants and tee shirt for rock.
RAB Soft shell pants - mountain and ice, MACPAC polartec alpha - warm breathable, Black diamond Alpenglow hoody for summer trad.

Q9 - Do you wear a helmet while performing a rock climbing?



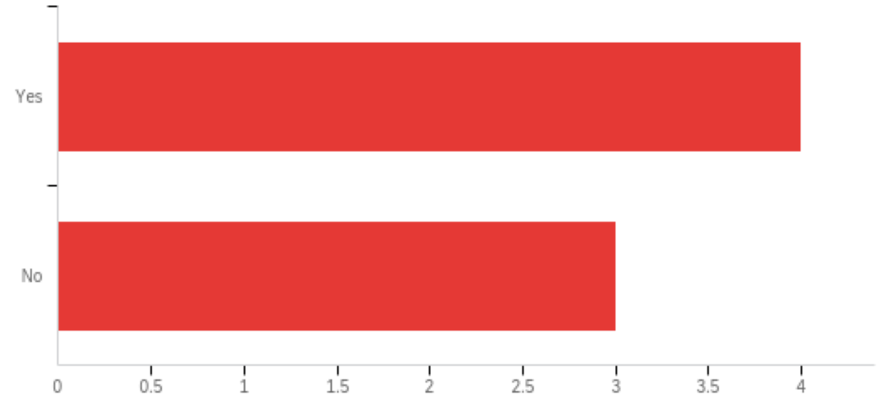
#	Answer	%	Count
1	Yes	85.71%	6
2	No	0.00%	0
3	Sometimes	14.29%	1
	Total	100%	7

Q10 - Do you wear a hat/cap while performing a rock climbing?



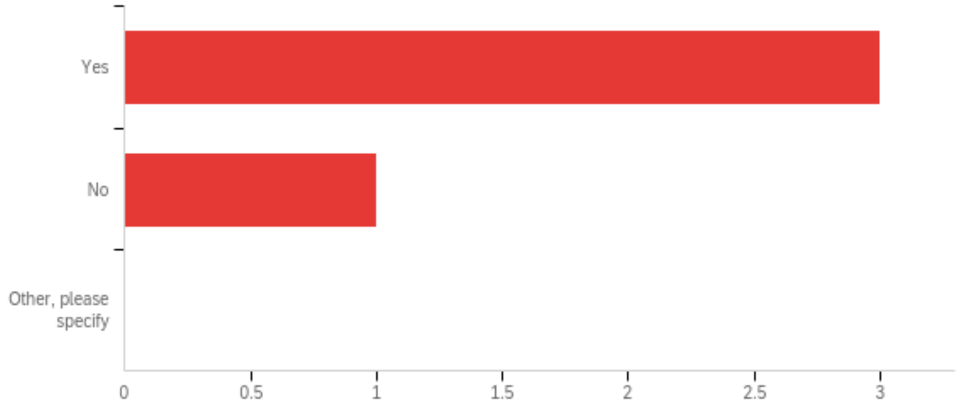
#	Answer	%	Count
1	Yes	14.29%	1
2	No	28.57%	2
3	Sometimes	57.14%	4
	Total	100%	7

Q11 - Do you wear a hood?



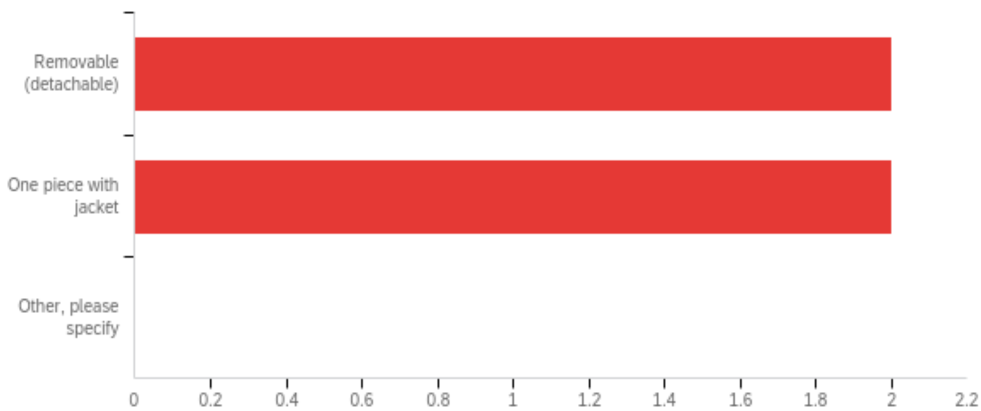
#	Answer	%	Count
1	Yes	57.14%	4
2	No	42.86%	3
	Total	100%	7

Q12 - Do you need the hood to provide additional protection to the lower part of your face, for example against the wind?



#	Answer	%	Count
1	Yes	75.00%	3
2	No	25.00%	1
3	Other, please specify	0.00%	0
	Total	100%	4

Q13 - What type of hood do you prefer?

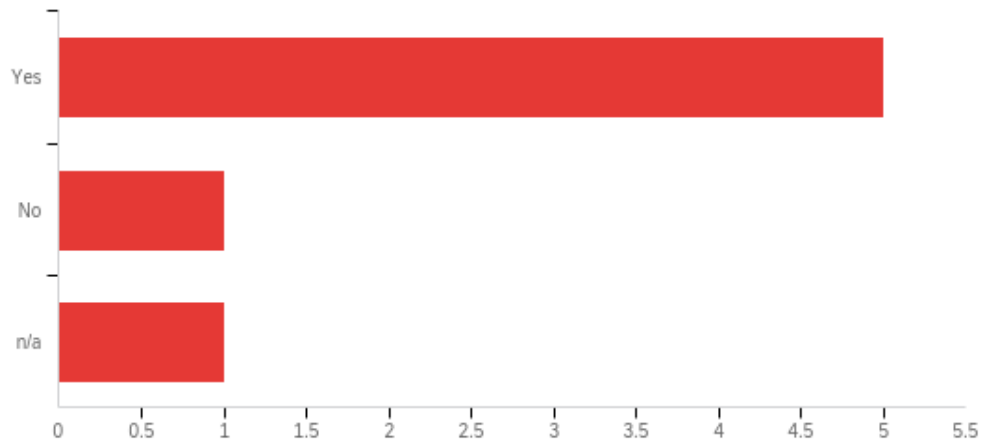


#	Answer	%	Count
1	Removable (detachable)	50.00%	2
2	One piece with jacket	50.00%	2
3	Other, please specify	0.00%	0
	Total	100%	4

Q14 - Have you had any negative experience while wearing a hood, hat, cap? Please specify

Not sure
limited visibility
I once had the hood of my jacket jam up in a belay device. I have lost several hats due to them slipping off my head. Mainly I have had user error negative experiences
Some hoods restrict hearing or seeing depending on design
hood makes it hard to see and hear
Hoods that are not adjustable or that cannot be secured back form coming over your face.

Q15 - Do you use pockets?



#	Answer	%	Count
1	Yes	71.43%	5
2	No	14.29%	1
3	n/a	14.29%	1
	Total	100%	7

Q16 - How many pockets do you need (minimum/at least)?

2, better 3 on jacket
3 on a jacket. I once owned a pair of pants that had big extendable cargo pockets on the thighs (above the knees, to the side) This was a very welcome addition to these pants. I have only had one pair of pants that had this feature, they were a pair of artic riggers pants that were made for Canadian Pole riggers in the 1990's.
handy to have the two chest pockets in jacket for alpine climbing
At least 4 pockets
At least one desent chest pocket on under garments and two chest pockets on outer layers such as soft shell or shell. One leg pocket can be ok but I do not find these very useful.

Q17 - Considering equipment, movement and any other factors, where are the best places for pockets to be positioned on clothing for climbing (and why)?

Chest outer pockets, internal breast pocket
This is a great question. Upon reflection I have always made do with what is available and never really questioned the placement of them. Some attention to this would be a significant area of research. However to answer the question I always use an internal breast pocket for things like glasses and outer pockets for everything else on jackets. I have never understood why pockets on climbing gear never adopted a cyclists approach to upper wear. i.e some pockets located behind the kidneys above the buttocks. This location would be interesting to try.
chest is good out of harness way. the pockets on side of leg on pants are also good
chest pockets are more useful. Pockets on the sleeves are good but not always convenient to use. Pockets that are in the legs should be lower than harness
two chest pockets are my ideal for storing compass or map or food etc. Lower pockets are a pain as they are almost always tucked into the harness. While they are good for general purpose, they are not useful when wearing a harness.

Q18 - Where are the worst places for pockets to be positioned on clothing for climbing (and why)?

Any pockets that are on pants usually restricted by harness
back pocket on pants is the worst as I always end up sitting on whatever is in this pocket. I am also not keen on pockets located on the arm of jackets. They are always too small and fiddley to operate.
under harness
Pockets are in the legs of pants often are blocked by a harness
Pockets that are in the legs of pants or hand pockets in paints are a pain for climbing movement as the harness will always interfere with these places. These pockets are useful for general walking in or unroped climbing but with harness are not useful.

Q19 - What type of fastener do you find more convenient for rock climbing clothes?

#	Answer	%	Count
1	Zipper	85.71%	6
2	Velcro fastener (Velcro tapes)	14.29%	1
3	Snaps/press studs	0.00%	0
4	Buttons	0.00%	0
5	Others (identify)	0.00%	0
	Total	100%	7

Q20 - Do your rock-climbing clothes caused any movement restrictions? Please identify bellow where these restrictions occur

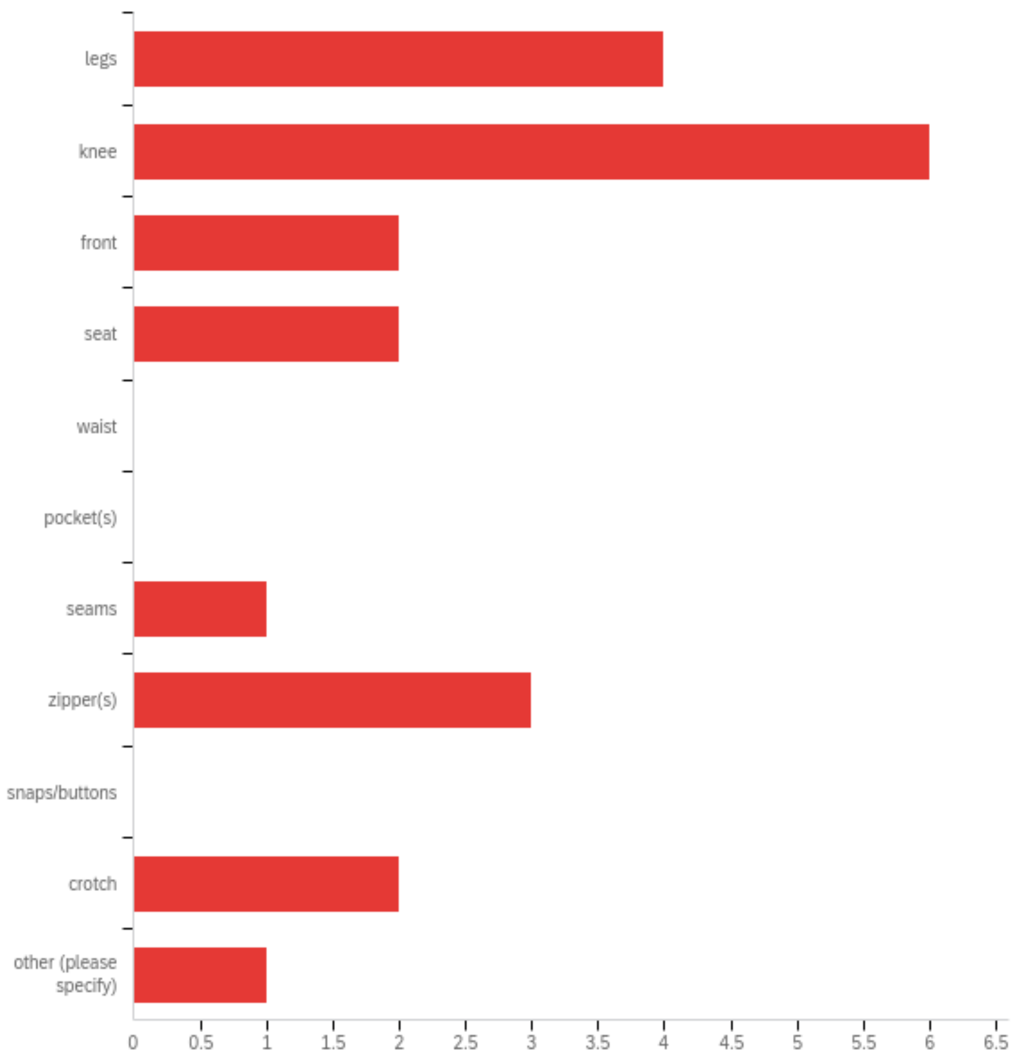
The knee area in pants sometimes causes the restriction of movement.
no
Yes rock climbing clothes cause movement restrictions. Generally I adapt to not putting my bodyline into configurations that cause the restriction. The main area of restriction in a jacket is in stretch underneath the arms. The main area of restriction in pants is around the knees which makes high stepping problematic

no
Sometimes pants were catching the feet while climbing due to excess length and fabric in pants Hip restriction while climbing in non-stretch pants. Clothes for mountaineering in a cold climate may be too bulky
no
the waist sometimes can be tight which is restrictive.

Q21 - Identify please the parts of clothes that have problems in terms of abrasion affected by an equipment, ropes, harnesses, rocks, etc.

Knees, cuffs
mostly just natural wear off, nothing in specific
Jacket abrasion is mainly around cuffs. Pants abrasion is always around buttocks and knees.
gloves if wearing from rubbing on snow.
knees
knees and elbows
Knees, wrist areas, shoulders when pack carrying

Q22 - Identify please the areas that have durability problems in the rock climbing pants you typically or most frequently wear? (You can choose more than one option)

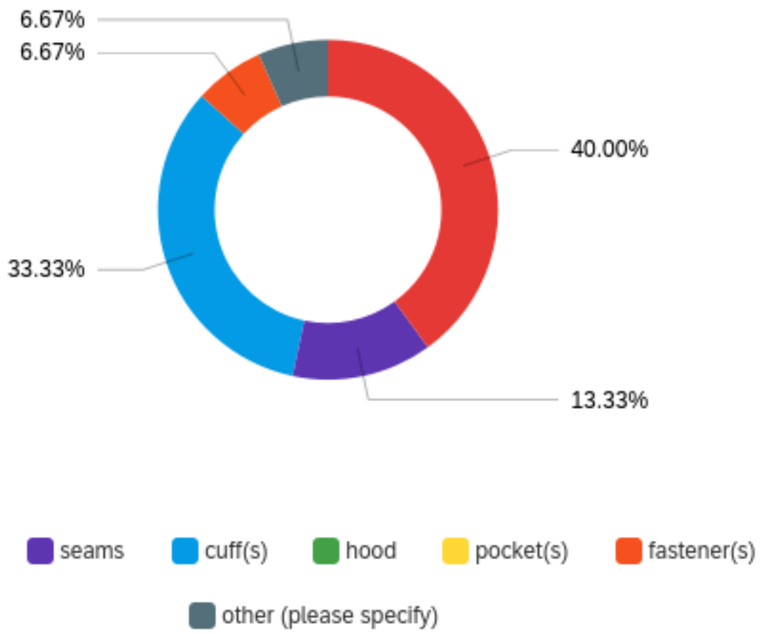


#	Answer	%	Count
1	legs	19.05%	4
2	knee	28.57%	6
3	front	9.52%	2
4	seat	9.52%	2
5	waist	0.00%	0
6	pocket(s)	0.00%	0
7	seams	4.76%	1
8	zipper(s)	14.29%	3
9	snaps/buttons	0.00%	0
10	crotch	9.52%	2
11	other (please specify)	4.76%	1
	Total	100%	21

Q22_11_TEXT - other (please specify)

hood where mouth is located.

Q23 - Identify please the areas that have durability problems in the rock-climbing jacket(s) you typically or most frequently wear?



#	Answer	%	Count
1	sleeves	40.00%	6
2	seams	13.33%	2
3	cuff(s)	33.33%	5
4	hood	0.00%	0
5	pocket(s)	0.00%	0
6	fastener(s)	6.67%	1
7	other (please specify)	6.67%	1
	Total	100%	15

Q24 - How many layers of clothing do you usually wear while rock climbing?

2-3
1-2
2 or 3
rock climbing in summer 1 -2. more in winter
In a cold climate I wear at least three layers of clothing.
1
Warm days 1 BD Alpenglow hoody, Cold days ice climbing or cold alpine rock 2-3

Q25 - Have you had a specific experience with your climbing clothes in relation to temperature (heating or cold) while rock climbing? Please describe bellow

I have been hot and wet while rock-climbing, sometimes have been cold while belaying
no
Yes. Several times after getting very wet and experiencing high winds makes for a cold experience.
not sure what this question is asking - I have been hot and cold while rock climbing
Because of different activities during climbing sometimes it could be hot when you climb and cold when having a rest or belaying
can be too warm climbing but too cold while belaying in the wind
The Polartec alpha material is fantastic at regulating your temperature, breaths really well. I very rarely wear a shell jacket anymore really only pull out the goretex if it is raining or a nasty snow storm.

Q26 - Have you had a specific experience with your climbing clothes in relation to humidity (wet) while rock climbing? Please describe bellow

In my experience, not breathable clothing got wet quickly and it was uncomfortable and heavy
when it is too hot and you don't want to be exposed to the sun would be nice to have something lighter but not less durable
Yes. Several times when climbing in the mountains when moving from a mode of belaying in the shadows to lead climbing in the sun. I have experienced my body heating up quickly because the jacket was to heavy and not breathable. This created a yucky sweat trapped inside the jacket layer situation. Generally climbing Clothing that does not repel water gets retired or thrown away.
Hopefully don't get caught out in the wet. In alpine climbing it can get wet with snow.
Clothes may get wet because of sweat withdrawal problems
no
I do not like climbing in merino clothing like a base layer I find it get wet easily and does not dry as fast as synthetics

Q27 - How do you usually regulate microclimate inside clothing layers (level of humidity or temperature) while rock climbing? Please specify

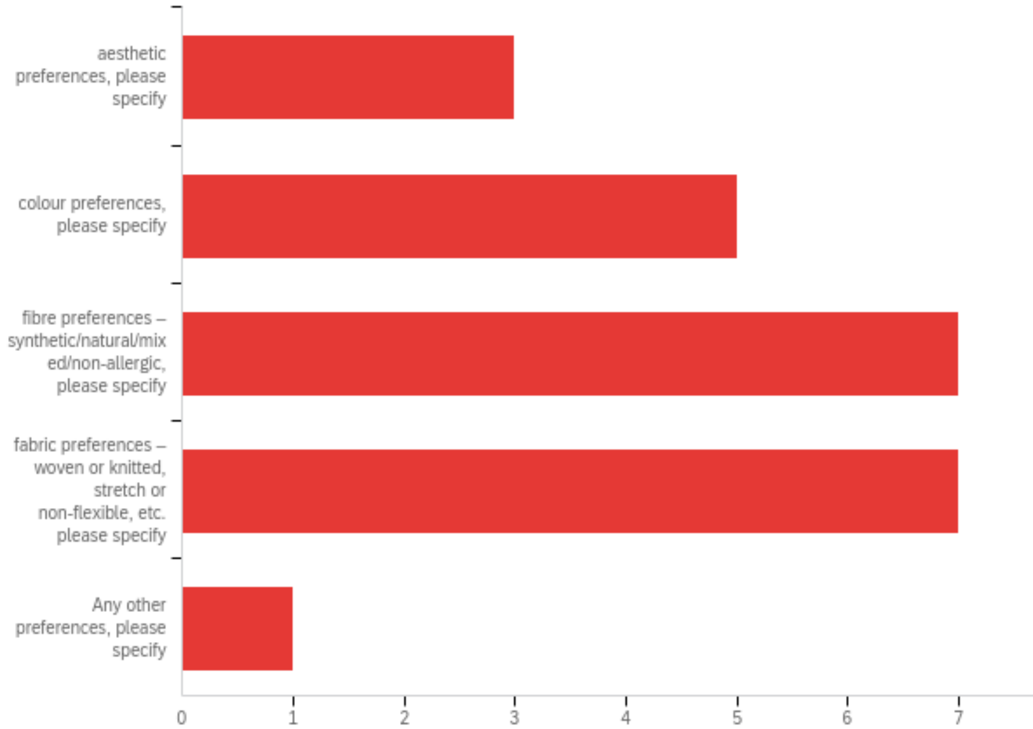
Prefer to buy clothing with zippers for venting (underarm) or can take some clothing layers off.
taking off or putting on another layer
Great question that would make a fantastic area for research. I think that there has not been much attention to how and where the body looses heat in general. I usually open up the zip on my jacket when getting hot or often I will stop and take the jacket off and stow it. I have often thought that climbing pants focus far too much on being able to zip them on and off as opposed to micro climate control. Such as Having vents around the knees which would be a useful thing. Like the jacket scenario if I get really uncomfortable I will stop and take the clothing item off and stow it.
wear multiple layers. use long sleeves for shade in summer too.
By using different clothing options, removing some layers, and opening functional zippers
open collar or use different clothing options
I like to have a multi layer approach to my clothing. Back in the day I would wear a thermal, fleece jacket and a goretex coat. Now I have 4-5 options with me that allows me to pick and choose based on the day and activity.

Q28 - Have you had any negative experiences while removing or putting on clothing while rock climbing? Please specify

It’s difficult to do it while on a climb
for climbing one pitch routes as I do, it is almost irrelevant as it is done on the ground
Yes I have had multiple negative experiences removing or putting on clothing whilst rock climbing. All of the experiences were either caused by fatigue or being in too much of a hurry to take care. Once I ripped my climbing pants in a catastrophic way on my crampons when I was putting them on. This was due to the zippers down the leg not working as expected. Definately human error but also a very cold nite.
moving around harness and pack. not dropping gear.
It’s uncomfortable in generall
you often cant adjust your clothing while on a climb, what you start with you are stuck with.
Not really other than clothing that sticks to others pulling off the other shirt or making it hard to put on as it pulls the sleeves of your under garment off. The RAB Vaporise material is really bad for this.

Q29 - Over time have you developed any preferences through your experience such as:

#	Answer	%	Count
1	aesthetic preferences, please specify	13.04%	3
2	colour preferences, please specify	21.74%	5
3	fibre preferences – synthetic/natural/mixed/non-allergic, please specify	30.43%	7
4	fabric preferences – woven or knitted, stretch or non-flexible, etc. please specify	30.43%	7
5	Any other preferences, please specify	4.35%	1
	Total	100%	23



Q29_1_TEXT - aesthetic preferences, please specify

Not loud colours
nice to look good
Bright colours are good. NZ only usually stocks brown's and blacks bright is better for safety and for photos ;)

Q29_2_TEXT - colour preferences, please specify

Bright colours
bright colors to stand out
Quiet colours that blend in to the environment.
nice to have options available. limited especially for women in NZ.
As above

Q29_3_TEXT - fibre preferences – synthetic/natural/mixed/non-allergic, please specify

Natural, mixed
prefer natural, sometimes can go for mixed
wear a mixture of synthetic and natural
Synthetic mixed with natural
synthetic fibres
Most of the time I have found synthetic to be better for movement activities. Down and wool are great when your standing still in a cold environment.

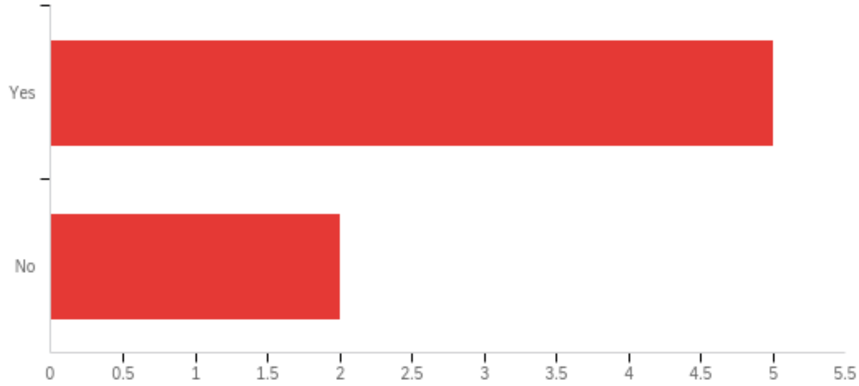
Q29_4_TEXT - fabric preferences – woven or knitted, stretch or non-flexible, etc. please specify

Stretch is better
stretch
for under garments stretchy and woolen
depends what type of climbing. good to have material that doesn't catch and is durable
stretch fabrics
stretch fabrics
Stretch is nice for undergarments.

Q29_5_TEXT - Any other preferences, please specify

Industrial grade clothing.

Q30 - Have you used any smart devices while performing rock climbing?



#	Answer	%	Count
1	Yes	71.43%	5
2	No	28.57%	2
	Total	100%	7

Q31 - Could you please specify what technological device(s) you have used and for what purpose(s)?

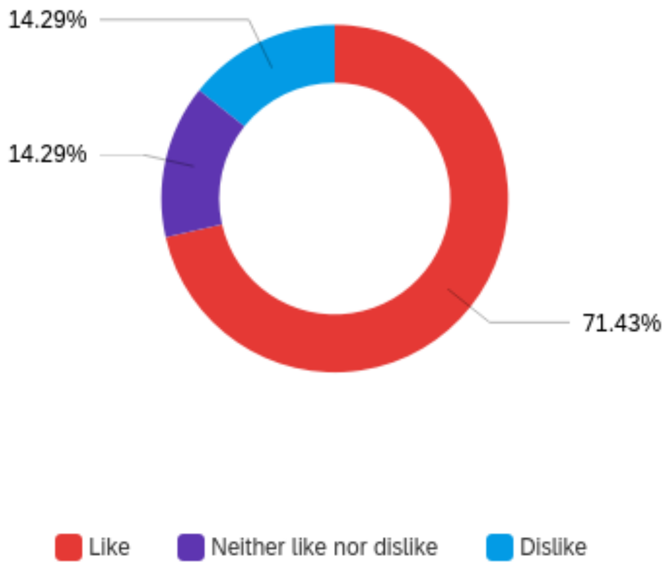
Smartphone with GPS, smartwatch
Barometer to measure height and rate of climb. Also very useful to monitor for any radical pressure drops (i.e beyond visual line of sight bad weather arriving)
Garmin watch
Phone/smart watch
Phone for looking at the route topo and GPS on the phone

Q32 - Have you used any smart clothing, while performing rock climbing?

No
No. I think this is a really import area of research that could have great value. Integrating new data sets into ones understanding of the environment, body performance and location would be great
no
No
No

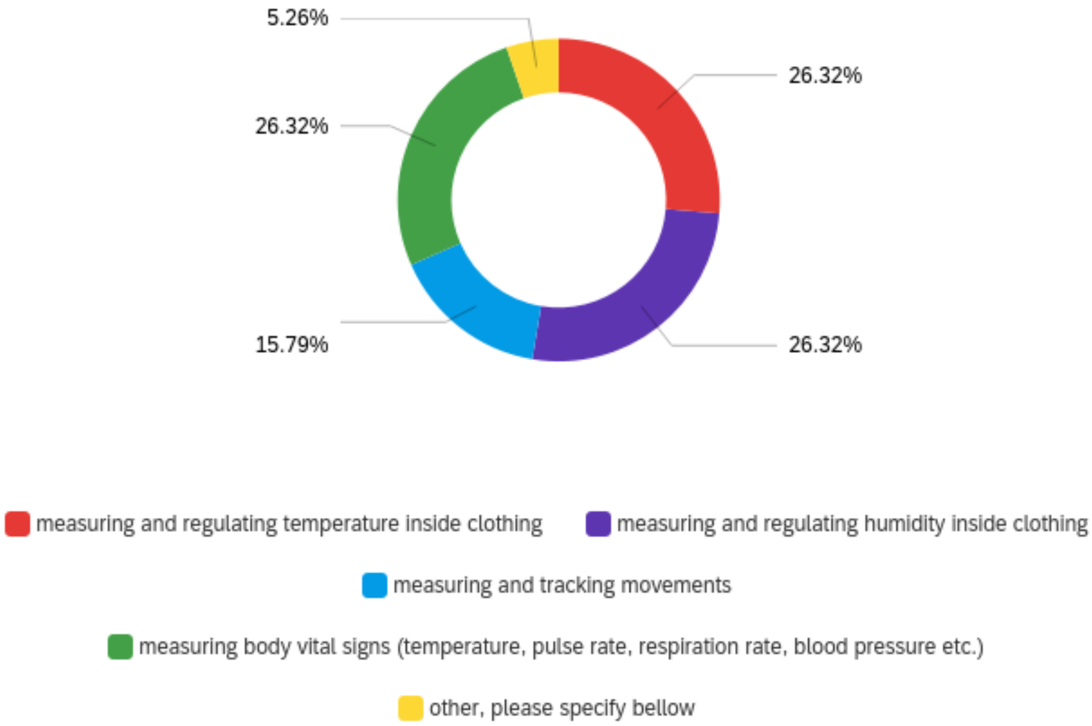
Q33 - Would you like to have rock climbing clothes that integrated with smart technology?

#	Answer	%	Count
1	Like	71.43%	5
2	Neither like nor dislike	14.29%	1
3	Dislike	14.29%	1
	Total	100%	7



Q34 - In your opinion, which sensors are more important for rock climbing clothing? (You can choose more than one option)

#	Answer	%	Count
1	measuring and regulating temperature inside clothing	26.32%	5
2	measuring and regulating humidity inside clothing	26.32%	5
3	measuring and tracking movements	15.79%	3
4	measuring body vital signs (temperature, pulse rate, respiration rate, blood pressure etc.)	26.32%	5
5	other, please specify bellow	5.26%	1
	Total	100%	19



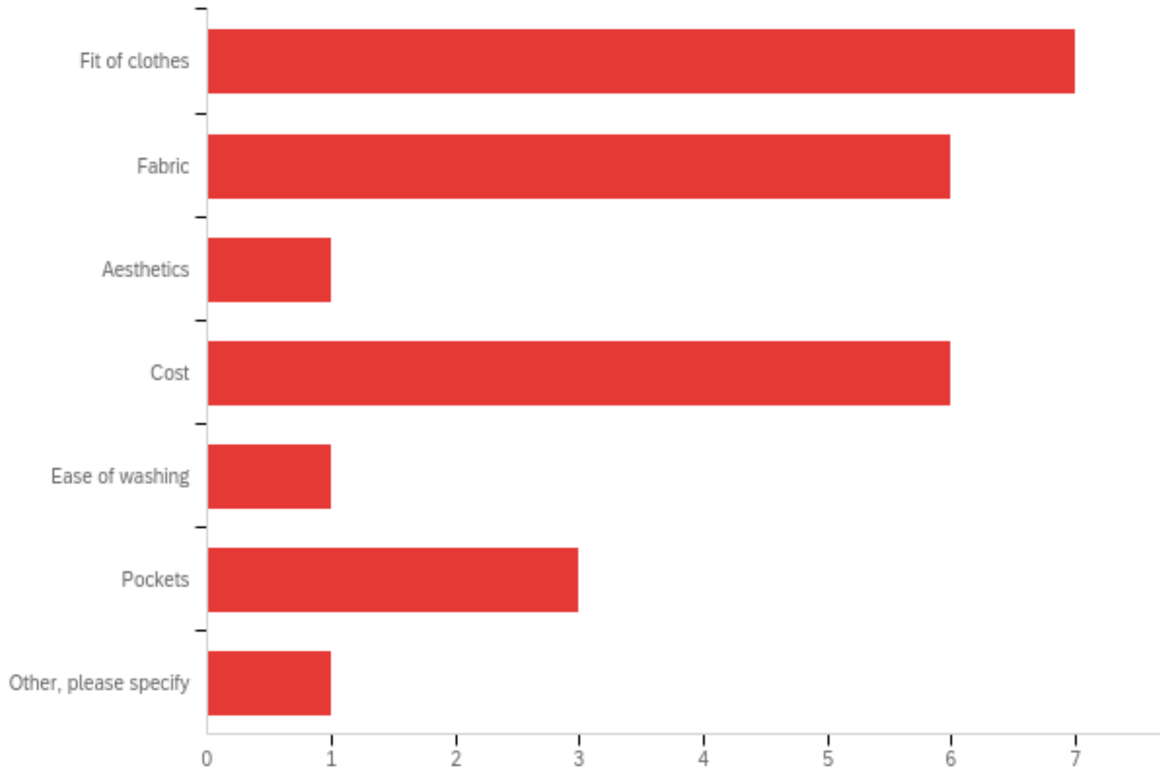
Q34_5_TEXT - other, please specify bellow

Weather, location and perhaps passive communication

Q35 - How often do you purchase rock climbing clothes?

Every year
every time i go on a trip, or when something gets worn off
Not so much these days. How ever in the past I would make seasonal purchases and also for a while in the 90s I would make purchases based on textile advancements by companies such as 3M.
6 months
Approximately once per two years
every year

Q36 - What factors are most important when you purchase rock climbing clothes? (You can choose more than one option)

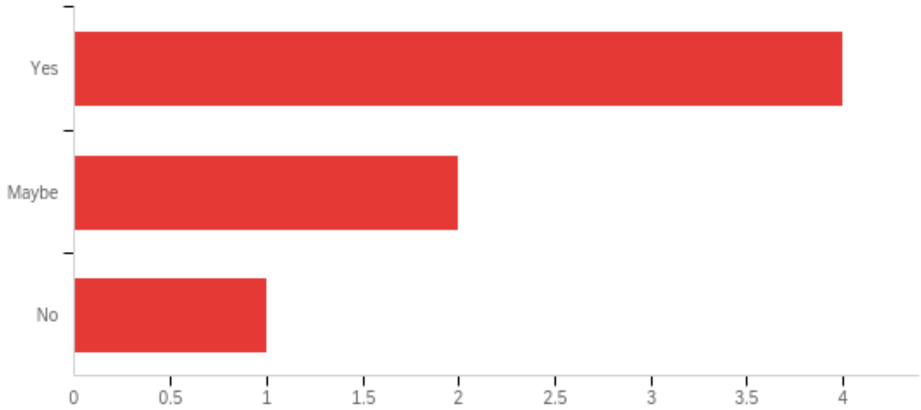


#	Answer	%	Count
1	Fit of clothes	28.00%	7
2	Fabric	24.00%	6
3	Aesthetics	4.00%	1
4	Cost	24.00%	6
5	Ease of washing	4.00%	1
6	Pockets	12.00%	3
7	Other, please specify	4.00%	1
	Total	100%	25

Q36_7_TEXT - Other, please specify

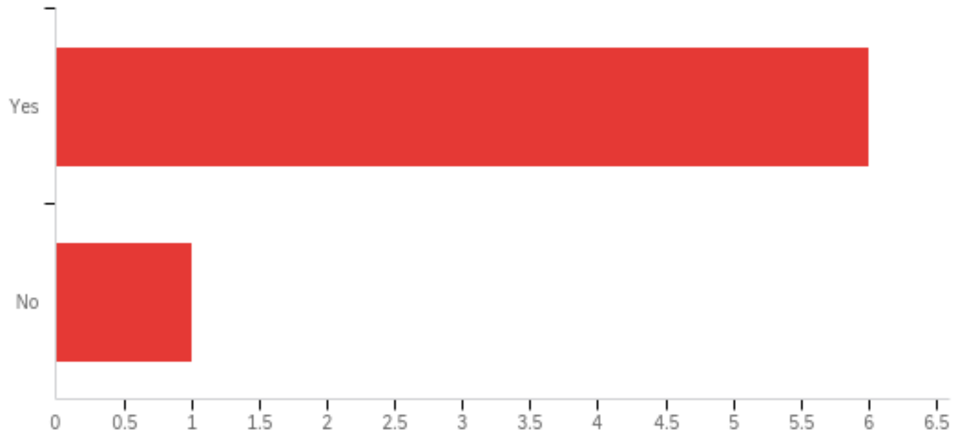
perceived durability

Q37 - Would you like to buy rock climbing clothes integrated with smart technology?



#	Answer	%	Count
1	Yes	57.14%	4
2	Maybe	28.57%	2
3	No	14.29%	1
	Total	100%	7

Q38 - Would you be interested in participating in further research into this topic? This would involve being observed while climbing (to study climbing movements and garment behaviour) and testing garment prototypes



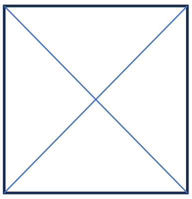
#	Answer	%	Count
1	Yes	85.71%	6
3	No	14.29%	1
	Total	100%	7

APPENDIX D. Analysis of Articles of Outdoor Rock-Climbing Clothing

D1. Brand - Black Diamond

Figure D1.1 (Image removed due to copyright restrictions)

Appearance of the Alpine light pants - Men's



Note. Image from https://www.blackdiamondequipment.com/en_US/product/recon-bibs-mens/?colorid=8641

Table D1.1

Characteristics of the Alpine light pants - Men's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Pants	An ultralight wind barrier, the Black Diamond Alpine Light Pants are the three-season solution for light, packable weather protection. Designed with a single-weave, four-way stretch fabric, they pack down so you can shove them deep into the recesses of your pack, and the DWR* treated finish gives you a layer of shelter when light precip rolls in. Two rear drop pockets and zippered thigh pockets stash essentials, and a ladder lock belt with belt loops and adjustable cuffs dial in the fit.	• Ultralight single-weave construction • DWR treatment • Two rear drop pockets • Zippered thigh pockets • Seat gusset • Ladder lock belt with belt loops	Four-way stretch woven with DWR finish (150 gsm, 85% nylon, 15% elastane)	290 g	$110 USD
https://www.blackdiamondequipment.com/en_US/product/recon-bibs-mens/?colorid=8641					
Note. *Durable water repellent (DWR), a treatment that is applied to the outermost fabric layer. DWR reduces the surface tension of the fabric, so that water simply rolls off.					

Table D1.2

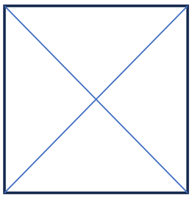
Analysis of some details of the Alpine light pants - Men's

Figure	Description	Function/Comments
	Zippered thigh pocket with diagonal access	**Ergonomics** The pocket's placement does not interfere with the position of a harness, thus ensuring unrestricted access. **Protection** Zippered pockets prevent loss of belongings while climbing.
	Cord-lock technology in hem of pants	**Comfort, ergonomics** This type of hem allows for pants to be fixed tightly around ankle if needed.
	Ladder lock belt with belt loops	**Protection, Ergonomics, Comfort, Fit** Additional lock to prevent the button opens.
	Seat gusset	**Ergonomics** Seat gusset allows for more movement in the hip and leg area allowing the climber to have a larger range of motion

Note. Authors' table 2022

Figure D1.2 (Image removed due to copyright restrictions)

Appearance of the Recon stretch bib – Men's



Note. Image from https://www.blackdiamondequipment.com/en_US/product/recon-bibs-mens/?colorid=8641

Table D1.3

Characteristics of the Recon stretch bib – Men's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Bib	The Recon Stretch Bib is a full-coverage, fully taped waterproof and breathable snow bib featuring a dynamic four-way stretch 20k/20k BD.dry™ laminated fabric, making it ideal for stormy days and backcountry tours. This bib is designed to protect against shoulder-deep conditions, wet spring snow, and everything in between. The dynamic BD.dry™ shell fabric effectively seals out external moisture, while the highly breathable, DWR-treated double-weave interior keeps a person dry by preventing overheating. A side zipper allows for easy putting on and taking off, and zippered chest, thigh, and hand pockets provide secure storage for a phone, lip balm, and other small essentials. Additionally, pack-friendly low-profile adjustable suspenders and a waistbelt ensure a perfect fit.	• Fully taped • 20,000mm waterproof, 20,000g/m^2/24 hr laminated BD.dry™ waterproof breathable four-way stretch shell fabric with DWR* • Nylon double-weave DWR stretch chest and back bib panels • Zippers on either side provide ventilation: 3/4 length two-way zipper for easy on/off and venting on right, and 1/2 length on left • Zippered bib pockets and two YKK Aquaguard zippered hand pockets • Pack-friendly low-profile adjustable suspenders • Belt loop waist with integrated adjustable belt • Articulated knees • Integrated snow gaiter • Reinforced instep kick patches	BD.dry™ 3L Nylon stretch woven with Jersey backer and DWR finish (189 gsm 84% Nylon, 16% Elastane)	919 g	$300 to $400 USD

		• Fit: Regular • Size: S-XL • Quick-access electronics pocket			
Note. Summary from https://www.blackdiamondequipment.com/en_US/product/recon-bibs-mens/?colorid=8641					

Table D1.4

Analysis of some details of the Recon stretch bib – Men's

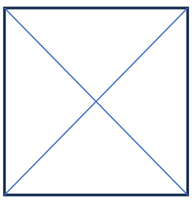
Figure	Description	Function/Comments
 	Loop waist with an integrated adjustable belt	**Ergonomics, Comfort, Fit** The loop waist with an integrated adjustable belt provides simple and quick regulation of size of the waist line.
	Two YKK Aquaguard zippered hand pockets	The pocket's placement can interfere with the position of a harness. **Protection** Zippered hand pockets prevent the loss of belongings while climbing.
	Right side 3/4 length two-way zipper	**Ergonomics, Comfort** A side zipper makes for easy on and off and venting.

	Articulated knees. Nylon double-weave DWR stretch knees	**Protection, Ergonomics, Comfort** The construction of the knee area (with additional darts, circled in the picture) and stretch fabric provide ease of movement. The double-weave nylon DWR fabric enhances the durability of the knee.
	Pack-friendly low-profile adjustable suspenders	**Ergonomics, Fit, Comfort**
	Parts of the pants reinforced by Nylon double-weave DWR fabric	**Protection** These reinforced parts of the pants provide additional durability.

Note. Authors' table 2022

Figure D1.3 (Image removed due to copyright restrictions)

Appearance of the Mission ski shell – Men's



Note. Image from https://www.blackdiamondequipment.com/en_US/product/mission-ski-shell-mens/?colorid=7996

Table D1.5

Characteristics of the Mission ski shell – Men's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Ski Jacket	The Black Diamond Mission Shell is our go-to, all-purpose ski jacket for hundred-day seasons and bell-to-bell days. Featuring GORE-TEX shell fabric for excellent waterproof and breathable protection, the jacket includes a soft interior lining for added comfort and extensive pocket storage for small essentials. The integrated Cohaesive cord-management hardware in the hood allows for an equalized, three-way adjustment with a single pull, perfect for low-visibility storm days. Extended, two-way zippered armpit vents enable quick release of excess heat on the skin track. An integrated powder skirt serves as a second line of defence on those epic deep days.	• Integrated Cohaesive™ cord-lock technology in hood and hem • Ski-helmet-compatible hood • Brushed microsuede collar • Extended two-way armpit zippered vents • Two concealed-zippered hand pockets, two concealed-zippered chest pockets and zippered sleeve pocket with internal stretch mesh pouch and two skin-compatible, internal stretch-mesh drop pockets • Underarm gussets for added range of motion • Internal stretch powder skirt • Custom-molded cuff tabs • Fit: Relaxed	GORE-TEX® 3L, 70d nylon plain-weave with brushed backer and DWR finish (175 g/m^2, 100% nylon face, 100% polyester back)	791g (1 lb 12 oz)	$650 USD
Note. Summary from https://www.blackdiamondequipment.com/en_US/product/mission-ski-shell-mens/?colorid=7996					

Table D1.6

Analysis of some details of the Mission ski shell – Men's

Figure	Description	Function/Comments
	Extended two-way armpit zippered ventilations	**Comfort, Protection** An extended two-way armpit zipper provides ventilation and prevention of overheating.

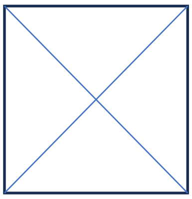
	Concealed-zippered chest pockets Custom-molded cuff tabs	**Comfort, Protection**
	Internal stretch powder skirt	**Protection, Ergonomics, Comfort**
	Integrated Cohaesive™ cord-lock technology in a hood and hem. Ski-helmet-compatible hood	**Protection, Ergonomics, Comfort, Fit**

Note. Authors' table 2022

D2. Brand - Marmot

Figure D2.1 (Image removed due to copyright restrictions)

Appearance of the WarmCube™ 8000M Suit



Note. Image from https://www.marmot.com/men/jackets-and-vests/insulated-and-down/warmcube-8000m-suit/AFS_889169611100.html

Table D2.1

Characteristics of the WarmCube™ 8000M Suit

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Suit	The 8000M Suit, featuring patent-pending 3D WarmCube™ technology, combines 800-fill-power goose down and Pertex Quantum® fabric to provide superior wind protection and warmth for summit-worthy adventures. Protected by a water-resistant layer of overlapping baffles, the removable liner features WarmCube™ construction that prevents the down fill from being displaced and traps heat in the surrounding channels, ensuring the wearer stay warm in extreme weather conditions. Adjustable suspenders with a mesh back panel and front detachment system customize wearer's fit and improve airflow. The attached hood with insulated muffs offers maximum coverage, featuring an adjustable drawcord at the back that will not interfere with a helmet.	• 800-fill-power-down provides exceptional warmth, loft, and compactability • Pertex Quantum® fabric protects the wearer from wind and improves the efficiency of insulation • Removable liner with WarmCube™ construction provides ultra-comfortable warmth in extreme weather conditions • Adjustable suspenders with mesh back panel and front detach system provides a customized fit and improves airflow • Attached hood with peripheral cord adjustment and insulated muffs provides maximum coverage • Four-way water-resistant center front zipper; Four-way rainbow seat zipper with stay-open hook • Dual internal mesh 1-liter water bottle pockets • Zippered hand and thigh pockets	Main Fabric: 100% Nylon, Dobby, 70g/sqm	3,175 g	$1600 USD
Note. Summary from https://www.marmot.com/men/jackets-and-vests/insulated-and-down/warmcube-8000m-suit/AFS_889169611100.html					

Table D2.2

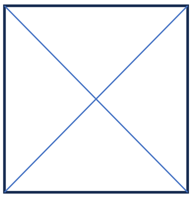
Analysis of some details of the WarmCube™ 8000M Suit

Figure	Description	Function/Comments
	Removable liner	**Protection, Ergonomics, Comfort** Removable liner with WarmCube™ construction provides ultra-comfortable warmth in extreme conditions.
	Four-way water-resistant center front zipper	**Protection, Ergonomics**
	3D WarmCube™ technology	**Protection, Comfort** This technology prevents the down fill from being displaced and traps heat in the surrounding channels, providing exceptional warmth, loft, and compactability.

Note. Authors' table 2022

Figure D2.2 (Image removed due to copyright restrictions)

Appearance of the unisex West Rib parka



Note. Image from https://www.marmot.com/men/jackets-and-vests/insulated-and-down/unisex-west-rib-parka/AFS_889169609039.html

Table D2.3

Characteristics of the unisex West Rib parka

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Parka (jacket)	The West Rib parka, featuring the combination of 800-fill-power goose down and Pertex Quantum® fabric to provide superior wind protection and warmth for summit-worthy adventures. Protected by a water-resistant layer of overlapping baffles, an innovative 3D WarmCube™ construction prevents the down fill from being displaced and traps heat in the surrounding channels, ensuring the wearer stay warm. Keep small gear organized and accessible in the interior mesh, zippered hand, and chest pockets. The attached hood offers maximum coverage with an adjustable drawcord at the back that won't interfere with a helmet. When it's time to head off the mountain, stow this packable jacket in the included stuff sack for space-saving storage.	• 3D WarmCube™ construction prevents down fill from shifting and traps heat in the surrounding air channels for maximum warmth and performance; water-resistant shingled synthetic insulation • Water-resistant overlapping baffles add warmth and protection even when wet • 800-fill-power goose down and 3M™ Thermal R 40 gram synthetic insulation, and Pertex Quantum® fabric protect the wearer from wind and improve the efficiency of insulation • Zippered hand pockets; and dual interior mesh pockets • Attached hood with peripheral cord adjustment and insulated muff • Stuff sack for space-saving storage • Unisex	Main Fabric: Pertex Quantum 100% Nylon, Ripstop, 39g/sqm	2 lbs 6 oz , 1,074 g	$600 USD
Note. Summary from https://www.marmot.com/men/jackets-and-vests/insulated-and-down/unisex-west-rib-parka/AFS_889169609039.html					

Table D2.4

Analysis of some details of the unisex West Rib parka

Figure	Description	Function/Comments
-	Fixed Hood with peripheral cord adjustment and insulated muff for extra coverage	**Ergonomics, Protection, Comfort, Fit**

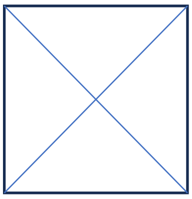
	3D WarmCube™ technology	**Protection, Comfort** This technology prevents the down fill from being displaced and traps heat in the surrounding channels, providing exceptional warmth, loft, and compactability.
	Stuff Sack for space-saving storage at base camp	**Ergonomics, Protection**
	Two-way water-resistant center front zipper	**Protection, Ergonomics**
	Multiple Pockets Zippered hand and dual interior mesh pockets stow small gear	**Ergonomics, Protection**
	Dual interior mesh pockets	**Protection**

Note. Authors' table 2022

D3. Brand - North Face

Figure D3.1 (Image removed due to copyright restrictions)

Appearance of the Summit L5 Futurelight ™ full zip bib – Men's



Note. Image from https://www.bivouac.co.nz/clothing/mens-clothing/mens-pants/the-north-face-men-s-summit-l5-futurelight-full-zip-bib.html?srsltid=AfmBOopUcaZN8Vjqhg63HZpXPbVPuprGwa431HWfepHmO--lnGQf9BqT

Table D3.1

Characteristics of the Summit L5 Futurelight™ full zip bib – Men's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Bib	The Summit L5 Futurelight™ full zip bib is a waterproof, breathable snowpant designed for the challenges of high alpine mountaineering. They are made with rugged 3-layer Futurelight™ stretch fabric and an articulated design for easy movement with Spectra® fabric reinforcement in high-wear areas to stand up to abrasion.	• Standard fit • Breathable and waterproof, seam-sealed Futurelight™ 3L shell • High-wear area reinforced with Spectra® ripstop provides increased durability • Articulated patterning provides fit and mobility • Low-profile bib provides breathability and all-day comfort • Attached, adjustable suspenders • Full-length #5 YKK® AquaGuard® side zippers • Two thigh pockets with #3 YKK® AquaGuard® zippers and an internal mesh pocket and gear loop in right pocket • Bib pocket with a #3 YKK® AquaGuard® zipper for quick-access storage of small items	Body: 70D x 20D 152 g/m² Futurelight ™ 3L-100% recycled nylon with tricot backer and DWR finish. Lower-leg exterior: 75D x 100D 141 g/m² Futurelight ™ 3L-91% recycled polyester, 9% poly-ethylene Spectra® ripstop with 100% recycled nylon tricot backer and DWR finish.	-	$1,000 USD

		• Elastic at back waist for low-bulk comfort and a secure fit • Adjustable snap tabs at hem • Integrated gaiters feature stretch fabric and adjustability for a seamless fit with boots • High-denier lining at hem and kickpatches to reduce internal boot abrasion • Lightweight stuffsack	Lower-leg interior: Keprotec®		
Note. Summary from https://www.bivouac.co.nz/clothing/mens-clothing/mens-pants/the-north-face-men-s-summit-l5-futurelight-full-zip-bib.html?srsltid=AfmBOopUcaZN8Vjqhg63HZpXPbVPuprGwa431HWfepHmO--lnGQf9BqT					

Table D3.2

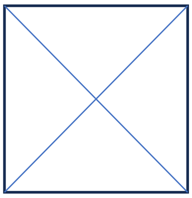
Analysis of some details of the Summit L5 Futurelight™ full zip bib – Men's

Figure	Description	Function/Comments
	Full-length #5 YKK® AquaGuard® side zippers	**Ergonomics, Comfort** Side zippers allow for easy putting on and taken off.
	Adjustable snap tabs at hem High-denier lining at hem and kickpatches to reduce internal boot abrasion	**Ergonomics, Protection, Comfort**
	Low-profile bib Attached, adjustable suspenders	**Fit, Ergonomics, Comfort** Low-profile bib for breathability and all-day comfort

Note. Authors' table 2022

Figure D3.2 (Image removed due to copyright restrictions)

Appearance of the Summit L5 Futurelight ™ jacket – Men's



Note. Image from https://thenorthface.co.nz/product/mens-summit-futurelight-jacket/NF0A4ANIT4S.html

Table D3.3

Characteristics of the Summit L5 Futurelight™ jacket – Men's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Jacket	The Summit Futurelight™ Jacket is designed for pushing limits in challenging conditions. Three-layer Futurelight™ fabric provides the highest level of durable, breathable-waterproof protection, plus it is windproof and has plenty of stretch, ensuring that reaching movements are not restricted. Designed with the mountaineer in mind, it has a host of features like an adjustable, wire-brim helmet-compatible hood, two-way harness-friendly zipper, an easy-to-reach chest pocket, and seamless shoulders, which makes caring a pack more comfortable.	• Standard fit • Breathable-waterproof, seam-sealed Futurelight™ shell • Windproof fabric • No shoulder seams for comfort with a pack • Attached, fully adjustable, helmet-compatible hood features a laminated wire brim • Exposed, two-way, matte polyurethane (PU), VISLON® centre front zipper • Exposed, matte PU chest and hand pocket zippers • Large internal mesh drop pocket • Hook-and-loop cuff tabs • Drop-tail hem • Adjustable, internal hem cinch-cord • Oversize cord locks at hood and hem are easy to use when you're wearing gloves	70D x 20D 152 g/m^2 FUTURELIGHT™ 3L- 100% recycled nylon with DWR finish	500 g (1 lb 1.64 oz)	$770 USD

Note. Summary from https://thenorthface.co.nz/product/mens-summit-futurelight-jacket/NF0A4ANIT4S.html

Table D3.4

Analysis of some details of the Summit L5 Futurelight™ jacket – Men's

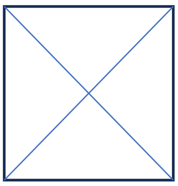
Figure	Description	Function/Comments
	Attached, fully adjustable, helmet-compatible hood features a laminated wire brim	**Ergonomics, Protection, Fit, Comfort**
	No shoulder seams for comfort with a pack Exposed, two-way, centre front zipper	**Ergonomics**
	Hook-and-loop cuff tabs Adjustable, internal hem cinch-cord Drop-tail hem	**Ergonomics, Comfort, Protection**

Note. Authors' table 2022

D4. Brand - Arcteryx

Figure D4.1 (Image removed due to copyright restrictions)

Appearance of the Sabre LT jacket – Men's*



Note. Image from https://arcteryx.co.nz/products/sabre-lt-jacket-mens-20?variant=31931627634752

*LT: Lightweight

Table D4.1

Characteristics of the Sabre LT jacket – Men's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Jacket	The Sabre LT Jacket is a highly versatile big mountain jacket designed for weather protection in a progressive design. The jacket features a high performance and minimalist design that offers durability relative to its weight. The jacket made of fully waterproof and breathable GORE-TEX fabric with GORE C-KNIT™ backer technology. Impervious to penetration by water molecules, these materials provide shelter and protection. Equipped with a comprehensive set of features tailored for freeride touring, the jacket includes a helmet-compatible StormHood™, RS*™ zipper sliders on both chest and hand pockets, and an RFID* pocket. It also features pack-compatible WaterTight™ pit zip-pers for effective venting, an integrated powder skirt with Slide'n Loc™ attachments for compatible pants, an internal laminated pocket, and an internal mesh dump pocket. The longer length offers additional protection from the elements during deep storm days. Designed with specific snow-sports features for efficient protection, layering and movement.	Technical features: • Waterproof • Breathable • Lightweight • Durable Design and fit: • Regular fit provides freedom of movement with room for layers Hood configuration: • Helmet compatible StormHood™ • Laminated brim • Glove-friendly hood adjusters Zippers configuration: • WaterTight™ external zippers • WaterTight™ Vislon front zip • RS™ pocket zipper sliders • WaterTight™ pit zippers angled for easy access while wearing a pack Hem configuration: • Adjustable hem drawcord • Laminated hem • Straight hem Snowsport features: • Powder skirt with stretch panel and gripper elastic • Slide'n Loc™ snap closures enable certain jackets to be fastened to ski pants to prevent snow entry • Hidden Recco® reflector Fabric treatment: • DWR finish repels moisture Construction: • Micro-seam allowance (1.6 mm) reduces bulk and weight • Fully seam-sealed for waterproofness	N80p 3L GORE-TEX fabric with GORE C-KNIT™ backer technology	660 gm	$1200 NZD

		• Supple, windproof and waterproof N80p 3L GORE-TEX with C-KNIT™ backer techno-logy is quiet and soft with excellent breathability Patterning: • Articulated patterning for unrestricted mobility • No-lift gusseted underarms Collar configuration: • Tall collar Cuff and sleeves configuration: • Relaxed cuffs to fit over gloves • Laminated die-cut Velcro® cuff adjusters reduce bulk, and do not catch or tear off • Large cuffs to fit over gloves Pocket configuration: • Two hand pockets with zippers • Two internal mesh dump pockets, one with a zippered pocket • Two chest pockets with zippers • Left hand sleeve pocket for RFID ski pass			
Note. Summary from https://arcteryx.co.nz/products/sabre-lt-jacket-mens-20?variant=31931627634752 RFID*: Radio Frequency Identification RS*: Rain Shield					

Table D4.2

Analysis of some details of the Sabre LT jacket – Men's

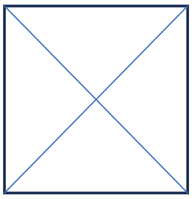
Figure	Description	Function/Comments
	Tall collar Two chest pockets with zippers Left hand sleeve pocket for RFID ski pass	**Ergonomics, Protection, Comfort**

	Powder skirt with stretch panel and gripper elastic Two internal mesh dump pockets, one with a zippered pocket	**Protection, Ergonomics, Comfort**
	Pit zippers for venting Ventilation, prevention of overheating	**Comfort, Protection**
	Adjustable hem drawcord Laminated hem	**Protection**
	Helmet compatible StormHood™ Laminated brim Glove-friendly hood adjusters No shoulder seams for comfort with a pack	**Protection, Ergonomics, Comfort, Fit**

Note. Authors' table 2022

Figure D4.2 (Image removed due to copyright restrictions)

Appearance of the Alpha AR jacket– Men's*



Note. Image from https://arcteryx.co.nz/products/alpha-ar-jacket-mens-1

- *AR: All Round

Table D4.3

Characteristics of the Alpha AR jacket – Men's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Jacket	The Alpha AR jacket is a highly versatile hard-shell designed to address the challenges of alpine environments, including extreme weather, shifting conditions, varied terrain, and both motion and rest. The jacket is constructed with GORE-TEX PRO, featuring the most rugged reinforcements in high-wear areas to enhance durability. The StormHood™ provides protection without impacting visibility, while a RECCO® reflector aids in search and rescue operations. Crossover chest pockets are easily accessible, and pit zippers provide ventilation.	Technical features: • Waterproof • Windproof • Breathable • Lightweight • Durable Design and fit: • Regular fit ensures optimal ventilation with comfort and mobility Hood configuration: • Helmet compatible StormHood™ • Laminated brim • Cohaesive™ hood adjustments for ease of use with mittens or gloves Zippers configuration: • WaterTight™ external zippers • Pit zippers for easy venting • Full front zip with wind flap • Custom TPU zipper pulls Hem configuration: • Cohaesive™ hem adjusters function as Hemlock™ to prevent jacket from slipping out from under a climbing harness • Slight drop hem Reinforcments: • Reinforced hood, shoulders and forearms Sustainability: • Contains materials that meet the bluesign® criteria	N40p-X GORE-TEX Pro 3L - Body N80p-X GORE-TEX Pro 3L	430 gm	$1100 NZD

		• Dope dyed black colourway Construction: • Micro-seam allowance (1.6 mm) reduces bulk and weight • Laminated high-strength hanger loop • Strategically placed narrow GORE seam tape (8mm width) • N80d Most Rugged 3L GORE-TEX PRO reinforce-ments increase durability Patterning: • No-lift gusseted underarms Collar configuration: • Tall collar • Laminated chin guard with brushed microsuede facing provides added comfort Cuff and sleeves configuration: • Die-cut Velcro® cuff adjusters reduce bulk, and will not catch or tear off Pocket configuration: • Two external volume pleated chest pockets with WaterTight™ zippers and RS™ Zipper Sliders • Internal zippered pocket Snowsport features: • RECCO® reflector hidden in hood brim Fabric treatment: • Arc'teryx Nu water repellent treatment			
Note. Summary from https://arcteryx.co.nz/products/alpha-ar-jacket-mens-1					

Table D4.4

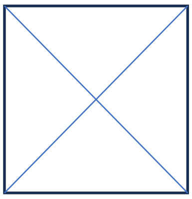
Analysis of some details of the Alpha AR jacket – Men's

Figure	Description	Function/Comments
	Cohaesive™ hem adjusters function similarly to Hemlock™, preventing the jacket from slipping out from under a climbing harness Slight drop hem	**Protection**

Note. Authors' table 2022

Figure D4.3 (Image removed due to copyright restrictions)

Appearance of the Gamma LT pants – Men's*



Note. Image from https://arcteryx.co.nz/products/gamma-lt-pant-mens?variant=30410103095360
*LT: Lightweight

Table D4.5

Characteristics of the Gamma LT pants – Men's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Pants	The Gamma LT is lightweight, durable, and highly versatile pants, that offers light weather protection, air-permeable comfort, and exceptional mobility. The abrasion-resistant Fortius™ DW 2.0 fabric combines quick-drying nylon with elastane fibres for enhanced performance stretch. A brushed polyester waistband provides additional next-to-skin comfort. The articulated construction and gusseted crotch provides outstanding mobility and freedom during activities such as hiking, rock climbing alpine climbing, trekking.	Technical features: • Moisture-resistant outer face fabric • Lightweight and Durable Design and fit: • Straight leg Zippers configuration: • Front fly with snap closure Waist and belt configuration: • Adjustable integrated webbing belt • Snap waist closure • Soft, brushed lined waist Logos and label configuration: • Reflective logo for low light visibility Construction: • Stretchy fabric provides freedom of movement Patterning: • Articulated patterning for unrestricted mobility • Gusseted crotch for comfort and freedom of movement Cuff configuration: • Adjustable pant cuff drawcord • Laminated cuffs Pocket configuration: • Thigh pocket with a laminated zipper • Two hand pockets with the laminated zippers • Mesh lined hand pockets Fabric treatment: • DWR finish repels moisture	Fortius ™ DW 2.0 - 88% Nylon, 12% Elastane	430 gm	$310 NZD

Note. Summary from https://arcteryx.co.nz/products/gamma-lt-pant-mens?variant=30410103095360

Table D4.6

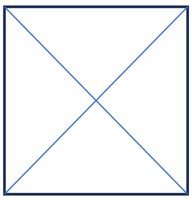
Analysis of some details of the Gamma LT pants – Men's

Figure	Description	Function/Comments
	Adjustable pants cuff drawcord Laminated cuffs	**Comfort, ergonomics** This type of hem allows the pants to be secured around the ankle if needed.
	Thigh pocket with a laminated zipper Two hand pockets with the laminated zippers	**Protection, Ergonomics, Comfort**
	Gusseted crotch for comfort and freedom of movement Adjustable integrated webbing belt Snap waist closure	**Ergonomics, Comfort, Mobility**

Note. Authors' table 2022

Figure D4.4 (Image removed due to copyright restrictions)

Appearance of the Sigma FL pants – Men's*



Note. Image from https://arcteryx.co.nz/products/copy-of-sigma-fl-pants-mens?variant=39378531024960
*FL: Fast and Light

Table D4.7

Characteristics of the Sigma FL pants – Men's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Pants	The Sigma FL Pants strike the ideal balance between lightweight construction and durability. These versatile softshell pants are designed for fast and light tactics on rock, alpine, and ice climbing routes. Material mapping incorporates Wee Burly™ Double Weave reinforce-ments in the seat and knees, while air-permeable, 4-way stretch Fortius™ 1.5 fabric in the body enhances mobility and reduces weight. The trim fit and tapered lower leg minimize excess fabric, while the articulated design enables a full range of motion. Additionally, a drawcord at the cuff helps seal out updrafts and debris.	Technical features: • Lightweight and durable Design and fit: • Trim fit ensures better line of sight while climbing Cuff configuration: • Adjustable pant cuff with grommets for installing a gaiter cord Pocket configuration: • Harness friendly zippered thigh pocket Construction: • Four-way stretch textile Patterning: • Articulated patterning for unrestricted mobility • Gusseted crotch for comfort and freedom of movement Waist and belt configuration: • Adjustable integrated webbing belt • Waistbelt fits comfortably under harnesses and backpacks Reinforcements: • Reinforced knees and seat Fabric treatment: • DWR finish repels moisture	Wee Burly™ Double Weave Fortius 1.5™ - 88% nylon, 12% elastane, 220 g/m². Light-weight, durable, non-insulated, stretchy nylon/spandex blend textile.	370 gm	$290 NZD

Note. Summary from https://arcteryx.co.nz/products/copy-of-sigma-fl-pants-mens?variant=39378531024960

Table D4.8

Analysis of some details of the Sigma FL pants – Men's

Figure	Description	Function/Comments
	Zippered thigh pocket	**Ergonomics, Protection, Comfort** The pocket's placement does not interfere with the position of a harness, thus ensuring unrestricted access.

	Adjustable pant cuff with grommets for installing a gaiter cord	**Protection**
	Adjustable integrated webbing belt	**Ergonomics, Fit, Protection, Comfort** Waistbelt fits comfortably under harnesses and backpacks

Note. Authors' table 2022

Figure D4.5 (Image removed due to copyright restrictions)

Appearance of the Beta LT jacket – Women's*

Note. Image from https://arcteryx.co.nz/products/beta-lt-jacket-womens-4
*LT: Lightweight

Table D4.9

Characteristics of the Beta LT jacket – Women's

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Jacket	Designed with purposeful simplicity to maximize versatility, the Beta LT jacket provides lightweight, durable, bluesign® approved GORE-TEX protection for a variety of activities. The helmet-compatible StormHood™ provides full	Technical features: • Waterproof • Breathable • Lightweight • Durable Hood configuration: • Adjustable StormHood™ • Helmet compatible Zippers configuration: • Pit zippers for easy venting • RS*™ pocket zipper sliders • WaterTight™ full length front zipper	N40d 3L GORE-TEX fabric with tricot backer technology	350 gm	$890 NZD

	coverage without obstructing sight lines, while pit zippers enable rapid ventilation. The women's-specific trim fit positions the GORE-TEX close to the body to enhance breathability, and the longer hem extends coverage, fitting comfortably under a harness.	Cuff and sleeves configuration: • Adjustable cuffs • Slight drop hem Pocket configuration: • Two hand pockets with WaterTight™ zippers and RS™ zipper sliders Fabric treatment: • DWR finish repels moisture Construction: • GORE-TEX three-layer construction delivers complete weather protection Hem configuration: • Dual lower hem adjusters Sustainability: • Contains materials that meet the bluesign® criteria			
Note. Summary from https://arcteryx.co.nz/products/beta-lt-jacket-womens-4 RS*: Rain Shield					

Table D4.10

Analysis of some details of the Beta LT jacket – Women's

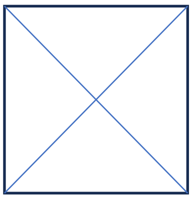
Figure	Description	Function/Comments
	Dual lower hem adjusters longer hem	**Ergonomics, Protection, Comfort** Dual lower hem adjusters and longer hem extends coverage that fits comfortably under a harness
	Helmet compatible and adjustable StormHood™ with a tall collar	**Protection, Comfort** The helmet-compatible and adjustable StormHood™ features a tall collar that provides protection for the lower part of the face from wind.
	Pit zippers for ventilation	**Protection, Comfort** Pit zippers provide easy ventilation to prevent overheating.

Note. Authors' table 2022

D5. Brand - prAna

Figure D5.1 (Image removed due to copyright restrictions)

Appearance of the Stretch Zion Pants II



Note. Image from https://www.prana.com/p/stretch-zion-pant-ii/1969791.html?dwvar_1969791_color=Flint

Table D5.1

Characteristics of the Stretch Zion Pants II

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Pants	The Stretch Zion Pants II is designed for versatility and performance, featuring ReZion™, an environmentally friendly and durable fabric. Key attributes include a concealed zip pocket with a key loop, a reinforced mobility gusset for enhanced movement, and mitered pocket corners to prevent dirt buildup. This pant combines strength and practicality, making it ideal for both outdoor adventures and casual outings.	• ReZion recycled nylon blend stretch performance fabric • Front thigh seam detail • Ventilated inseam gusset • Snap roll up feature at hem • Mesh lined pockets • Webbing adjustable waistband • Left thigh zipper cargo pocket with double entry • Concealed zipper coin pocket with elastic key loop • Back patch pockets with flap at back right pocket • prAna woven label at back right pocket • Relaxed fit through the hip and thigh • Straight leg opening • Abrasion resistant • 4-way stretch • PFAS-free DWR • UPF 50+ • Fair trade certified™ factory • Bluesign® approved materials	95% Recycled Nylon, 5% Elastane	-	$95 NZD

Note. Summary from https://www.prana.com/p/stretch-zion-pant-ii/1969791.html?dwvar_1969791_color=Flint

Table D5.2

Analysis of some details of the Stretch Zion Pants II

Figure	Description	Function/Comments
	Additional functional zippered pocket for small valuables	**Protection, Comfort**
	Ventilated inseam gusset Webbing adjustable waistband	**Ergonomics, Protection, Comfort**

Note. Authors' table 2022

D6. Brand - Sivera

Figure D6.1 (Image removed due to copyright restrictions)

Appearance of the Argamak Parka (Аргамак, original Russian)

Note. Image from https://sivera.ru/catalog/man/down/2713/

Table D6.1

Characteristics of the Argamak Parka

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Parka (jacket)	The Argamak is a warm, elongated down parka designed for severe sub-zero temperatures. It is ideal for high-altitude and winter mountaineering, polar expeditions, extreme winter tourism, and is also suitable for urban use during harsh winters. This model utilizes warm seam technology and is insulated with over 500 grams of high-quality SmartDown 700 goose down. Additional compact synthetic insulation inserts are strategically placed in the shoulders and elbows for enhanced warmth. The parka is made of durable D'Fusion classic membrane fabric, that provides complete wind protection and minimizes convective heat loss. When combined with moisture-proof fittings, it effectively protects from external moisture. These features make the Argamak one of the most practical choices for a versatile warm sport down jacket.	Temperature: • -35C (low activity), • -45C (medium activity), • -60C (high activity) Technical features: • Synthetic insulation in the shoulders and elbows Technologies: • Quality goose down with hydrophobic treatment Features of a design:. • Wind and snow protection inner skirt, ‘warm seams’ Hood: • A voluminous warm hood with a convenient system of adjustments. Pockets: • Two large warm side pockets with waterproof zippers. • Two inside pockets: zippered on the left, open in stretch jersey on the right. Zippers and straps: • Central two-way waterproof zipper with an internal insulated (without a through seam) strap. Cuffs and sleeves: • Profiled sleeves with adjustable, rubberized cuffs with Velcro. • Volume adjustment at the bottom of the jacket. Additional features: Ultra-light kit included.	Main Fabric: D'Fusion Classic 2L, Nylon 50D, 90 g/m2, WP 20 000 mm/24hrs, MVTR 20 000 g/m2/24hrs (B1) Lining: A'ris 20, Nylon 20D, 33 g/m2 Inner layer: high-quality goose down SmartDown FP 700+ 501g	1172 gm	32,900 RUB ($565 NZD)

Note. Summary from https://sivera.ru/catalog/man/down/2713/

Table D6.2

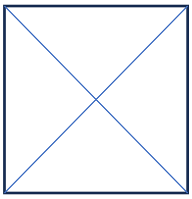
Analysis of some details of the Argamak Parka

Figure	Description	Function/Comments
	A voluminous warm hood with a convenient system of adjustments, helmet compatible, protection from wind (tall collar)	**Ergonomics, Protection, Comfort, Fit**
	Additional adjustment to make hood more contoured	**Protection, Fit**
	Inside zippered pocket	**Protection, Comfort**
	Wind and snow protective inner skirt, ‘warm seams’	**Protection**
	Profiled sleeves with adjustable, rubberized cuffs with Velcro	**Protection**
	Ultra-light kit included	**Ergonomics, Protection**

Note. Authors’ table 2022

Figure D6.2 (Image removed due to copyright restrictions)

Appearance of the Emurluk 2.2 jacket (Емурлук 2.2, original Russian)



Note. Image from https://sivera.ru/catalog/man/hardshell/2610/

Table D6.3

Characteristics of the Emurluk 2.2 jacket

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Jacket	A Emurluk jacket is a versatile top-class storm jacket. The model is designed for all kinds of outdoor activities, and is also suitable for everyday wear. Using StormGuard 3L membrane fabric with the latest porous submicron membrane, the jacket provides a high level of comfort in a wide range of conditions and reliable protection against precipitation of any intensity. A durable nylon upper and a woven laminate inner layer provide superior strength and durability in this weight class.	Design Features: • Underarm ventilation with the waterproof zippers. Hood: • Set-in hood of increased volume with a convenient system of adjustment along the front cut and volume. Pockets: • Two outer pockets with the waterproof zippers. • Laminated interior zippered chest pocket. Zippers and straps: • Central two-way waterproof zipper with an inner strap. • Velcro cuffs. • Adjustment on the bottom of the jacket with an elastic cord.	StormGuard 3L 40, WP 20 000 mm, MVTR 13 000 g/sm/24 hrs (A1), 20 000 g/sm/24 hrs (B1), Nylon 40D, 117 g/m2	440 gm	28 900 RUB ($500 NZD)
Note. Summary from https://sivera.ru/catalog/man/hardshell/2610/					

Table D6.4

Analysis of some details of the Emurluk 2.2 jacket

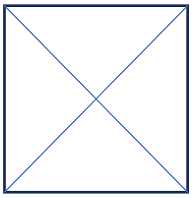
Figure	Description	Function/Comments
	Set-in helmet compatible hood with a convenient system of adjustment along the front cut.	**Ergonomics, Protection, Comfort**
	Additional adjustment for regulation of hood volume	**Ergonomics, Protection, Comfort**
	Pit waterproof zippers for ventilation	**Protection, Comfort** Pit waterproof zippers provide ventilation and prevent of overheating.
	Adjustable hem	**Ergonomics, Protection, Comfort**
	Laminated interior zippered chest pocket	**Protection**

	Adjustable cuffs with a Velcro tape	**Ergonomics, Protection, Comfort**

Note. Authors' table 2022

Figure D6.3 (Image removed due to copyright restrictions)

Appearance of the Skimen P pants (Скимен П, original Russian)



Note. Image from https://sivera.ru/catalog/collections/alpine/man/2995/

Table D6.5

Characteristics of the Skimen P pants

Type of clothing	Description from manufacturer/seller	Characteristics	Materials	Display Weight	Price
Pants	The Skimen Pants for men are lightweight stretch pants designed for climbing, multi-pitch rock routes, and everyday wear in both hiking and urban conditions. This model features a comfortable wide anatomical design that provides complete freedom of movement. The pants made of quick-drying, highly breathable, and stretchy fabric that effectively wicks excess moisture away from the body while providing sufficient wind protection.	Design features: • Anatomical design construction. • Adjustable bottom parts of the pants allow them to be converted into 3/4 shorts. • Waistband with the belt loops. • Loop at the back of the waistband for attaching a chalk pouch. Pockets: • Two side pockets. • Two zippered hip pockets.	Actiweave, double weave four-way stretch 207 g/m2	417 gm	10600 RUB ($200 NZD)

Note. Summary from https://sivera.ru/catalog/collections/alpine/man/2995/

Table D6.4

Analysis of some details of the Skimen P pants

Figure	Description	Function/Comments
	Two zippered hip pockets	**Ergonomics, Protection, Comfort** The pocket's placement does not interfere with the position of a harness, thus ensuring unrestricted access
	Anatomical design	**Ergonomics, Comfort, Fit**
	Adjustable bottom parts of the pants	**Ergonomics, Comfort** Adjustable bottom parts of the pants allow them to be converted into 3/4 shorts.

Note. Authors' table 2022

APPENDIX E. Arduino Code for Functional Prototype

```
//Assigning names to pins for readability
int fetPin = A7;
int tempSensor = A9;
//Declaring Variables
float temperature;
int pollRate = 2000;
unsigned long timePassed;
unsigned long prevTimePassed = 0;

//Declaring Functions
float tempSensFunc();

//Declaring PID Variables
float setpointTemp = 30.0;
float kp = 200.0;
float ki = 0.1;
float kd = 10.0;
float integral = 0.0;
float prevError = 0.0;

void setup() {
  //Declaring Outputs
  pinMode(fetPin, OUTPUT);
  //Declaring Inputs
  pinMode(tempSensor, INPUT);
  //For serial communication
  Serial.begin(9600);
}

void loop() {
  //Checks how long has passed since the program began running, stores in
variable
  timePassed = millis();
```

```
  if (((timePassed - prevTimePassed) >= pollRate)) { //If the pollRate
has passed
    prevTimePassed = timePassed; //Save the timePassed to a variable
    temperature = tempSensFunc(); //Retrieve the temperature

    //PID Calculations
    float error = setpointTemp - temperature;
    integral += error;
    float derivative = error - prevError;
    float controlOutput = kp * error + ki * integral + kd * derivative;
    prevError = error;
    float heaterOutput = constrain(controlOutput, 0, 1023); //If the
value is below 0 or above 1023, bring back between bounds
    Serial.println("Control Output:");
    Serial.println(heaterOutput);
    analogWrite(fetPin, heaterOutput); //Write the output to the heating
pads
  }
}
float tempSensFunc() {
  int sensValue;
  float tempValue, celsius;
  sensValue = analogRead(tempSensor);
  tempValue = sensValue * (5.0 / 1023.0); //ADC
  celsius = (tempValue - 0.5) * 100.0;
  Serial.println("Temperature(C):");
  Serial.println(celsius);
  return celsius;
}
```