The Design Space for Interactive Pose Tracking as an In-Action Training Tool for Climbing

by Koen Vogel

January 19, 2025

Master Thesis
Interaction Technology

University of Twente

Supervision

dr. ir D. Reidsma
Human Media Interaction
Faculty of Electrical Engineering,
Mathematics and Computer Science (EEMCS)

dr. A. Karahanoğlu
Interaction Design
Faculty of Engineering Technology (ET)

Contents

List of acronyms

AI Artificial Intelligence

AR Augmented Reality

CNN Convolutional Neural Network

EDA Exploratory Data Analysis

FOV Field of View

GAN Generative Adversarial Network

GBL Game-Based Learning

HCI Human Computer Interaction

HMD Head-Mounted Display

HPE Human Pose Estimation

HR Heart Rate

HRV Heart Rate Variability

IICW Integrated Interactive Climbing Wall

IMU Inertial Measurement Unit

KPI Key Performance Indicator

LLM Large Language Model

MMC Markerless Motion Capture

MBVG Movement-Based Video Games

MoCap Motion Capture

MVC Maximal Voluntary Contraction

RFD Rate of Force Development

SMR Strength-to-Mass Ratio

TRL Technology Readiness Level

UES User Engagement Scale

VSM Video Self Modeling

VR Virtual Reality

XR Extended Reality

Chapter 1

Preface

1.1 Abstract

Climbing is a rapidly growing and evolving discipline, for which there is room for interactive technology-based interventions. Mapping out existing work reveals opportunities for motion-tracking technologies, but also a trend towards engagement focussed or out-of-action solutions, leaving a gap for in-action training tools to explore. Using a participatory, possibility-driven ideation process, design spaces for problems, possibilities, and solutions were iterated upon, resulting in four concepts. The most promising, according to end-users and experts, is a gamified on-the-wall warmup routine, derived from the discovered problem of climbers tending to skip conventional warm-up exercises.

A prototype three-phase warm-up game was implemented on an interactive projection-based climbing wall. It is supported by an inertial motion tracking suit, selected because of its accuracy and latency compared to other pose-tracking technologies. Using a repeated measures experiment (n=12), engagement was found to be significantly higher in the prototype compared to a conventional warmup sequence, on all metrics except perceived usability. Warm-up effectiveness was rated similarly by participants, though quantitative measurements through heart rate collection were ineffective, and should be improved. Overall, gamified warm-up is promising and should be considered to increase warm-up frequency, thereby preventing chronic and acute injuries.

1.2 Acknowledgements

The process of writing this thesis has not always been smooth. Although the topic of climbing has always interested me, the open explorative nature of the assignment meant there were endless possibilities and challenges to tackle within the field. This made it tricky to limit the volume and direction of work, as I am inclined to pursue every option. Ultimately, the body of work was more expansive than I would have preferred, including an entire chapter on comparing pose estimation, which is arguably out of scope, as well as a complex prototype installation. However, this does make the end product very complete. After two years of work, I can say I am proud of the research, prototype, and climbing wall installation, and can look back on it confidently. On top of this, there were some real highlights of working with climbers and building interactive technologies for them, which motivated and pushed me to finish the research as presented below. I hope you, the reader, have as much fun reading the work, as I had building.

Throughout the process, I had support and help from my colleagues, friends, and the faculty, who provided me with opportunities and pushed me to go beyond. In particular, I want to thank my supervisors Dennis Reidsma and Armağan Karahanoğlu for guiding me during the project and for the many sparring sessions we had to discuss my research. I also want to thank the Sports Interaction Lab, especially Dees Postma, Daniel Davison, and Sam Beard. The lab had a pivotal role in the development of my thesis, and the IICW platform in particular. It provided the funds to allow for such a large and complex project to be built, equipment to test and work with, and was a pleasant place to work. In addition, Irene Pieper was essential in the output of my ideation research. Her input and expertise shaped my direction and prototype. Irene, as well as the climbing association TSAC, also provided climbing holds for us to build and prototype with, for which they have my gratitude. Then there is my partner Sterre, who supported me through thick and thin, and is responsible for the beautiful title page graphic. Finally, I want to mention all the participants who took time out of their busy schedules to attend all my design sessions, interviews, and experiments.

Happy reading!

1.3 AI Disclaimer

This work makes use of generative Artificial Intelligence (AI), such as Large Language Model (LLM)s and image generation models. The goal is to enhance research fidelity, increase scope, and decrease workload while minimizing potential biases that can degrade our accuracy and research integrity.

1.3.1 Uses

Several sections of the thesis and work performed are supported in some way by AI models, which is always denoted in the relevant section. Generative images are used throughout the ideation process, in making personas and concept illustrations, as well as during game design, particularly in creating sprite assets for the prototype. LLMs are used primarily for programming tasks, ranging from prototype development, sensor comparison, and results analysis. Additionally, they supported report formatting tasks using LaTex, and some data structuring tasks like table generation. *Note that LLMs have **not** been used for writing contents of the report*.

The LLMs used for coding are Gemini 1.5 Pro[1], GPT-4[2], GPT-4o[3] and Claude-3-Sonnet-200k[4]. The generative image models used are Dall-E 3[5], Midjourney[6], and modified by Firefly[7] and/or online AI vectorizers[8]. The voice synthesis model is from Elevenlabs[9].

1.3.2 Bias

Because text-based uses of AI only apply tasks that have a clear measurable goal, without room for creative exploration (e.g. coding not writing), little bias is expected. Image models, however, have significantly higher risks of incurring biases in research output. As they are trained in a large database of existing images, often from the public domain, the potential biases to occur in the output image often come from the existing input.

The most critical database bias is in demographic representation, which includes societal racial and gender stereotypes. Most models have a form of countermeasures, but these are of varying effectiveness [1]. The bias is reflected in our concepts, as initial drafts consisted of white muscular male climbers only, in the output images. These could be countered by manually inserting our own bias, either in the generation or modification stage, to ensure demographic representation aligns with our target population. This marks our method of manually screening results and employing counter biases to adjust the accuracy.

Another possible database bias is *reinforcement bias*, where generated content aligns with the most widely accepted popular trends, excluding niche or specific topics. Generated images could, for instance, steer the ideation process, leading the design in a direction where it might otherwise not go. To counter this, before generation, clear goals are set up for the results, making them function as illustrated examples only.

A more complete list of possible biases is compiled by Mehrabi et al [2].

1.3.3 Ethical implications

Besides biases, the use of AI has some ethical implications which should be considered. First off, there is a morally grey area in how the training database for most models came to be; from what it seems, most databases are based on the public domain, including content for which the author did not give permission to use. This copyright discussion is especially relevant for images, as there are obvious influences of non-consenting artists visible in the generated output.

[1] https://deepmind.google/technologies/gemini/
[2] https://openai.com/index/gpt-4/
[3] https://openai.com/index/hello-gpt-4o/
[4] https://www.anthropic.com/news/claude-3-family.
[5] https://openai.com/dall-e-3
[6] https://www.midjourney.com/home
[7] https://www.adobe.com/nl/products/firefly.html
[8] https://www.kittl.com/feature/ai-image-vectorizer
[9] https://elevenlabs.io/

Another concern is the sustainability of the model's excessive power use. For each generated image, for instance, the equivalent amount of power of a single smartphone battery charge is consumed. This increases the climate impact of the thesis work, and therefore should only be used to accelerate the research significantly.

Chapter 2

Background

2.1 Introduction

Compared to other sports, the increasingly popular sport of climbing has seen few technology-assisted interventions. Where many sports disciplines have enjoyed the benefits of personalization, brought about by the proliferation of fitness trackers [3], climbers have yet to see such innovation. By enabling users to adjust climbs to their pace, skill, and body, they could optimize their training in various ways. This opportunity will be explored in this section. Both the relevance of this niche will be brought into view, as well as a foundation will be set for building potential solutions that aim to solve this issue, by analyzing technological and non-technological techniques for personaliation.

This report is part of a larger Thesis about using Interactive Technology as a means of personalization of climbing training. As such, this report will bring related work and background literature into view, to investigate the design space and find opportunities for technologies in this field. The conclusions in this work will steer the direction of the thesis, and form a foundation of knowledge in which technical implementations can be rooted.

Lastly, the user context is examined more closely, by conducting sessions with actual end-users. The goal is to get more insights into climbing behavior, paintpoints and highlights, to explore where opportunities lie for improvement, using technology enabled interventions. In short, this sections will explore the field of climbing from different perspectives; literature, state-of-the-art, and user context.

2.2 Exploring literature

This section will use literature to explore the field of climbing, by examining common climbing processes. Then we set out to find the most effective performance indicators for climbing training, by running a deeper analysis on related studies. These works will be screened from a selection of trusted online libraries, to have a complete overview of the relevant topics;

- ACM
- Scopus
- PubMed

In addition to database searches, snowballing techniques will be exploited to cover as much of the space as possible. This process will be assisted by AI-enabled tool *ResearchRabbit*[1] to discover links and relevant matches and make sure no gap in the literature is left.

2.2.1 The sport of climbing

Climbing is a physically demanding and mentally challenging activity that involves scaling vertical surfaces using specialized equipment and techniques. While its origins can be traced back to early human history as a means

[1] https://www.researchrabbit.ai/

of accessing remote locations, contemporary climbing has emerged as a popular recreational and competitive sport. Both indoor and outdoor climbing have grown in popularity in recent years, with purpose-built climbing walls providing a controlled environment for practice, training, and competition, while outdoor climbing provides a more unpredictable and dynamic challenge. The evolution of climbing as a sport has led to the development of various disciplines, including sport climbing, bouldering, and traditional climbing, each with its unique challenges and rules. With a growing number of dedicated practitioners and competitions worldwide, climbing has become a recognized and respected sport within the field of sports, as shown by the admission of the climbing sport into the Olympic Games in 2020[2].

The variety of climbing disciplines provides a challenge in the design of any personalization or training tool. There are significant differences in goals, technique, endurance, and strength. This can be seen in the work of Fanchini et al [4], where the muscle function is compared among climbers. They found that bouldering climbers had significantly higher strength in both Maximal Voluntary Contraction (MVC) force and Rate of Force Development (RFD).

With these differences, how can we design functional systems that are effective for all disciplines? For the entire research and design process, the scope has to be narrowed down to accurately measure, design, and evaluate possible technical implementations. While not a necessity, it is beneficial to select a climbing discipline with a high transfer (the ability to apply the learned skill in a novel context [5]) to other disciplines, to increase the overall impact. One of these is *bouldering*, which shows climbing performance to be indicative of outdoor rock climbing [6]. Throughout this thesis, we aim to show valid results for climbing as a whole but may use literature and cases specific to the bouldering discipline.

Bouldering is an indoor climbing discipline that involves scaling shorter sections of a wall marked by colored holds without ropes or harnesses. In contrast to outdoor rock climbing, the height of the walls is restricted, typically with a maximum of 4.5 meters. The different colored holds typically form routes of certain difficulties, which are graded and categorized on skill level in a variety of scales.

Due to limitations in route length, bouldering routes are often more dense and rely on challenging moves and hold shapes. They can therefore be considered a puzzle, and are also described as climbing problems or challenges. The goal of a climber is thus not the be the fastest, but to be technically skillful enough to complete specific routes, using a combination of strength, balance, grip, flexibility and strategic thinking.

2.2.2 Injuries

Among sports, climbing, and bouldering are some of the riskiest disciplines concerning the rate of injury. On pretty much any skill level, climbers in both indoor and outdoor scenarios are prone to injuries from a variety of causes. The extremity of the injuries is relatively uniformly distributed [7]. The anatomical location of the injuries is most common in the fingers and shoulder, and the specific injuries range from Tendon strain, Muscle strain, Joint sprain, Tendonitis, and bone fracture [8]. In the whole climbing population, the most common cause of these injuries is overuse, but the use of strenuous moves can be a big contributor as well [9], [10].

Overuse is a type of chronic injury, which Neil et al described as ”injuries due to overuse are characterized by a mechanism of gradual onset and an underlying pathogenesis of repetitive microtrauma” [11]. These prevalent overuse injuries have a variety of causes. The most significant factors in a climber that predict overuse injury is the type of climbing, with bouldering as the most injury-prone, and lead grade [12]. Years of climbing was also mentioned as a predictor, with injuries being more common with climbing experience.

On the other hand, acute injuries related to strenuous moves were strongly associated with the difficulty of the route, especially in indoor bouldering scenarios [13]. The higher the rating of a route within a grading scale, the higher the probability of injuries in climbers.

These injuries in climbing can often impact the quality of life, and ability to continue climbing. With over 700 surveys analyzed, McDonald et al [8] saw 44.9% of respondents experiencing some form of chronic symptoms after suffering a climbing injury, and 28% of climbers could not manage to return to climbing after their injury. With many of the injury causes being related to climbers choosing routes that are too difficult, personalizing routes to the climber seems a desirable outcome.

[2] https://olympics.com/ioc/news/ioc-approves-five-new-sports-for-olympic-games-tokyo-2020

2.2.3 Learning Process

When designing technology in any sports context, it is important to examine the current state of training. How do athletes learn and practice their discipline? What are the most effective techniques at this time? And what are the opportunities and challenges in designing technologies to support this process?

While moving is a natural and inherent capability, *skillfully* controlling movements of the body to achieve a certain goal is referred to as **Motor Skills** in movement sciences [14]. This can be anything from climbing, and playing the piano, to operating woodworking tools. The acquisition of these skills, meaning enhancing or learning new ones, is then defined as **Motor Acquisition**. Together with the ability to maintain these skills (*Retention*), and the ability to apply the learned skill in a novel context (*Transfer*), this is known as **Motor Learning** [5].

Typically, the practice of sports should resemble the performance context as much as possible, to maximize the transfer [15]. However, technological interventions embedded in sports practice can be invasive, e.g. on-body sensors or Head-Mounted Display (HMD)s. These implementations can impact the transfer of skill and therefore the effectiveness of the intervention itself. Precautions need to be taken to keep experiments as similar as possible to the actual performance context of the sport.

In the end, the design of technological interventions for training purposes should maximize transfer, motor acquisition, and motor learning in general. As opposed to a general approach, a training tool tailored to the climber could offer an advantage, by closing the motor skill gap. This way personalized training could make motor acquisition more effective.

2.2.4 Training flow

Bouldering training takes place in an indoor bouldering hall. A training typically consists of a short warming up, before a number of climbs are executed. A climber will choose a route to climb either using a training schedule, or more often by improvisation, using a mix of their proven skill level, body proportions, and personal preference. Generally, a single route can be split into two distinct aspects, Climbing and Between-Climbing, e.g. in-action and out-of-action. An overview of a climber's flow can be seen in figure 2.1.

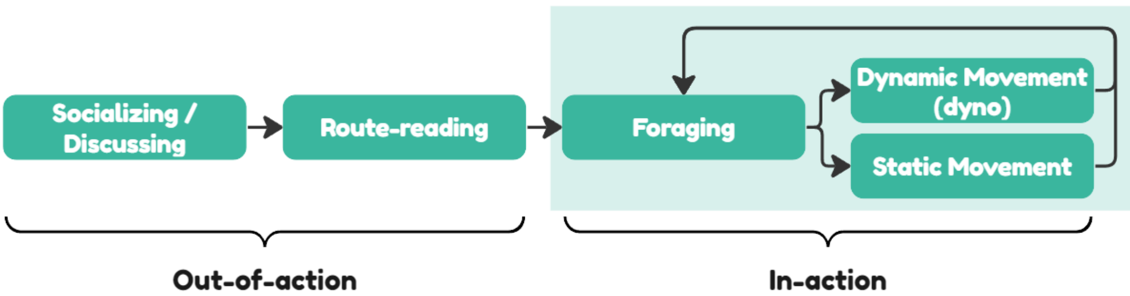


Figure 2.1: The flow of a single bouldering route during climbing practice

Warming up

Warm-up exercises are a well-known benefit for nearly every sport discipline, including climbing. According to Horst [16], "Five to fifteen minutes of light aerobic activity followed by a few minutes of mild stretching will increase the temperature and range of motion of the working muscles". This is confirmed by consulting professional climbing coach Irene Pieper for this project, as well as external sources[3], who specified the importance of dynamic stretching over static stretching. Together with the climbing expert, warm-up exercises are broken down into four distinct phases;

- Aerobic activity (cardio), for blood flow
- Dynamic stretching, for loosening muscles

[3] https://www.climbing.com/skills/climbing-warm-up/

- Grip training, for finger blood flow
- Climbing difficulty ramp-up, to avoid overloading

To maximize readiness, a complete climbing warmup should incorporate all these elements during its exercises.

Route-reading

To decrease the cognitive load during the climb, thus improving efficiency and speed, climbers often explore the route pre-climb from the ground. In this out-of-action process, called route reading, athletes memorize their route, pre-planning the holds, grips, and moves required for a successful climb. Young et al [17] demonstrated how essential this process is, by comparing climbs with and without route-reading beforehand. Climbers of similar skill levels differed in their climbing speed over the same route, showing a need for route-reading practice as a part of climbing. Again, this process takes up a cognitive load in the climber, with inhibited climbers during route-reading putting down worse performance numbers overall [18].

Foraging

To navigate during the climb, an athlete has to strategically choose which holds to use, and subsequently determine the the right kind of grip. This process is called foraging and can be roughly divided into two categories, visual and tactical scanning [19]. As the name implies, climbers use their vision and their hands in the discovery of holds/rocks, which then feeds into the decision-making process. With years of experience, this process gets more efficient, as shown by Hartkop et al [19], who found that experts use tactile exploration far less, suggesting they rely more on visual clues to acquire information. The findings, including how to grab holds, and the direction to shift body weight are called *Beta*, a climbing synonym for external information used in successfully finishing a route.

This foraging process is a vital part of the climbing discipline and can be a complex task with a significant cognitive load. Blakely et al [20] confirmed this by adding interference tasks during a climb. They found the impairments detrimental to climbing performance, suggesting the complexity of the task and the need for focus.

Movement

After foraging for *beta*, the climber is attempting their choice of move. In climbing there are a large number of different moves, with often multiple correct options for a single hold or section within the route. Choosing the right move is (mostly) based on the position on the wall, arm and leg reach, body weight distribution, and energy expenditure. Roughly, climbing moves can be divided into two different types, static and dynamic movements. A description of the most used moves of each type goes as follows;

Static Movements

- Smearing: Applying pressure with the foot on a featureless or low-friction surface to maintain balance and control.
- Edging: Using the edges of the climbing shoes on small footholds or ledges to gain stability and traction.
- Lock-off: Holding a static position with the arm muscles engaged at a specific angle to maintain stability and control.
- Rockover: Shifting body weight from one foot to the other while maintaining contact with the wall to surmount an obstacle or reach a higher hold.
- Flagging: Extending one leg to the side and using it as a counterbalance to maintain balance and control while reaching for a hold. Dynamic Movements:

Dynamic Movements

- Dyno: Making a dynamic leap or jump from one hold to another, often bypassing intermediate holds.

- Campus: Using only the upper body to powerfully move from one hold to another without using the feet or legs.
- Gaston: Applying outward pressure with the hand against a hold to create leverage and generate momentum for a dynamic move.
- Deadpoint: Executing a controlled, dynamic movement to reach a hold at the peak of its swing, using body tension and timing for accuracy.
- Mantle: Performing a quick, explosive movement to transition from a horizontal position to a vertical position, often involving pushing down on a ledge or hold while pulling up with the other hand.

2.2.5 Performance Indicators

Both recreational and competitive climbers are known to use bouldering halls for training, even if they typically climb outdoors. To track progress, climbers, as do athletes of most types of sports, use some metrics to get feedback on their improvement. This section sets out to find performance metrics of the climbing discipline to use in research and implementation. Then, the metric will be broken down into a cohesive set of Key Performance Indicator (KPI)s for bouldering or climbing.

Performance metric

By far the most used performance metric in both indoor and outdoor climbing is the best ascent reached by a climber, expressed in climbing grade. Best ascent is the most advanced route a specific climber has completed, which is typically self-reported. While effort has been made to standardize bouldering grades, especially in the context of research [21], the overall landscape is quite scattered. Different climbing rates originate from different countries and commonly consist of combinations of letters and numbers [4], making conversions relatively simple. This work uses the Fontainebleau grading system, which denotes difficulty in numbers 1 to 8, with letters a, b, c, and d as subdivisions.

The use of climbing grades in indoor climbing proves effective and is one of the most widely used metrics. Existing tools and solutions already exist that claim to accurately predict climbing grades based on mental and physical ability[5], suggesting a strong correlation. Furthermore, even climbers themselves appear to accurately assess their own ability measured in climbing grade. This is shown by Draper et al [22], who found no significant differences between self-assessed ability and self-reported reached ascent, both in climbing grade, except for a small over- and under-estimation for males and females respectively.

Indicator Analysis

KPIs, inspired by the finance sector, are measurable values indicating progression towards an objective. Establishing these for athletes helps them practice and set goals for performance capabilities. In a general sports context, performance indicators can be categorized into a few types. Hughes and Bartlett defined these as Match classification, Biomechanical, Technical, and Tactical performance indicators [23]. These indicators have different characteristics and goals, and the authors put forward recommendations about the use and application of these indicator types.

An overview of the found performance indicators for climbing can be seen in figure 2.2. Performance Indicators categorized as *Match Classification* have already been described as Performance Metrics in section 2.2.5. *Technical* performance indicators are values classifying the technical skill and performance of an athlete, such as pass rate and accuracy of goal shots in soccer. In climbing, these could be compared to climbing speed, fall rate, and successful jumps. Tactical, also described as strategic, indicators would be route reading and planning, both in-situ and ex-situ, see section 2.2.4. The more interesting category, especially for technological interventions, is the biomechanics.

[4] https://alpinist.com/climbing-grade-comparison-chart/
[5] https://test4climbing.com/climbing-assessment

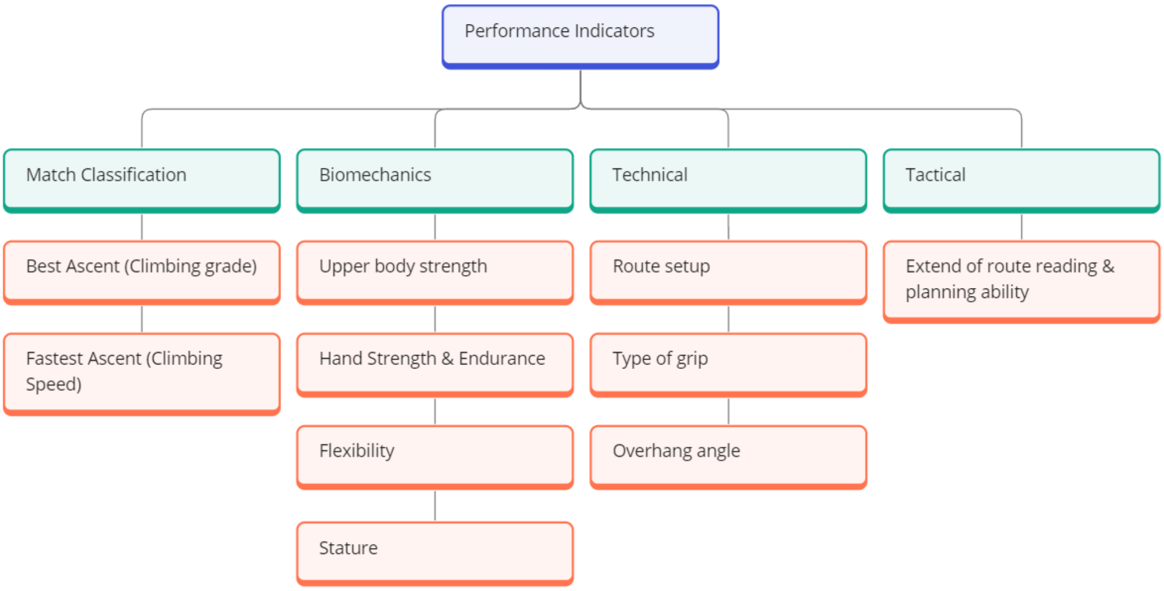


Figure 2.2: Performance Indicators for climbing, per category

There are two types of biomechanical determinants, anthropometric and physiological [24], which both can play an important but different role in personalization. Anthropometric determinants have been studied thoroughly, and clear trends can be seen among high-level climbers, which suggest a correlation with performance. Among these are small stature, very low body fat, and high muscle-to-mass ratio [25], which in a personalization system, would function as an input parameter, rather than targets. Physiological determinants, however, are more clearly actionable properties, like grip strength, endurance, and aerobic capabilities [26] [27]. In personalization and training systems these could be described as key targets to work towards. An overview of specific physiological determinants can be seen in table 2.1, together with units of measure.

Hand-Arm strength & endurance

Balas et al [28] tested hand strength and especially endurance in climbers of different skill levels, and found a clear correlation with performance. Macleod et al [29] confirmed that finger strength, measured in MVC, was significantly higher in climbers (485 N) compared to non-climbers (375 N). For both endurance and strength, however, it is interesting to note that even greater variance can be explained by structural equation modeling, where the properties are combined with the athlete's mass to find more significant indicators of climbing performance in Grip Strength-to-Mass Ratio (SMR) and MVC to Body Mass ratio.

One of the best exercises for hand strength endurance is the finger hang. This endurance test has the athlete hanging from a specific grip for as long as they are able, measuring the time in seconds. This exercise has proven a successful distinguishing metric [30], for the whole spectrum of skill levels in climbing athletes.

Table 2.1: Overview of KPIs for climbing performance

Determinant	Type	Measure	Source	Unit
Hand Strength Endurance	Biomechanical / Physiological	Finger hang	[30] [28]	Seconds
		MVC	[29] [26]	Newton
		MVC to body mass	[29]	N/kg
		Grip strength to body ratio (SMR)	[27] [29] [25]	ratio
Upper Body Strength	Biomechanical / Physiological	Bent-arm hang	[28]	Seconds
		Powerslap test	[31]	cm
Stature	Demographic / Anthropometric	Body-fat	[25]	%
		Muscle-to-mass ratio	[25]	%
		Mass	[25]	kg
Flexibility	Biomechanical / Physiological	Lateral Foot Reach	[32]	cm
		Adapted Grant foot raise	[32]	cm
Climbing Activity	Demographic	Climbing Experience	[24]	Years
		Volume of climbing	[24]	Meters /week

2.2.6 Personalization

As discussed in chapter 2.1, there is reason to believe personalization in climbing specifically is very beneficial. However, there do not seem to be many existing trends or interventions out there toward that goal.

One of the few research projects working on climbing personalization is by Ivanova and colleagues [33], who aim at providing decision support to athletes by building a recommendation system for outdoor rock climbing. They first collect user data as parameters through the climbing app and online platform from their commercial partner vertical-life, which have assembled a detailed database. They then designed a recommendation engine based on similar engines from other sports, that builds a user profile based on the personal preferences of climbing discipline, climbing grade, climbing style, and wall steepness, see figure 2.3.

They included contextual factors like location, seasonality, and accessibility [34], and combined their system into a functional high-fidelity website [35], which was well-rated on usability and is aimed for public release as of writing.

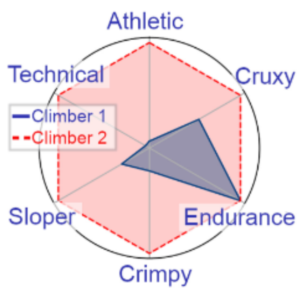


Figure 2.3: 'Climbing preference' as a personalization factor, source: Ivanova et al [33]

Figure 2.4: Birds

2.3 Exploring the field

While the idea of personalization in climbing using interactive technologies is relatively novel, the climbing sport is rich in technological solutions. This section aims to explore the state of the art of existing climbing interventions, both in research and practice.

2.3.1 Modeling

The second step in the 'see, think, act' paradigm is thinking. Between input and output in an interactive climbing wall, how is the data modeled and augmented? In this section, we answer that question by examining literature & related work, looking specifically for the technologies that process or tailor climbing data in some way, and which could prove useful in building a personalized interactive climbing wall.

In recent years, AI exploded in popularity, due to its rapid advances in capabilities. While the umbrella term describes a lot of different machine learning technologies, especially generative AI and LLMs are trending as of writing. While these are very promising technologies, their application in sports is limited for now, especially for climbing. However, alternative machine learning algorithms, which have matured a little, have propagated the sports world much more.

A perfect example is the work by Naderi et al [36]. The authors work on path and movement planning using humanoid agents, climbing given digital bouldering routes. Their approach of calculating routes and moves using a graph and custom heuristics works well, and even accounts for individual physical differences in climbers, like arm length.

If you reverse the problem statement, you find the work of Stapel F [37]. Instead of giving a route as input, their algorithm generates its own route, based on a system board and the climber's capabilities as input. As system boards allow for an almost infinite combination of holds to form a route, this work can process a lot of data to form a promising personalization system, if though it has not been proven yet. As these training boards, with a predefined hold layout, often already include a large database of user-generated routes and challenges, it is yet to be determined if tailoring algorithms are better suited to filtering existing routes, instead of generating new ones.

2.3.2 Feedback Modalities

In a system for complete climbing training, the final phase is closing the loop by presenting feedback to the user. There, what has been tracked and modeled will come back to augment the user's behavior either in-action or out-of-action. While this feedback can come in many forms and will depend on the data, we can generally break it down into sensory modalities. These are auditory, visual, tactile, or olfactory user feedback, which we translate to technology medium (e.g. haptic technology for tactical feedback). The olfactory and auditory senses in climbing have been omitted as no literature could be found on the topic.

The more immersive user feedback is, the better. Mixed or Extended Reality (XR) technologies excel in immersing users in believable environments, and can therefore effectively integrate (data) visualization into the environment. While XR is a semi-continuous spectrum, it can roughly be divided into two categories, Augmented Reality (AR) and Virtual Reality (VR), which both have shown promise in sports and climbing specifically.

Virtual Reality

VR is characterized by complete user immersion. This can be done in a variety of ways, such as using projectors, but the most common and immersive technology is HMDs. Using these headsets in sports is not unheard of, but going beyond simulation to integrated sports training is less common. One example is in rowing. Besides gamification elements, the setup by Delden et al [38] aims to improve rowing training in a virtual environment, while rowing on an indoor ergometer. They accomplish this by visualizing real-time position from external VR trackers and using the data in error-detection algorithms, which can motivate the rower to adapt their technique. Due to the use of detailed user movement data, personalization is a relatively small step away from their current technique improvement study.

In climbing, VR has yet to be used for just training, instead there have been solutions with different situations and goals. For example, there are a lot of climbing games and simulators, which are described in section 2.3.3. More towards serious applications, Tiator et al [39] proposed and developed a system architecture for a VR simulation training for fear of heights. By putting climbers in a frightening and risky environment (e.g. high height) in an actual safe space (low height), they allow risk-free training.

Then there are the uses of VR on climbing or system walls. A simple version of this concept is proposed by Kosmalla et al [40], where users with HMDs are climbing a virtual version of a real bouldering wall, but visualized as an actual rockwall on a mountain. These setups can be described as Mixed Reality, as they incorporate physical elements into a digital experience. However, in this work, they will from now on be classified as VR, as they are distinctly different from AR experiences using overlays and augments on top of climbing walls.

Kosmalla et al [41] tried to tackle a different problem, specifically for climbing in VR, namely the limited play space. Any virtual environment aiming at realistic rock climbing requires an extremely large, and especially tall physical climbing wall, to match the grips to. To circumvent this, the authors designed a virtual climbing system based on a physical treadmill, the climbstation[6], which enables a theoretically infinite climb to be performed. Their showcase of a virtual skyscraper climb performed well but requires more user testing to evaluate.

Figure 2.5: Using a drone with a laser pointer to direct climbers in a virtual environment [42]

While self-described as Mixed Reality, the application by Tiator et al [42] uses an HMD to simulate climbing on a rock wall. This would not be that innovative, if not for the inclusion of a drone in their setup. To simulate the guidance often given by 'on the ground' climbers, see section2.2.4, they included a virtual laser pointer, which can be controlled by ex-situ climbers through the movement of a quad-copter. This looks to be a creative, though slightly convoluted way to include a social aspect to an otherwise isolated experience.

In both serious and game-based VR climbing applications, immersion plays a central role. This is why Kosmalla et al [43] tested and stressed the importance of tracking the user's hands, and especially feet, in virtual environments. As climbers are referring often to the positions of their limbs in actual climbing situations, including that process in virtual approximations increased the realism and thereby skill of virtual climbers. While hands are present in most applications, if only an approximation through controllers, feet are often absent and should be taken into account in any future VR climbing solutions.

Especially in the context of sports, VR has one major disadvantage, which is nausea. Also known as cybersickness [44], this side-effect affects users differently, but mostly causes disorientation, nausea, and visual discomfort. While there are a variety of factors, such as biological features, age, and susceptibility [44], the main cause of cybersickness is a movement mismatch between the virtual and real environment. When in a virtual roller coaster, for example, the body expects a significant physical response in orientation and acceleration, while the body of the user sits completely still in the real world. The larger this movement offset is, the higher the probability of cybersickness. This is exactly the reason interactive sports applications face a significant challenge in using VR effectively. Sports with a static non-moving reference point such as the boat in rowing can decrease the effects, but sports characterized by high acceleration or sudden movements, such as climbing, are very prone to cybersickness.

[6] www.climbstation.com

Augmented Reality

An arguably more promising technology for climbing is AR. This is in no small part because in contrast to VR, the environment/play space needs less modification to adapt to the technology. Instead of creating a custom climbing wall, AR-enabled interventions can often work on a variety of climbing/bouldering walls, or sometimes even all of them, making the technology much more flexible. There are a few examples of AR -enabled climbing interventions, which can be roughly divided into the categories augmented climbing walls and mobile AR.

Augmented climbing walls, like the one by Kajastila et al [45] [46], overlay information onto an existing wall. While they use a high-power projector, a climbing wall with integrated LEDs, such as the Kilterboard[7] and moonboard[8] could come close in functionality. By aligning the projection with a compatible climbing wall or system board, information can be overlayed onto specific holds. This becomes a powerful system when combined with tracking technologies such as Human Pose Estimation (HPE), as described in section 4.1, enabling the projections to react on the user's movement. While tracking-less systems are limited to showing routes or goals for the climber to reach, tracking-enabled AR interventions can turn climbing into a game, by showing ever-changing goals to reach, enemies to dodge, or scores to beat.

Besides gaming, this type of technology has been used for training purposes as well. Kosmalla et al [48] proposed their *ClimbVis* feedback system, which demonstrates climbing techniques during a user's climb, using different projections, as well as a Google glass. This is done by showing a projected video of a climbing instructor, which the climber can use as a reference. While the Google Glass variation was not well received, the projection-based feedback systems showed promise, with their participants preferring a life-sized version of the feedback system.

The same authors also pioneered a more versatile AR projection system, called the *BetaCube* [49]. They are less focused on a complete climbing intervention but are improving the technology itself, by making it more adaptive. Instead of being confined to a single (or multiple) pre-calibrated climbing wall, they achieve a projector that can calibrate to **any** climbing wall, including overhangs. Their integrated mobile prototype also includes a full HPE system using the Microsoft Kinect, and comes with two interactions, which they plan on expanding.

In contrast, climbing interventions using mobile AR typically don't use pose recognition. This is because the biggest difference between the two categories is that mobile AR is used primarily *Out-of-action*. This means that users use the application before or in-between climbs, mapping out their route in the route-reading process, described in section 2.2.4. Augmented Climbing walls, on the other hand, can be used during the climb of a user, meaning *In-action*.

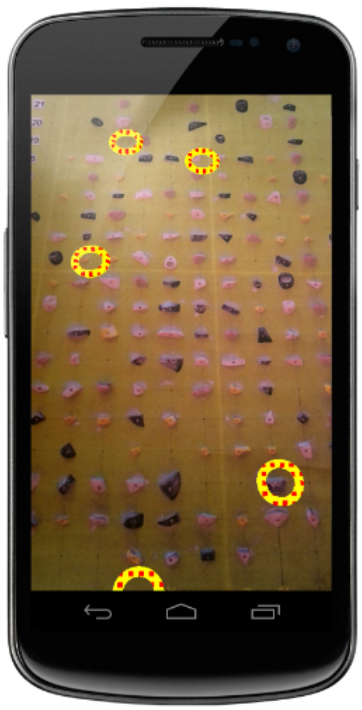


Figure 2.6: AR interface for climbing problems, as a mobile app [47]

Mobile AR, such as the application by Daiber et al [47], typically don't focus on game elements, but on climbing training improvements, using a database of challenges to share, create and visualize, such as described in section 2.3.3. Because mobile phone cameras are dynamically moving and not statically mounted, such as with most projection systems, they have to compensate for the user's hand movements while visualizing data. They thus have to recognize the climbing wall and keep track of it, making use of more complex AR algorithms. As the technology has come a long way, these tracking systems are readily available, even in mobile AR frameworks like ARKit, ARCore, and ARFoundation. Still, these complexities explain why the application by Daiber et al only works with

[7] https://settercloset.com/pages/kb-overview
[8] https://moonclimbing.com/what-is-moonboard

a small selection of climbing walls, against their preference, as they would need to have a large database of recognizable anchors to keep track of the wall.

2.3.3 Interactive Task-setting

Besides the application of specific technologies in climbing, a few general directions of climbing innovations can be distinguished. These will be explored in this section, together with existing work in the field.

Simulation

An interesting game-based technique in sports is simulation games. Rather than augment existing physical sports, these games attempt to closely simulate or copy the experience, often in digital form. This can be a low-friction training method, by allowing the user to practice sports at home or in a convenient location, without needing the regular equipment. In climbing, these arguments make sense, as the sport takes place in specialized locations like climbing halls, and require specialized equipment and clothing to perform.

An example of an applied simulation game is The Freeclimber VR[9], a "game" that aims to simulate the real climbing experience as accurately as possible, using VR. This voxel-based PlayStation game is made by an experienced climber, who applied their climbing skills to their digital experience. These applications can be confused with climbing games that focus on entertainment value, such as The Climb [10], and therefore make concessions concerning accuracy. This balance between goal and entertainment-oriented serious games is described by Delden et al [50], who argued the importance for designers to consider the effectiveness of the approach early in the ideation process.

Social Collaborative

For many climbers, social interaction is an important part of the climbing experience. A climbing or bouldering gym can facilitate a social gathering place and a way of meeting new people. More importantly, some core aspects of climbing sports can be enriched by sharing them with others. First is route reading & planning, a pre-climb strategic process described in section 2.2.4. Discussing routes with other athletes can lead to the discovery of new techniques and improvement in the strategic assessment of climbing routes. Furthermore, climbing with other Athletes is often done competitively, which is a strong motivator for high climbing performance.

Daiber et al [47] designed their intervention focused on this collaborative aspect of climbing training. Their approach uses AR to project routes and problems on a specific system board climbing wall, making it easy to replicate. This then supports their proposition of sharing, creating problems and challenges for friends, possibly even the general public. While the initial feedback from their participants was promising, collaborative training needs to be explored further.

This basic concept of the sharing of climbing problems is not that new, however. In the last decade, more basic technologies like mobile applications[11] have been used extensively for collaborative training. Functionalities like creating, sharing, and browsing climbing problems using images and text are common, while some[12] even contain online databases of challenges in bouldering/climbing gym locations. Users can typically rate or review climbing problems, creating a curated high-quality collection, which can be filtered and searched through by users to tailor their experience.

One of the best examples of this is from the manufacturer of an actual climbing board. Moonboard[13] is a system board for climbing, with a modular set of grips, adjustable overhang angle, and integrated LEDs in each grip. The Moonboard application works similarly to other climbing apps, with their database of climbing challenges, but with one powerful addition. User-created problems can be 'projected' on the physical moonboard LEDs, thus visualizing the path an athlete should take. This approach removes the need for route-reading & planning completely, which can be considered a disadvantage, but is overall extremely intuitive for the athletes.

[9] https://indreams.me/dream/mgArSjJoDhZ
[10] https://www.theclimbgame.com/
[11] https://www.theclimbingguy.com/climbing-mobile-apps/
[12] https://toplogger.nu/en
[13] https://moonclimbing.com/what-is-moonboard

In personalization, social collaborative features like these could play an important role. A large well-labeled user-created database, for example, could be filtered down to offer tailored problems for users based on specific criteria. Or the personalization engine could adjust its algorithm based on the achievements and characteristics of other climbers. Furthermore, effective sharing methods of climbing routes could be used by climbing coaches to assess an athlete's training schedule.

Gamification

One of the trends that can be identified is the use of gamification and Game-Based Learning (GBL) in climbing training and sports in general. GBL in sports, refers to the design of game-like experiences to foster and train real competencies [51]. This is not to be confused with gamification, which means adding game-like elements to existing training applications and programs. Both techniques have been applied to sports applications, especially since the proliferation of electronic fitness devices, and both have merit. Tóth and Lógó [52] analyzed different game elements added to sports applications and measured the effectiveness among other things. While the authors found that users did not at all choose applications with game elements in mind, the game elements related to progression had the most positive impact on the volume of workouts, showing that it is a very effective tool.

More specifically for climbing, Jenny et al suggested that Movement-Based Video Games (MBVG) can be effective in teaching climbing strategy [53]. They tested an intervention using a Kinect-based climbing game against on-wall climbing. While the lack of extreme movements and strength required differs from authentic climbing, strategy-making and arm movements were perceived as similar.

However, there can be disadvantages to applying game elements to climbing training and sports in general. Jensen et al analyzed trends of using novel game elements specifically in handball, but they propose three challenges for sports-interactive training games in a broader sports context. [54].

- Maintaining relevance when translating physical elements into digital representations.
- Choosing an appropriate level of sensing as game input.
- Introducing points in training exercises without reducing sports relevance.

The authors also provide some strategies for circumventing these stated issues, which have to be taken into account during the design of gamified climbing training applications.

While not strictly gamification, Kajastila and Hämäläinen developed an augmented climbing wall [45] [46], which is designed primarily for climbing-related games. Their solution added a layer of gamified elements on top of the wall, that added fun to various climbing training's. These 'games' were well perceived and are still in use as of the time of writing, as a commercialized venture[14], primarily by children.

2.3.4 In conclusion

While climbing as a sport has clearly seen an uptake in popularity, technology-supported climbing applications are lagging behind, especially on the topic of personalization. However, there are quite some technologies that seem promising and could be applied effectively to climbing, as indicated by a significant Technology Readiness Level (TRL).

[14] `https://www.valomotion.com/valoclimb`

2.4 Exploring user context

To design a climbing application, a clear understanding of the end-user if crucial. A proven design method for this goal is participatory design, also known as co-design. Rosenzweig [55] defined participatory design as ”Participatory design is a process that involves stakeholders and end-users in the early stages of design to ensure that the result meets their needs and is usable”. Both in research and in product design, it has been used to advocate the interests and requirements of the end-users, thereby delivering more effective solutions. While there is no one detailed method that works for all, there are many design activities that involve users, that fit within the participatory design philosophy. As the fundamental goal of good design is understanding the product user, Rosenzweig [55] suggests starting off a participatory design process by creating a persona.

Persona

A persona is a common tool to create empathy and understanding for the end-user [56] and defines a more clear boundary of the design goals. While we previously vaguely described them as ’climbers’, the target users of this thesis can be more clearly defined in the form of one or multiple personas. It’s important that these personas accurately reflect segments of the target users, and provide a comprehensive overview of its population, as to avoid discrimination [57].

While ideally, this is done by basing the personas on a lot of analytics and data about the target users, in reality, this is often done using tacit knowledge. Mahamuni et al [58] argue that this so-called *Concise Personas* can speed up creation, and their comparison established the use of tacit knowledge to be ’useful and adequate to create workable personas’. Data-based personas are still preferable to prevent subjective biases from the researchers, as well as to capture more of the target population.

After a short general description of climbers, we segmented the climbing population into four distinct personas, see figure 2.7. These should cover a large part of the population, though not all. For example, all archetypes are physically fit, and not injured or impaired, which can be considered a bias. The images are generated by a Generative Adversarial Network (GAN)[15], a type of AI model, as to avoid copyright issues.

2.4.1 Possibility-driven design

Traditionally in product design, participatory or not, the ideation process is problem-driven. This means designers start with a given problem, or discover problems during user study experiments. While this is a completely valid and effective method, it might fail to discover good inventions that improve the experience without solving a direct problem. This is where possibility-driven design comes in [59]. Not a replacement, but rather complementary to problem-driven design, this method starts the ideation process by exploring highlights or ’happy moments’ within an experience, instead of the challenges and issues. Salamanca et al suggest a structured approach, where these positive moments can be clustered in a converging process, after which the designer ends up with a few key design themes.

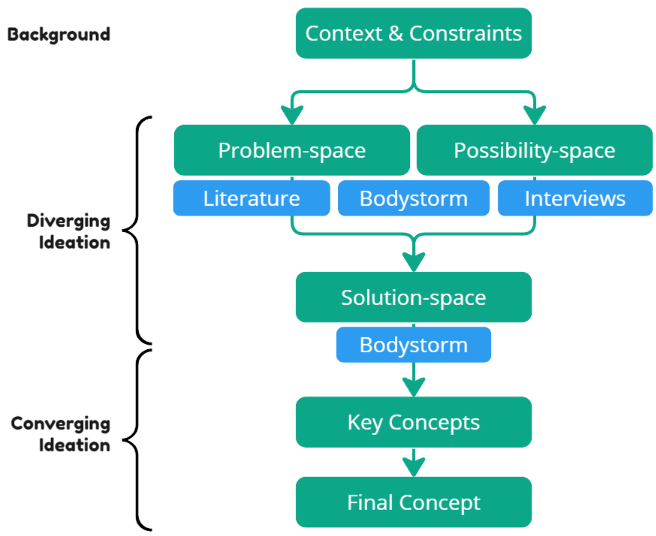


Figure 2.8:

[15] https://www.thispersondoesnotexist.com

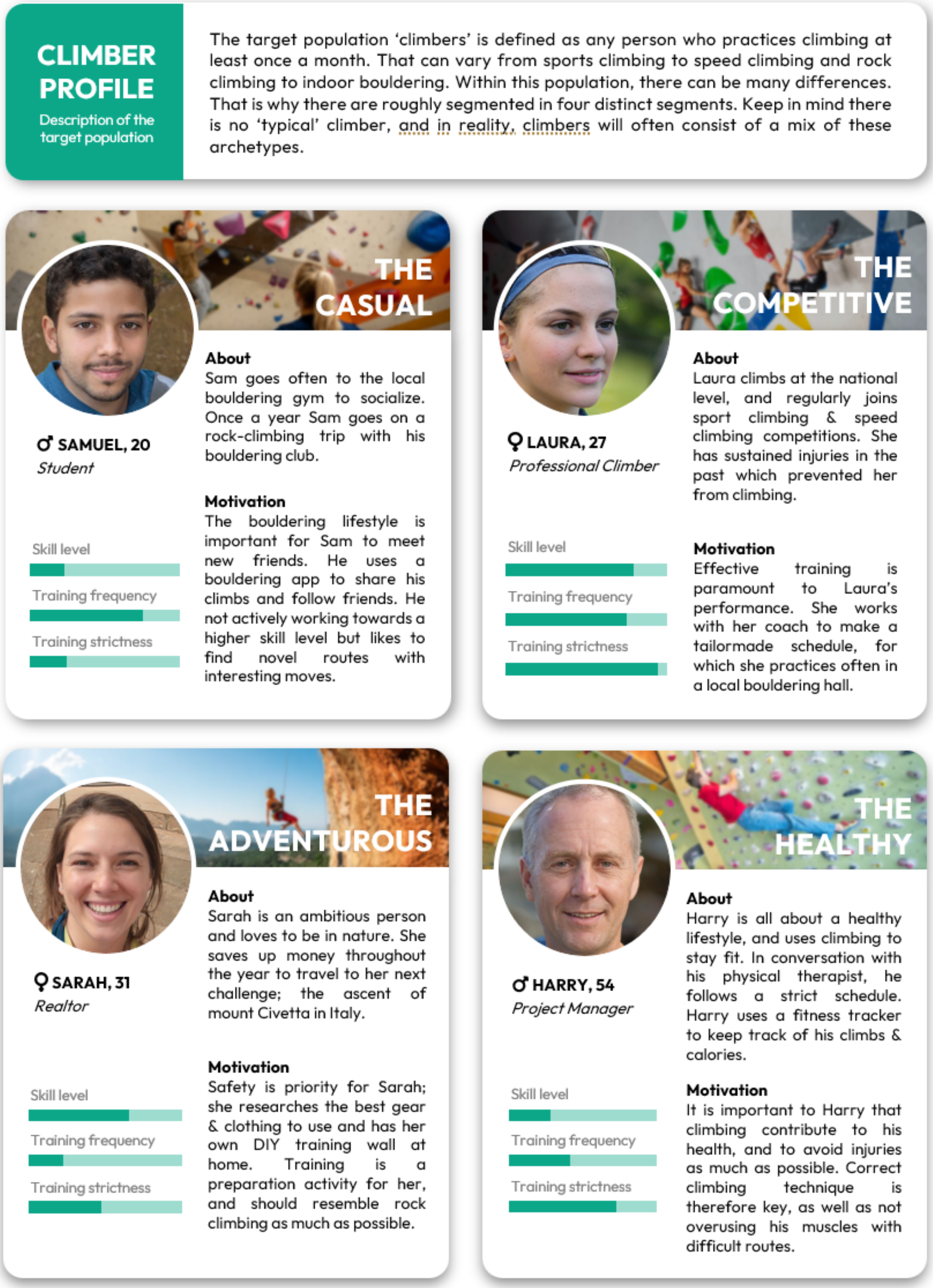


Figure 2.7: Overview of the climbing population, divided into four segments

A combination of problem-driven and
solution-driven approaches should be a more thorough way to bring as much of the design space in view as possible. Together with the solution space, these problem and opportunity spaces will form the backbone of this ideation process. An overview of the process can be found in figure 2.8.

2.4.2 Background Interviews

The first step within the diverging phase is defining our problem space. While several problems in the domain of climbing have been found in background literature, it's always beneficial to explore the end-user perspective, as per participatory design. This helps confirm previously defined problems, as well as expand upon them.

Objectives

- What impact do climbing injuries have on climbers?
- What does the typical climbing session, both in-action and out-of-action, look like?
- To what extent is there a need for mid-climb guidance?
- What strategies are employed by climbers to attain progress?

Method

As found in chapter 2, climbers of different skill levels have different training methods and, thus different needs, as seen in section 2.4. To represent a variety of the population, three climbers were selected of skill levels 3-7 on the Fontainebleau bouldering scale, to be recruited for a semi-structured intervew [60].

For each participant, a session of up to 20 minutes was held with informed consent. Afterward, the interview was conducted, with the audio being recorded and anonymously transcribed after the session. Being a semi-structured interview, the script consisted of both closed and open-ended questions, a few per goal. The complete list can be found in appendix A.1. There was ample opportunity for optional remarks, anecdotes or diving deeper into participant's answers.

Highlights

The small sample size and lack of quantitative data do not allow for an analytic approach to results. Instead, here are the summarized key findings of the interviews;

- Apart from bone fractures, the minor injuries did not stop participants from climbing, due to ambition, against advice from health professionals
- Climbers typically climb 20 routes in a session of 1.5 hours, going from easy to their maximum skill grade. They spent little time route-reading, and repeated failed routes 4-5 times before giving up.
- As most participants climb with others often, they are used to guidance, and more likely, demonstration.
- Besides beginner courses, the participants tend to climb 'intuitively', without a coach. For a particular move, they occasionally employ the use of online tutorials. This tendency might differ on higher skill levels though.
- Participants tend to skip or minimize warm-up, as they prefer spending time on the climbing wall.

In addition, the semi-structured approach allowed for exploration beyond the initial questions. For instance, findings go into the feeling of 'cheating' when receiving guidance from other climbers, or conceptually, from a technology-enabled assistance tool. While responses were mixed, all climbers saw the advantage of such hints, to different extents. They stated that the cognitive task of climbing, the 'puzzle' aspect, was of varying importance and that guidance should be offered hesitantly.

2.5 Defining research direction

2.5.1 Knowledge Gap

In the list of related work and existing literature, a few trends have been established. Technology-enabled climbing and bouldering interventions tend to embed in a climbing flow either in-action or out-of-action, and are mostly focussed on entertainment, or improving climbing training. This spectrum can be visualized on a 2D plane, with the existing solutions mapped onto it, see figure 2.9.

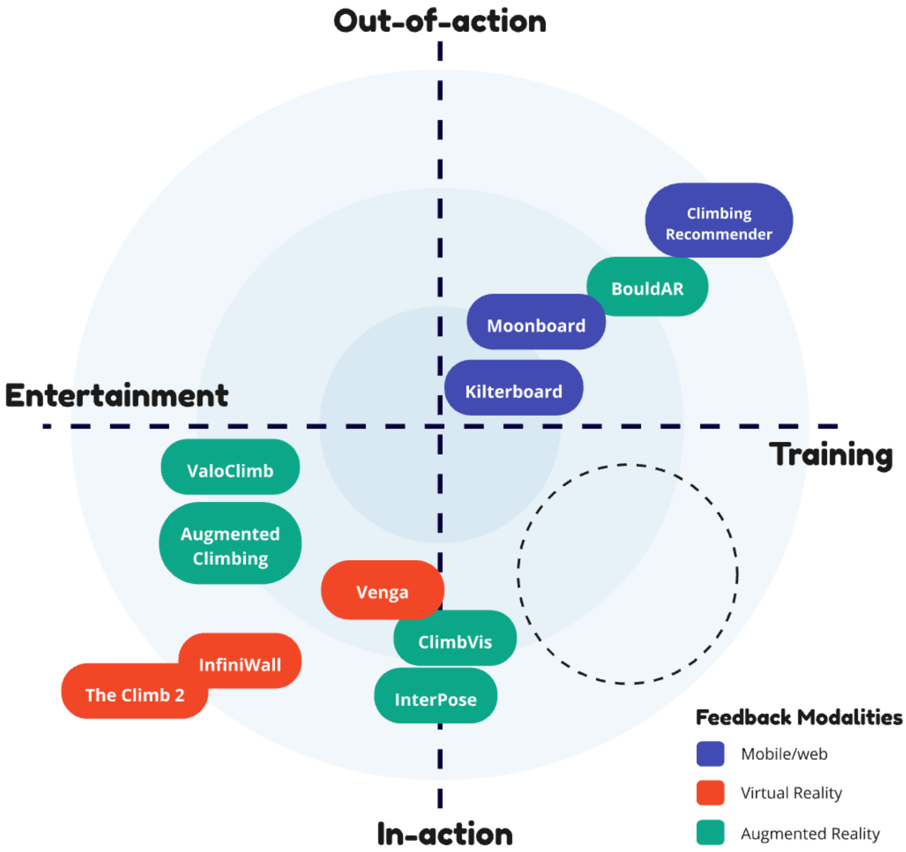


Figure 2.9: Related work mapping

2.5.2 Constraints

As described in section 2.2.2, injuries are common among climbers, beginners especially, largely because of a lack of personalized practice. This sets out an opportunity for technology-enabled tools to support climbers and accelerate their training. Going forward, we set out to develop such a training tool, embed it into climbing practice on an actual wall, and evaluate it on end-users. Before proceeding into ideation, some boundaries can be laid out, with insights from related work, to give a clear direction on which the thesis body can be based.

- In-action training
- Motion tracking technology
- See, Think, Act

In-action training

The related work mappings clearly show a lack of in-action training tools, as well as out-of-action entertainment solutions for climbing. As sports training benefits more from scientific research, and engagement from embedded practice [15], in-action training is deemed a more impactful direction for further exploration. The goal should thus be embedding some interactive technology 'on the wall' in a climbing training flow.

Motion tracking

It is no coincidence most of the state of the art is using some form of user tracking, be it in different forms. To gather input for an interactive system, measuring the position and kinetics of a climber in-action is the most logical solution. While other sensing technologies can be considered (force, touch, sound), constraining the system to body tracking simplifies the ideation process while keeping many possibilities open.

See, Think, Act

Technology-wise, we analyzed related work in the three categories of tracking, modeling, and feedback, based on a see, think, act system. While the ideation process has yet to come down to a solution, we can use these three pillars as a guiding hand. Combining different technologies from each to find synergies that work together in an effective climbing system, hence we use them in our research questions.

2.5.3 Research Questions

To conclude this preliminary research, we make take more concrete steps toward the final design, by formulating research questions for the research methodology;

Main question

- ➤ What is the design space for in-action training tools using motion tracking for novice climbers?

Sub questions

- ➤ How can embodied co-design methods inform the design process for in-action climbing training tools?
- ➤ What specific climbing task-setting provides the most relevant problems & opportunities
- ➤ What are the qualities of effective tracking technologies for in-action measurements?
- ➤ What are good objectives for evaluating in-action training systems on novice climbers?
- ➤ To what extent does the final solution contribute to these objectives?

Chapter 3

Designing with climbers

The background research has provided us with the context to start ideating a technology-enabled intervention. This includes a concrete set of constraints and limitations. During the ideation process, we will define the problems and solutions that come up more clearly, within our design space. We will use the design space definition from Bisjaer et al. [61] [62] [63].

> **Design Space:** A conceptual space, which encompasses the creativity constraints that govern what the outcome of the design process might (and might not) be.

We can distinguish design spaces between problem and solution spaces. As first described by Maher et al [64], but defined in more detail by Dorst and Cross [65], problem and solution space are closely connected. Instead of the problem space leading the solution space, they propose a bidirectional approach, where learning about the solution space can reframe the problem. Using this idea, the spaces can evolve together during the ideation process, ending up with a more complete design space.

Goal

At the end of the ideation process, we should have filled in our problem and solutions, and made future direction more clear. But what does that direction look like? The most important goal would be a single defined problem-solution concept, to be able to build upon. This should already isolate and define a user problem, and clearly describe an intervention, including potential technologies and interaction flow. This problem-solution concept should be selected from a pool of ideated problem-solution fits, based on both climber and expert feedback.

3.1 The climber perspective

The design space is constantly evolving. With each step in the diverging ideation process, the space gets expanded, and new connections will be formed. To foster creative exploration, brainstorming is a logical next step in expanding on the current ideas. The goal is to involve the end-user as much as possible, per participatory design, to design from the perspective of the climber.

3.1.1 Bodystorming

There exist many participatory brainstorming methods. Traditionally in product design, popular options are brainwriting, 100 bad ideas, or mindmapping, which work great for digital or static physical objects. However, designing Interactions for a moving body poses an additional challenge. To examine the physical and collocated aspects of the interactions early on in the design process, bodystorming is a fitting choice. Bodystorming employs embodied experiences such that they inform the ideation [66], thereby using them as a foundation of the product. Segura et al [66] describes five characterizing principles for a bodystorming activity;

- Employ an activity-centered approach;
- Use the physical and spatial context as a design resource;
- Use nonscripted hands-on activities, harnessing the participants' free ways of acting as a design resource;
- Use both movement and play as a method and design goal;
- Facilitate a sensitizing and design-conducive space, working at the same time towards problem understanding and a solution.

These fit well within our context, and especially the last principle confirms our method for exploring both the problem-opportunity as well as the solution-space concurrently.

Oulasvirta et al [67] expands upon bodystorming, and stresses the importance of carrying out bodystorming sessions on location or 'in the wild'. This embedding of the design activity in situated practice enables an increased understanding of contextual factors, and allows for more immediate feedback on generated ideas. This is especially relevant when exploring the problem-opportunity space, as context-based tasks like climbing re-enactments are a crucial part. This could be accomplished in a local bouldering gym, by placing down a whiteboard and bringing attributes. Alternatively, we chose a Virtual Bodystorming approach.

(a) Controlled lab environment

(b) Virtual Environment

Figure 3.1: Embodiment of virtual avatars in a climbing environment

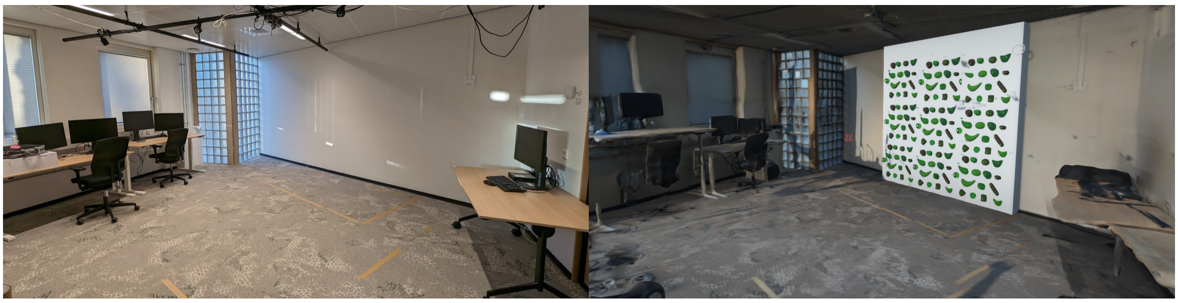
Although a very new and sparsely documented design activity, the idea is that the high immersion levels of VR technology should provide close to an 'in the wild' experience, by creating a digital representation of the application environment [68]. This brings additional benefits, such as customization and automation, not to mention the potential cost and time savings for certain specialized target environments. The obvious downside is the ease of use of using the VR equipment, which could incur a learning curve before optimal immersion is reached. This effect is magnified when involving novice users, which is often the case in participatory design.

3.1.2 The setup

For the design activity, we need a suitable physical and digital environment. For the physical, a large empty lab space was used, which had clear boundaries for the VR systems to recognize. It was equipped with four high-performance Windows computers, to which a variety of Meta and Valve HMDs were connected. The headsets that used outside-in tracking (positional references to do spatial tracking), were provided with a few base stations, which were mounted to the ceiling using trusses.

The digital environment was set up using the *Resonite* application. This multi-platform software allows for collaborative and customizable 3D worlds, and works well with VR. The world was divided into three distinct sections; First, the onboarding area, where participants receive the explanation, can get used to the controls, and select a digital avatar. Then, a large representative bouldering wall 3D model was imported [1], to be the location for context-based climbing task re-enactments for the participants. During these tasks, participants can naturally identify problems and opportunities.

For exploring the solution space in the third section, a more customized approach was taken. As the final prototype has predefined physical and technical constraints, the environment should reflect this context to allow for more transferable solution concepts. To create this 3D section as accurately as possible, a digital twin of the lab space was created using *Photogrammetry*. Photogrammetry is a technique that uses sensors, in this case, optical and lidar sensors on an Apple iPad Pro, to reconstruct an object or space in digital 3D as a pointcloud representation. This digital twin was imported into Resonite and customized to include a rough concept of the not-yet-built climbing wall. The final environment can be seen in figure 3.2, and serves as the canvas to sketch out explored solutions and concepts.



(a) Controlled lab environment *(b)* Virtual Environment

Figure 3.2: Translation of the lab space to a digital twin

Session structure

Guided by the five principles of bodystorming, the design activity is structured as follows;

1. Consent Form & disclaimer
2. Introduction & explanation
3. Ice-breaker warmup exercise (Get to know Resonite); Avatar Selection
4. Once Upon a Smile [59]
5. Context-based re-enactment of climbing tasks
6. Divergent solution brainstorm
7. Recording, rewarding & finalizing

[1] `https://www.sketchfab.com`

3.1.3 Results

The participants were of significant technical ability, presumably thanks to convenience sampling, making the on-boarding process smooth, though still taking around 20 minutes. This might take significantly longer in different settings and with different participants, presenting a challenge for Virtual Bodystorming in general.

During the design activity, a lot of new ideas and concepts came up. These are described as a ’local design space’ before they are integrated into the existing concepts and can be seen in figure 3.3. Identified problems include vertigo and sweaty hands, while some interesting solutions involve the automatic detection of user parameters like ape index (arm span divided by height [24]) and center of mass.

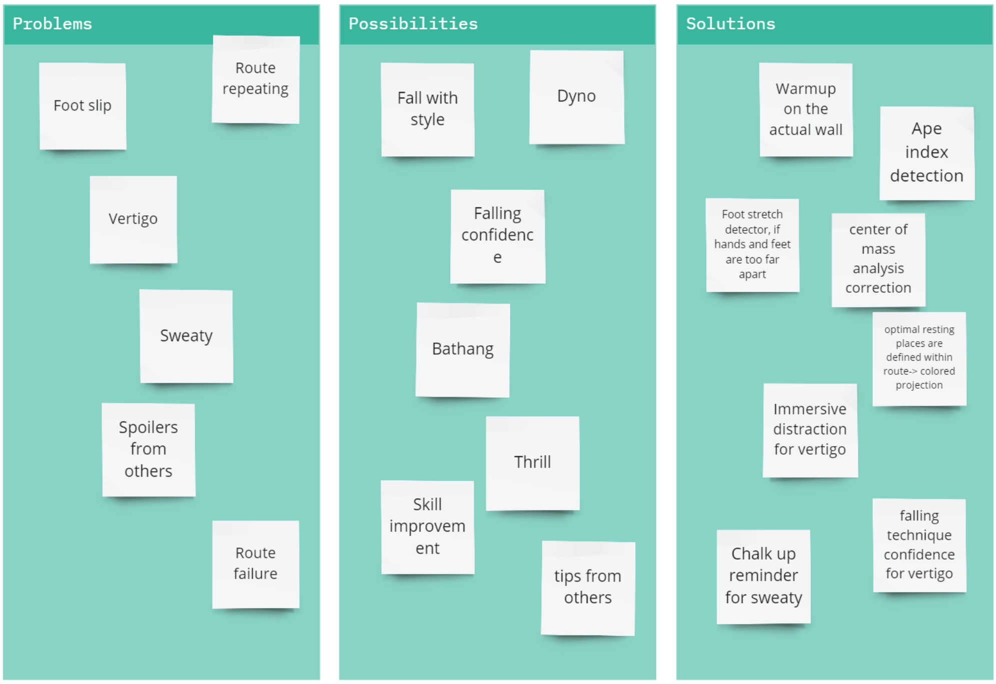


Figure 3.3: The local design space explored during the Virtual Bodystorm activity

3.2 The Concepts

With the plethora of knowledge fragments contained in our design space, we can start to converge towards a final design. We do this by analyzing the trends in the discovered design space, elaborating on them, and grounding them in literature. With the creation of **four** concept descriptions, we should have the groundwork for further iteration.

3.2.1 Method

For each concept, a clear goal is to be formulated, although specific metrics or evaluation criteria can be determined in a later stage. Then the intervention is described, which is based on the knowledge fragments from the current design space. From the target population, a selection is made from the persona segments, which is kept in mind for the development of the specific concept. Furthermore, the technical implementation is described. This includes the hardware and software specifics, but also their strengths and weaknesses. Within the constraints of the project, what is feasible? And what issues may arise during the realization of the solution? Lastly, the details of the concepts will be illustrated by a sketch generated by generative AI models. The art style of these is kept consistent by feeding back the first concept image to the context window of the next. Note that using AI could incur biases in the output, such as demographic representation, you can read more about our use of AI and its biases in section

3.2.2 Concept A: Realtime feedback through learning model

Target Personas
The Casual, The Adventerous

Knowledge Fragments
route failure, strenuous moves, tips from others, autonomy, learning model

To prevent strenuous moves, and support acceleration of the climber's process of motor skill acquisition, see section2.2.3, we can employ *Observational Learning* [5]. This is a process also found in the situated practice of a boulder gym, where novice users often observe more skilled climbers perform a particular route, before attempting themselves. According to Magill et al [5], observing a skilled demonstrator, preferably visually, is an effective way to transfer movement patterns and motor skills to a performer. This is done before attempting a particular movement pattern, but especially also during, with more observation being linked to better skill transfer.

Intervention design

Using a camera or Motion Capture (MoCap), a video or movement recording is made of a skilled climber. When a novice climber is practicing a route, the learning model (recorded demonstrator) can be displayed on the wall using a projector, ahead of the novice climber. This way the novice can observe the model in realtime, and accelerate the skill acquisition process.

One caveat of this approach is the feeling of 'cheating'. Found during the interview session, see section2.4.2, climbers stated that the puzzle aspect is a key aspect of climbing, and that hints should be given only when they attempted the move beforehand. A solution to this would be measuring climber inactivity in-action. If the climber is not moving for some time, e.g. is stuck, only then will the learning model be initiated. This is visualized in figure 3.4 as a small cooldown clock.

Figure 3.4: Concept A: Realtime feedback through learning model

3.2.3 Concept B: Terminal (augmented) feedback for self-observation

Target Personas
The Competitive, The Healthy

Knowledge Fragments
route repetition, skill improvement, autonomy, replay

Similar to using a *Learning model* [5], observational learning also includes self-observation, also known as *self-modeling*. Dowrick [69] defines self-modeling in their comparison, as follows: 'Self-modeling is an intervention procedure using the observation of images of oneself engaged in adaptive behavior'. Most commonly, this is done using 2-4 minutes of video feedback, known as Video Self Modeling (VSM), *after* a particular move execution, which is a form of *terminal feedback*. While the procedure has been tested for skill acquisition in sports such as volleyball [70] and skating [71], the only climbing-related mention seems to be no longer available [72], for unknown reasons.

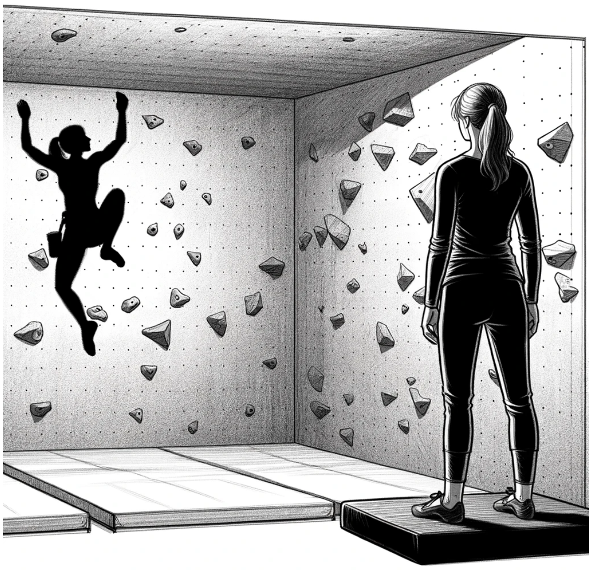


Figure 3.5: Concept B: Terminal augmented feedback for self-modeling

Intervention design

Instead of direct terminal video feedback, this concept slightly changes the traditional formula, by recording using a MoCap system, instead of a video recorder. This enables us to tweak (augment) and analyze the climbing movements, point out possible points of improvement, or just monitor aspects of the climb, such as the center of mass. The (augmented) terminal feedback can then be displayed on the climbing wall itself, as opposed to a regular display, to increase immersion.

Additionally, the concept could be adapted to include a degree of user control. Letting the performer influence the observation speed and progress during a self-modeling procedure is shown to promote better skill acquisition [73], and could be a valuable addition to the final prototype.

Feasibility

As for practical implementation, the technologies separately have been proven, though the communication between them is not yet. The evaluation of the base concept should also be feasible, as there are plenty of methods out there to measure skill acquisition. The augmentation of the feedback might pose challenges though, as the type and amount of modification is crucial and depends on expert input to implement successfully.

3.2.4 Concept C: Tackling energy waste through a real-time correction in center-of-mass and elbow angle

Target Personas
The Casual, The Adventurous

Knowledge Fragments
energy waste, sweaty hands, optimal resting place, realtime hints

As established earlier, a climber's management of energy use is essential, as optimizing the efficiency allows them to execute more climbs in a single session, and spend more time on the wall during a climb without getting tired. Intermediate climbers learn several techniques to avoid such unnecessary energy expenditure, which we can attempt to teach novice climbers to accelerate their training.

Energy Optimization Techniques

One of these techniques is the passive hang. During moments of rest, tactile exploration, or mental movement mapping, novice climbers intuitively tend to put tension in their bicep and upper back muscles, in an attempt to prepare for the next move, which is called an *active hang*. The better way to rest is with a *passive hang*, by relaxing your muscles and relying on your grip, which allows for a way longer resting period and less muscle soreness.[2]

The other technique is moving your body as close to the climbing wall as possible. This improves the climber's balance and allows them to spend less energy hanging or clutching to the wall. The crucial point here is the climber's center of mass. The angle of the wall presumably affects this technique in some way, though that is to be further explored.

A last notable inclusion might be the detection of optimal resting places. While bodystorming, climbers mentioned that not all resting places are equal and that some require significantly more energy to hold out on than others. Therefore, prompting novice climbers to the best locations within a certain route might be advantageous

Figure 3.6: Concept C: Tackling energy waste through a real-time correction in center-of-mass and elbow angle

Intervention design & feasibility

All of these moves could be plausibly detected using a MoCap system, by analyzing joint angles, calculating the climber's center of mass, and locating their position in the current route. In real time, novice climbers can be prompted to correct their posture, at the moment the system detects insufficient technique, using a form of augmented feedback. The best modality and structure of feedback is to be further explored but could include projection, virtual, auditory, or haptic feedback. The biggest challenge is how to measure the effect of the concept. What metric, e.g. heart rate, could function as an accurate proxy for energy use, and could thus validate the overall effectiveness of the solution?

[2] `https://blog.calimove.com/2023/06/30/passive-and-active-hangs-benefits/#:~:text=For%20active%20hanging%20activate%20the,stretching%20the%20pecs%20and%20lats.`

3.2.5 Concept D: Gamification to incentivize warmup exercises

Target Personas
The Casual, The Healthy

Knowledge Fragments
strenuous moves, gamification, real-time hints, on-wall warmup

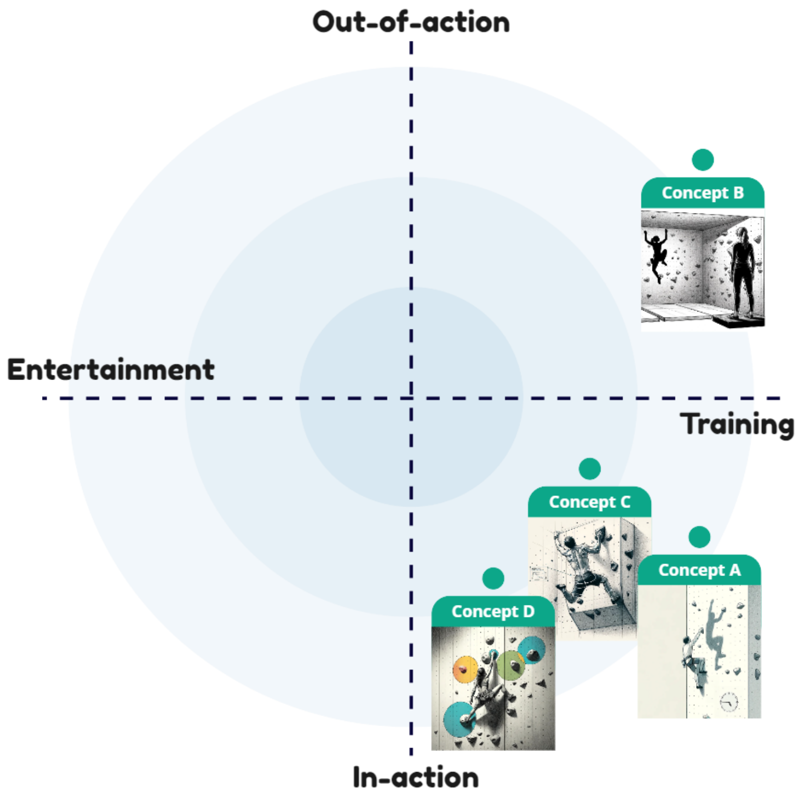
Warming up is an essential part of any climber's training schedule, as confirmed during our interviews, see section 2.4.2. Typical exercises include foam roller, pre-exhaustion, and static stretching [74], which aim to decrease injuries by stimulating blood flow and loosening muscles. However, Yu et al [74] suggest that more complex warm-up movements, which mimic climbing postures more accurately, are a promising improvement. This is confirmed in our ideation, where climbers mentioned the need for an 'on-the-wall' warmup, something that is not yet common in the climbing world. This could be as simple as a low-difficulty climbing problem. An additional advantage of this technique is that it should be more engaging and accessible than traditional warm-up sessions, denoted by our participant's preference.

Figure 3.7: Concept D: Gamification to incentivize warmup exercises

Gamification
While game-based climbing has been explored in previous work, see section 2.3.3, they focus on climber engagement, 'making it fun'. Data-based gamification to actively support a climber's training schedule is yet to be done. The idea is that a game could be designed and developed, which includes useful warmup exercises. Experts should be consulted on the best exercises and ways to integrate them. The exercises can then be linked to game elements and objectives, such as collecting apples by reaching for them using a stretching climbing move.

Personalization
A possible addition to this concept would be personalization. To prevent strenuous moves, the exercises could be adapted or tweaked to better match the climber's body properties. For example, someone with shorter arms should not be incentivized to collect apples that are just out of reach for them, as it could incur injuries through a strenuous move.

Feasibility
Visual and possibly auditory fidelity is important for an embodied and engaging climbing game, for which a high-resolution projector could be used. Using MoCap or grip sensors, the game state can be detected, e.g. to make sure the climber collected the apple. The challenge would be the evaluation of such a concept. How do we measure engagement accurately? With what methods can be gauged to what extent the warm-up exercises were effective?



b!

Figure 3.8: Mapping our four concepts to the framework

3.2.6 Concept Mapping

Before the concepts are further developed, we can reflect upon their alignment with our overall goal and direction. Using the previously identified framework, the concepts can be placed alongside related work, to get a better idea of their comparison in the overall landscape. The mapping can be seen in figure 3.8. Notably, the identified area of interest overlaps with some, but not all concepts.

3.3 The expert perspective

There are a lot of uncertainties about the current concepts. Before selecting or combining them to converge towards a final design, they should be evaluated on a few key criteria.

- **Relevance**: How impactful would the solution be? In what way would it integrate in situated practice? What academic and real-world value does it provide?
- **Feasibility**: How much time, resources, and knowledge are required to build this solution?
- **Evaluation criteria and validity**: What is the best way to evaluate this concept? How valid would the results be?

We discuss the concepts with these points in mind, with a selection of experts. These are divided into two groups; Movement Scientists & Climbing Coaches, which both have expertise in slightly different aspects. While Movement Scientists can help discuss technical feasibility, academic relevance, and evaluation validity, climbing coaches could elaborate on the impact on end-users, as well as inform on the correctness of the specific climbing moves from each concept.

For climbing experts, professional head trainers were selected from local bouldering gyms. They report climbing skill grades between 8A and 8C, both have been training climbers for more than five years and regularly participate in climbing competitions. A movement science expert was contacted within our Human Media Interaction department at the University of Twente. They have extensive research experience in movement science and sports technology.

To understand expert feedback in-depth, semi-structured interviews are conducted, which allows us to dive deeper into potential concerns raised by experts [60]. The session is conducted as follows, with the entire question list in appendix A.2.

1. Briefing & Informed Consent
2. Introduction of project, goals & framework
3. Discussion Concept A
4. Discussion Concept B
5. Discussion Concept C
6. Discussion Concept D
7. Preference selection

3.3.1 Results & Conclusion

The sessions took place on location and took around half an hour. The experts provided in-depth feedback and new insights. Based on the transcribed conversations, feedback has been paraphrased into tables 3.1 and 3.2. The movement scientist and climbing expert gave their preference to concepts C + D and B + D respectively, although for different reasons. Overall, based on their feedback, concepts C and D seem most promising, as they provide the most academic *and* real-world novelty, with concept D having the most overlap between the two expert preferences. Therefore, concept D will be used as a base for further development, while some elements from multiple different concepts can be integrated into the concept, in the specification phase.

Table 3.1: Table: Movement Expert feedback

Concept	Pros	Cons	Recommendations
Concept A: Realtime feedback through learning model	There is academic value in Augmented feedback for motor skill acquisition	Observational learning without augmentations has been done, and studying the behavior in a new context, namely climbing, offers limited academic value	Concepts A and B are so similar that they should be considered as one concept. The value lies in the specific abstraction and visualization of climbing techniques, which requires more in-depth research.
Concept B: Terminal (augmented) feedback for self-observation	There is academic value in Augmented feedback for motor skill acquisition	VSM without augmentations have been done, and studying the behavior in a new context, namely climbing, offers limited academic value	Concepts A and B are so similar that they should be considered as one concept. The value lies in the specific abstraction and visualization of climbing techniques, which requires more in-depth research.
Concept C: Tackling energy waste through real-time correction in center- of-mass and elbow angle	Good use-case of our tracking technologies	Evaluation will be difficult and requires more in-depth knowledge about energy use	Look into types of feedback systems
Concept D: Gamification to improve and incentivise warmup exercises	Interesting, could be combined with Concept A	Users can try to 'speedrun' or game the system, which might impact usefulness. Also make sure to stay clear from the work of Daiber [47], Wiehr [49] & Kajastila [45] [46]	Look at and compare definitions of playification vs gamification

Table 3.2: Table: Climbing Expert feedback

Concept	Pros	Cons	Recommendations
Concept A: Realtime feedback through learning model	Learning by example is a proven strategy that works well	The instructing 'example' climber should be very thoughtful not to include techniques too hard to perform for beginners	Look into Implicit Learning vs Explicit Learning. I recommend this method for beginners only, as the 'puzzle' aspect is more important for intermediate, expert, and especially competition climbers
Concept B: Terminal (augmented) feedback for self-observation	We use a lot of VSM, which is similar, and works well, especially for advanced climbers	VSM has been done for climbing, small scale as well as large scale (climbing hall equipped with cameras for example). I think projection will work better, but the question is how much?	While beginning climbers use reference videos more for hand and foot placement, more advanced climbers can analyze their own movement and body position.
Concept C: Tackling energy waste through real-time correction in center- of-mass and elbow angle	The described energy conservation techniques are well-researched, and I expect to be relevant for both beginning and intermediate climbers. The heart rate sensor could also be a valid indicator for energy use	Technically complex to implement, as sharp elbow angles are not always bad, and can have their uses in specific climbs. There is also a risk of too high a cognitive load during a climb.	Consider VO2max sensing as an alternative to heart rate sensors. Also, look into resting 'break' places within a route
Concept D: Gamification to improve and incentivize warmup exercises	I am a big fan of climbing games, especially for beginning climbers and children. It is also definitely true that most climbers skip warm-up.	On-the-wall warmup is not a complete replacement for pre-warm-up. They should be divided into two phases, cardio (on the ground) and grip (on the wall), the latter of which can be gamified	Look into three important categories of warm-up: Injury-prevention, Cardio, and Grip.

Chapter 4

Tracking Climbers

Before further designing and implementing the ideated novel concept, we are taking a slight detour. As the constraints of our design space are partly defined by using pose tracking, they are an integral part of all the generated concepts. However, we have not yet concretely defined what these technologies look like, what their state of the art is, and how it could be applied to climbing. This section will dive into these tracking technologies, comparing their effectiveness and efficiency on several metrics. The climbing sport specifically will be looked into as well, by discussing existing implementations of pose recognition in technology-assisted climbing applications, as well as climbing-specific considerations for implementing tracking technologies. Finally, the chapter should end with giving concrete recommendations for the use of a specific tracking solution, for all generated concepts, based on both literature and measurements.

4.1 Pose Tracking Technology

The 'see' part of the see, think, act system paradigm is where we employ technologies to sense a climber's movement during their warmup routine. This information can then be processed, 'think', and used to present feedback, 'act', to the user. This sensing of human movement, or biokinematics, can come in many different forms, and many different technologies, which can have slightly different applications. Even within the climbing context, different sensing technologies come to mind for different aspects of climbing analysis, such as eye-tracking during route reading [75] and grip force measurements for performance analysis [76].

However, for our purpose of designing a climbing 'game' for warmup exercises, as well as the other concepts, we are interested in different relevant biokinematic properties to detect. These are the rough position of the climber on the wall, as well as relatively accurate joint angles of the climber's limbs, which in combination gives us a wide range of possibilities in game design. These properties are a result of measuring a user's *pose*, a representation of the body's position at a given moment. In practice, this often consists of a configuration of body joints, each with a position and rotation. The methods that aim at measuring this pose, through time, is called *Pose Tracking*.

Pose Tracking is a subset of the wider MoCap field, but focusing on the human pose, as opposed to objects. While there exists a variety of technologies able to estimate the pose of a human, they can be roughly divided into on-body (relative) sensing and outside-body (absolute) sensing, see figure 4.1.

4.1.1 Outside-body

While on-body sensor-based solutions can be more accurate, outside-body sensing can offer quite some advantages. First, the technology is far less invasive, with the user not having to wear or attach bulky sensors. This is advantageous especially in a sports context, as the devices can inhibit movement. Second, the hardware used is often significantly more cost-effective and easier to set up and use. This is because optical sensors like cameras are used most of the time, which have grown to be ubiquitous. This section describes the state-of-the-art pose recognition technologies, both 2D and 3D, and their implementations in sports and climbing specifically.

While outside-body pose recognition is a varied field, with different sets of technologies used, in the context of sports and biomechanics, optical MoCap systems are most often used [77]. They are often mentioned as

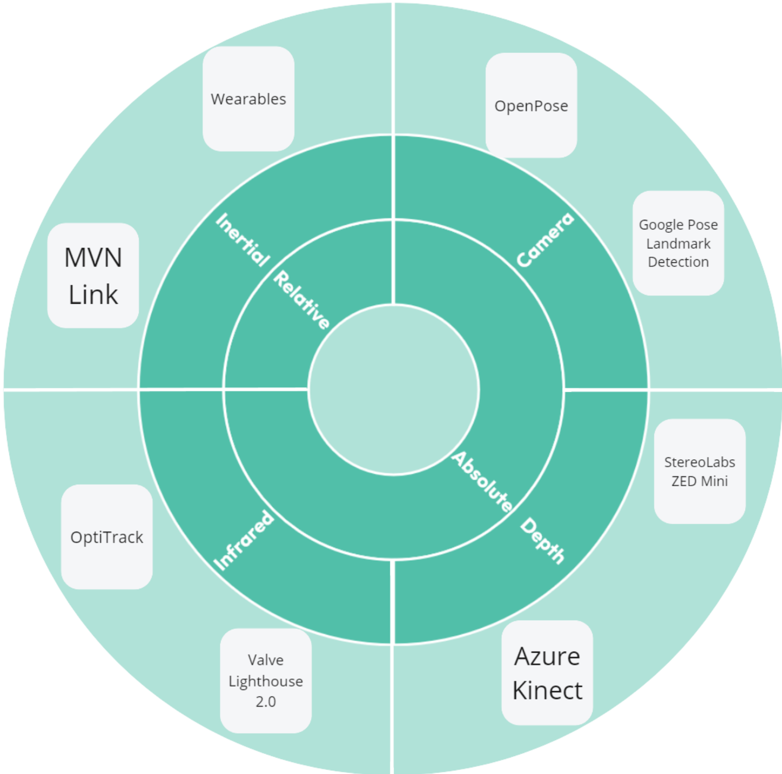


Figure 4.1: Categorized overview of MoCap technologies

the 'Gold Standard' for movement quantification [78], and are even integrated in technologies such as Virtual Reality systems, which in turn are often effectively used in sports and climbing, see section 2.3.2. These types of MoCap technologies are often complex, expensive, and power-hungry, and thus limited to laboratory environments, which can be a hurdle, especially for hands-on sports like climbing.

As an alternative to these complex systems, HPE can be used to track a person's pose through time, which is called Pose Tracking. Instead of using multiple expensive sensors from different angles, only one, or a few, camera sensors are used. The tracking accuracy of HPE implementations is significantly worse and faces additional challenges like occlusion and different lighting conditions. However, the ease of use and cost-effectiveness propel the popularity of these technologies into consumer products, like the Microsoft Kinect [79].

Different HPE methods are often compared through benchmarks. These are sets of images and videos of human movements designed to extract human poses, with a variety of challenging features such as different clothes, occlusion, and different lighting conditions. Two of the most used and well-regarded benchmark datasets are from Johnson and Everingham [80] and the 'MPII Human Pose' by Andriluka et al [81].

Markerless

While HPE has been used with sensors like IR before, think of the Microsoft Kinect [79], HPE using a single camera feed has been gaining more attention. This so-called Markerless Motion Capture (MMC) is largely thanks to technological advances in machine-learning-based computer vision [82]. One of the main methods that has seen improvement is Convolutional Neural Network (CNN)s, with impressive results tested on benchmark sets of pose image references [83]. Over the years, these algorithms have contributed to a simple workflow, where a single camera input yields a relatively consistent pose skeleton output.

On top of these improving 2D MMC algorithms, 3D variations of the technology have also gained attention. By using stereo-imaging, multiple points of view can effectively be combined into a pose estimation in three dimensions, as described by [84]. This can be especially useful in the context of climbing, where routes can have challenging three-dimensional aspects like overhangs or corners.

In climbing, these techniques have been applied successfully. Especially in the AR-enabled interventions, see section 2.3.2, where it interacts well with projections. In practice, most of these solutions make use of a Microsoft Kinect for their HPE, because of its ease of use and its compact form factor for 3D HPE. Between input and output, there is also room for adaptation of the pose skeleton by algorithmically modifying specific joints. In climbing, there is only one example of pose modification being applied in existing work, namely by Shiro et al [85]. They attempt to tackle the challenge of bridging the gap between beginner and expert climbing techniques. This gap exists as climbers of different skill levels tackle the same route differently, for instance by applying high-level moves that are inaccessible for beginning climbers. Their proposed system *InterPoser* interpolates between recorded pose animations of beginner and advanced climbers, see figure 4.2, making a flexible and customizable visualization. While not yet evaluated, such an algorithm could prove especially useful in personalization systems, where it can be adapted to the specific skill level of a user.

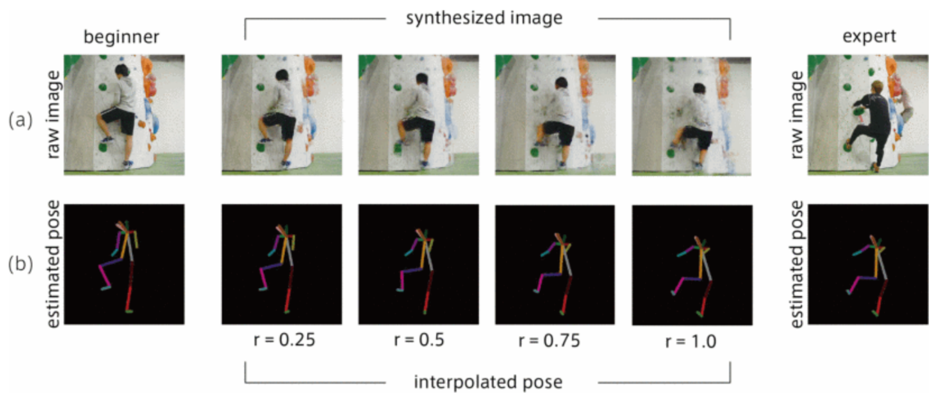


Figure 4.2: Interpolation of Human Pose recordings during climbing, based on skill level [85]

4.1.2 On-body

While in the context of sports and bio-mechanics, MoCap systems are most often used for joint angle analysis, on-body sensing is gaining attention, due to the proliferation of Inertial Measurement Unit (IMU) in ubiquitous computing. The small sensors can be placed on the body of an athlete, and an IMU can detect semi-accurate movement and position data through gyroscopes and accelerometers [86]. While the possibilities are impressive, these sensors have limitations, especially compared to outside-body tracking, in the form of drift. Integration drift comes from small errors in the inertial sensor data, which over time are compounded into larger inaccuracies in the reported position. [87]. While there are some reasonably effective countermeasures in the form of drift reduction algorithms [87], the lack of external reference points means there is always a need to calibrate the sensors to a specific point in space before every recording session.

4.2 Comparing technologies

Equipped with knowledge of the workings and state-of-the-art of existing pose tracking technologies, it's time to select a winner. This is not necessarily the most accurate technology, but can depend on a variety of climbing-specific factors. This section will evaluate a selection of the most promising technologies, of different types, see figure 4.1, based on a few factors. With the results, one of the technologies will be selected and used in the implementation of the concept.

Designing climbing applications can be challenging. During the ideation, there are a few factors that have to be taken into account, which could impact the effectiveness of pose tracking, specifically for climbing. These are ordered by perceived importance to the climbing context.

- Accuracy

- Invasiveness
- Latency
- Accessibility

The following pose tracking technologies will be compared; The selection contains the most promising technology from each category, see figure 4.1.

- Movella Xsens MVN Link
- Google 'BlazePose' Landmark pose detector
- Microsoft Azure Kinect
- OptiTrack

Not only should all experiment conditions be consistent between tests, but they should also be as reflective of the final conditions as possible. That means integrating the pose tracking into the entire IICW pipeline, including sensing, engine processing, rendering, and projection. A quick experiment was carried out, where the different systems collected data during a climb, which could then be analyzed to calculate joint angle accuracies between systems.

The comparison is structured as follows; The Xsens Link suit is used as a *ground truth* to compare the other systems. The ground truth means not 100% accuracy of real-world movements, nor does it mean the best state-of-the-art tracking hardware, called the *Gold Standard* (which is the Vicon intertial solution[1]). Rather a close enough system with superior accuracy as per specifications[2] compared to the other systems.

4.2.1 Precision

The first and most obvious factor is precision. The data representation of the climber's pose should be as close to reality as possible, specifically the position and rotation of the joints. This precision can be broken into things like resolution, precision, and temporal consistency, but as the main points of focus will be Joint Angle Analysis, it seems fitting to start the comparison based on that. This also creates a fair comparison between relative and absolute position systems, as there are no potential calibration-related issues when comparing absolute positions of inertial technologies.

Accuracy Conditions

Applications of pose tracking, even in sports, embed the technology in situated practice at certain locations. For absolute position systems, such as cameras and infrared sensing, this is often in front of the user, or on all sides to capture every perspective. Climbing poses an additional challenge, which is the climbing surface or wall. This completely occludes the front of the user, making it impossible to place sensors. Configurations of sensors placed behind or to the sides of the user could potentially impact tracking accuracy, depending on the specific technology, for a couple of reasons; First, many optical tracking systems use a selection of sensors to triangulate position, by removing half of the perspectives, the pose data could drop significantly in accuracy or even stop working completely. These issues highlight again the importance of testing these technologies in situated practice.

Each of the tracking systems has different conditions in which they behave optimally. The MVN Link is the most flexible of systems, as it is not restricted to physical boundaries, perspectives, or mixed lighting. Both Kinect and Blazepose however, suffer from all three. While lighting and boundaries are easily lab-controlled, the perspective of the climber might pose difficulties. This is because the algorithms of both systems, especially blazepose, are heavily optimized for a frontal view of the user. Kitamura et al [88] argue that this is because the algorithms are not designed with a sports context in mind. On a climbing wall, of course, front view is never

[1] https://www.vicon.com/hardware/blue-trident/

[2] https://www.movella.com/products/motion-capture/xsens-mvn-link#specifications

the case, as the sensors would need to be placed opposite to the climbing wall, thus observing the user from behind. During precision testing, this perspective has to be kept in mind.

Optitrack faces similar challenges, yet they are amplified, as the optical tracking system uses not one fixed sensor perspective, but 14. These cameras have to be placed all around the user, to ensure the position of the reflective dots can be triangulated from multiple perspectives.

To start measuring, the Optitrack cameras are placed around the climbing wall, and configured through a central server. The researcher wears the reflecting markers while climbing a simple route on the wall. After initial testing, **11/14** cameras are able to see at least part of the climber. However, several markers on the front of the suit, are obscured by the climbing wall, and can only be seen by one or two cameras, or in the case of two markers, none at all. The resulting skeleton output has a very low precision and accuracy, with significant temporal inconsistencies, as well as glitches from time to time. For the use-case of interactive games, and plausibly most other use-cases on the climbing wall, the performance is deemed unacceptable, and the system is disqualified before continuing the other comparison measurements.

Lens Distortion

An unexpected issue which MMC specifically is prone to, is Lens Distortion, specifically barrel distortion. This phenomenon warps the output image due to the physical properties of the camera's lens, and its effect increases with a greater camera Field of View (FOV), an example can be seen in figure 4.3. Feeding this image into the pose detection pipeline can incur a degree of inaccuracy in tracking quality. Some HPE systems have implemented a form of *Warp Correction*, a technique which adjusts the image to better reflect reality, but this is notably lacking in the software-based models such as *OpenPose*[3] and *Google Pose Landmark detection*. [4]

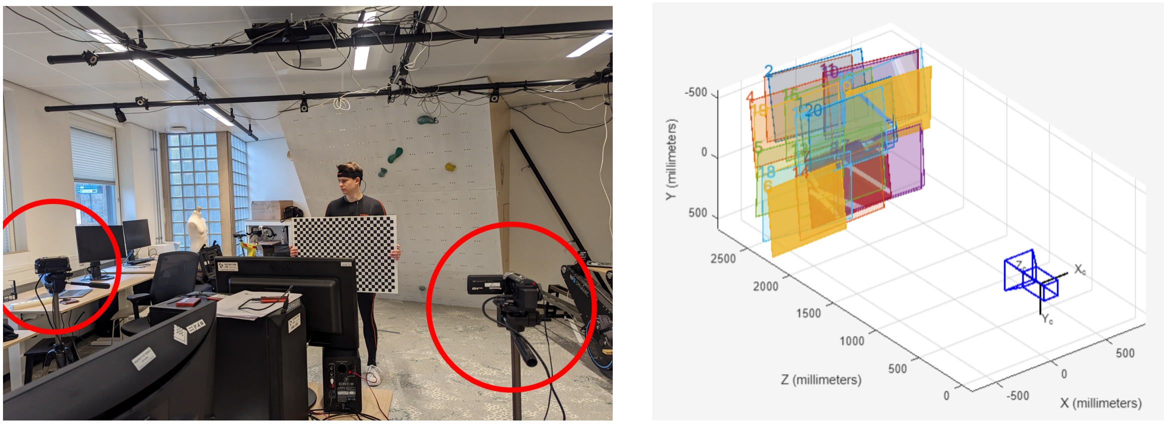
Figure 4.3: Example of lens distortion

[3] https://github.com/CMU-Perceptual-Computing-Lab/openpose

[4] https://developers.google.com/mediapipe/solutions/vision/pose_landmarker

Lens Distortion Measurements

To ensure accurate tracking, warp correction algorithms can applied to raw input footage from a tracking camera. These can evaluate the amount of warp error, and correct the image before it is processed by the HPE pipeline. While it is true that the distortion error is less impactful than the inaccuracy of the computer-vision method, it can still be advantageous to correct the distortion as much as possible. This is because they add up to an accumulative error in the overall output. Ideally, warp correction is applied in *realtime*, meaning every frame is corrected live during operation. However, this is very computationally expensive and can add a significant amount of latency in the pipeline, not to mention the lack of existing solutions for easy implementation. Still, if not implemented in real-time, we can at least use the warp error measurements to select a suitable camera to use. A camera with low warping, as determined using the Matlab Calibrator[5], should improve the overall tracking quality of MMC.



(a) Stereo-camera setup, using a checkerboard pattern for calibration

(b) Visualization of camera parameters

Figure 4.4: Process of calibrating camera hardware for distortion

We grabbed a selection of cameras, of different types, and connected them to a pc through a capture card. Then 30 seconds of footage was recorded on each one, where a fabricated calibration pattern was held in front of the camera in various positions. From the footage, around 20 single frames were exported, and fed to the MatLab Calibration Tool to extract a set of *Camera Parameters*. These include intrinsic parameters like Radial and Tangential camera distortion coëfficients, which can be quantified into a single distortion magnitude. This so-called *Distortion Coëfficient* is calculated in equation 4.1, with k being radial distortion coëfficients, and p being tangential distortion coëfficients;

$$D = \sqrt{k_1^2 + k_2^2 + p_1^2 + p_2^2} \tag{4.1}$$

The resulting ranking of distortion coëfficients, per camera, can be seen in table 4.1. While the best-ranking camera, the Genius Webcam, has very low distortion, it only has a resolution of 1080p, which can impact the tracking resolution significantly. Therefore we select the runner-up, the still very low distortion of the GoPro, as the device to be used for further evaluation of MMC systems.

End-to-end Measurements

Finally, all four selected tracking systems are compared in precision, spanning the entire pipeline from hardware to software. For the most consistent conditions, the intertial suit is worn during the recording of other tracking sensors, to ensure simultaneous data collection. The researcher carries out a representative series of varied climbing movements. The resulting data consists of joint positions and rotations for each of the 25 standard body joints, transferred onto an avatar, a real-time digital representation of the user's pose. For the most important climbing joints, the elbows and knees, a joint angle calculation was done over time. This is done by defining

[5] https://nl.mathworks.com/help/vision/ug/using-the-single-camera-calibrator-app.html

Table 4.1: Comparison of several camera types in Lens Distortion

Model	Resolution	k (Lens Distortion Coëfficient)
Logitech Webcam	1080x1920	0.1279
Panasonic Lumix G9 DSLR	2160x4096	0.0692
Panasonic HC-V720	720x1080	0.0380
GoPro Hero 7	2160x4096	0.0182
Genius Webcam	1080x1920	0.0177

custom time segmentation of 10 frames per second within the Unity engine and determining a quaternion representation of the joint's angle each frame. This gathered data was compared to form similarity scores between systems; the smaller the difference, the more precise the system is.

Results

Unfortunately, the results are extremely mixed. Precision in joint angles is inconsistent, to the point that visualizations make no sense. Even after several attempts, using this method, the measurements show no discernible pattern, both in timing, joint angles, and joint positions. This marks our method of quantitatively comparing precision across systems unsuccessful.

Presumably, the reason for this mess is the variation in input data. Each system has its proprietary software pipeline, up to the integration with the 3D engine. This means that each avatar implementation has wildly different proportions, data rate & precision, units, smoothing, compensation, and sometimes even joint configuration[6][7][8]. All these factors incur compounding errors until the output is difficult to compare.

This presents a challenge, which could possibly be solved with a lot more time, resources, and collaboration with tracking system manufacturers. However, for the scope of this project, we have to rely on external sources of precision measurements, from either a third-party review [79] [89], or manufacturers specifications[9][10], see figure 4.5. According to this data, is a significant difference in precision across systems, with the *MVN Link* being the most precise, which is confirmed with informal observations. Keep in mind that these precision specifications are not end-to-end nor in a climbing context, meaning the rest of the software and hardware pipeline in our prototype could add a degree of error.

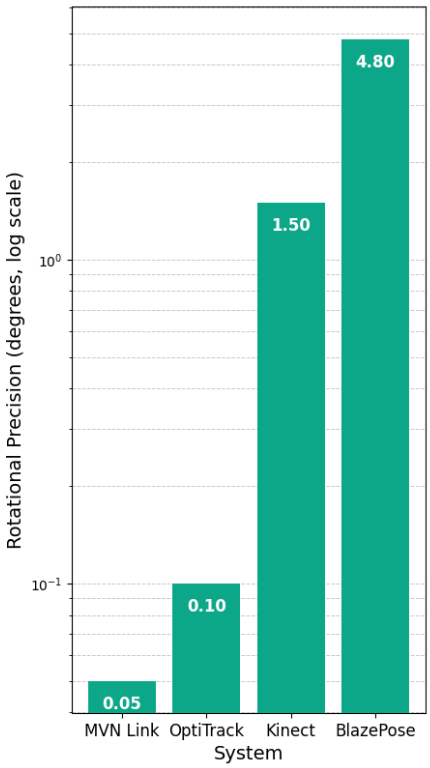


Figure 4.5: Estimated rotational precision per system

4.2.2 Invasiveness

When analyzing emotional responses from climbers, Mencarini et al [90] put forward their hesitations on the application of wearable technology. Climbers had mixed responses, with some finding the technology obtrusive, especially in the context of outdoor climbing. With the evaluation of their prototype [91], they concluded that "Wearable devices should support the competencies of expert climbers or help beginners acquire them", and not go beyond scope. Many tracking

[6] https://docs.optitrack.com/plugins/optitrack-unity-plugin
[7] https://base.movella.com/s/article/MVN-Unity-Live-Plugin-2020-0?language=en_US
[8] https://rfilkov.com/2013/12/16/kinect-with-ms-sdk/
[9] https://optitrack.com/cameras/prime-13/specs.html
[10] https://www.movella.com/products/motion-capture/xsens-mvn-link?utm_source=chatgpt.com

andMoCap solutions employ the use of on-body wearables to measure climbing behavior, particularly inertial types. Thus attention has to be put into minimizing any on-body tracking devices as much as possible.

4.2.3 Latency

Videogames are often a real-time experience, where the user depends on reflexes to respond quickly to in-game events. It is therefore important that the time between an action and an on-screen result, also known as latency, is as short as possible. This latency is caused by everything from input device delay to processing delay, display latency, and more. In the context of the IICW, that latency is a combination of Pose Tracking sensing & processing, game engine processing, (wireless) IP communication, and projection latency. While it is difficult to pinpoint the exact amount of latency for every step, it is plausible that a significant chunk of latency, if not most, comes from pose tracking, which is why it is an important factor in the selection. While determining pose tracking latency in isolation is difficult, comparing the total 'end to end' latency should be a completely valid approach, as long as all other factors that could influence latency are constant between tests.

Claypool and Claypool examined the importance of latency to video games [92], and defined different categories of player actions, with different latency requirements. High-precision first-person games like shooters are much more prone to high latency than third-person story-driven games or even 'omnipresent' games like strategy. They provide clear acceptability thresholds, after which a gaming experience and player performance are significantly degraded. These are *100ms* for First-person perspectives, *500ms* for Third-person perspectives, and *1000ms* for Omnipresent perspectives. In testing, these can be guidelines to classify systems into certain types of games.

Method

For comparing latency among the three systems in the selection, quick measurements were conducted. A high-speed camera was used to record a side-by-side view of the researcher and a screen with a tracked avatar on it, at 120 Hz. The researcher shows some quick movements, which can be matched to the correct frame in post-analysis. The time difference between frames is used as a measure for end-to-end latency, meaning the complete stack of recording to displaying is counted.

Results

As can be seen in figure 4.6, there were clear measured differences in latency, with the inertial tracking suit performing the best, and visual tracking performing worst with a wide margin. The results of the latter, with over 2 seconds, mean it is unacceptable for any real-time operation. We can also conclude that Azure Kinect has suitable latency for *Omnipresent* perspective games, and the MVN Link even being good enough for *third-person* applications, as per Claypool's thresholds [92].

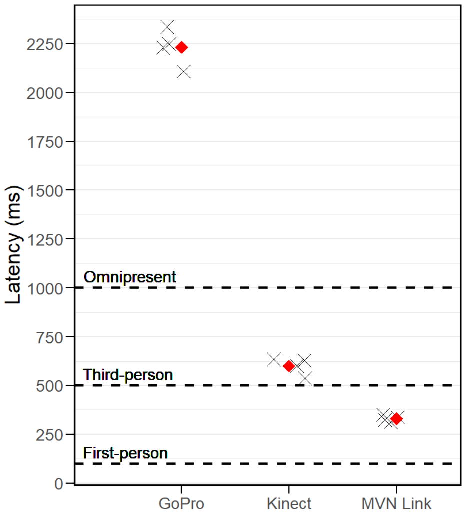


Figure 4.6: Latency comparison measurements between different Pose Tracking systems

4.2.4 Accessibility

To a lesser extent, the impact of climbing solutions is defined by their reach; The more people that can make use of the technologies and solutions, the better. This depends on the resources required for implementation, such as time, space, knowledge, and most importantly, money. Again, these factors are true for all aspects of the climbing solutions, though pose tracking shows arguably the most complexity and resources required. Taking the costs of different pose tracking technologies into account can thus meaningfully improve its impact.

4.3 Results & Conclusion

Bringing all measurements and comparisons together, we see table 4.2. Notable is the MVN Link, which scores best in precision and latency, but worse in invasiveness and cost, while the Kinect seems to be a decent trade-off between precision, latency, invasiveness, and cost.

Table 4.2: Table:HPE system Comparison

System	Type	Precision	Latency (ms)	Drift	Invasiveness	Cost (€)
MVN Link	Inertial	High	330	High	High	50.000
OptiTrack	Optical	High	-	Low	Moderate	30.000
Kinect	Depth	Moderate	600	Low	Low	1000
Google 'BlazePose' Landmark Detection	Visual	Moderate	2232	Low	Low	300

While the conclusion from this chapter supports the chosen concept, it can be useful for the other ones too. Matching the four concepts to tracking systems might benefit future research. So, given the cost and accessibility factors, the following recommendations are given for each concept, see table 4.3, based on the measurement results from this chapter. Keep in mind, that the recommendation is given only based on the tested systems, and should not necessarily be generalized to all systems within the category. While the recommendation for the current concept remains the *Azure Kinect* depth system, the conditions of implementing the prototype present a challenge. The slanted climbing wall, with an incline of 30 degrees, is not suitable for the depth sensing system, as discussed in section 4.2.1. Therefore from now on, we will be working with the *MVN Link* system instead, due to its latency, and results should be somewhat representative. For vertical climbing wall installations, we will still recommend the *Azure Kinect* solution.

Table 4.3: Recommendations for pose tracking systems, per ideated concept

Concept	Required Accuracy	Required Latency	Recommended System
Concept A	Medium	Medium	Depth (e.g. Azure Kinect)
Concept B	Very high	High	Inertial (e.g. MVN Link)
Concept C	High	Medium	Inertial (e.g. MVN Link)
Concept D	Low	Low	Depth (e.g. Azure Kinect)

Chapter 5

The movement-based warm-up game

Having selected concept D to be explored, we can incorporate some expert feedback into the implementation early on, as well as grounding it in theory. This leaves us with a concrete set of guidelines and constraints for use during implementation. The second half of the chapter will describe the concrete realization of the prototype, including its technical workings and design choices made.

5.1 The routine

The core premise of the selected concept, as suggested by Yu et al [74], is that warm-up exercises should resemble actual climbing, with consideration for climbing posture. As a reminder, see section 2.2.4, the climbing expert suggests focusing on Aerobic activity, dynamic stretching, grip training, and difficulty ramp-up, for an effective conventional warmup routine. When transferring these elements to an 'on-the-wall' experience, some of these elements can be combined. Namely grip training overlaps significantly with any 'on-the-wall' activities, because the mere holding of a climbing grip, given the difficulty is low, can be considered effective grip training. Therefore, we are left with the other three elements, which are directly incorporated into a new three-phase novel warm-up routine, containing gamified and on-the-wall experiences. This aligns with the GBL guidelines set out in section 2.3.3, which recommend a strong maintaining of relevance when translating sports elements into digital representations.
However, not every phase of warm-up might benefit from on-the-wall exercises to the same degree. Especially cardio exercises (for climbing a typical example would be jumping jacks), would be extremely difficult, if possible at all, to translate to on the wall. This is because even positioning oneself on a climbing wall requires strict tension and control in muscles, as opposed to maximum exhaustion in aerobic exercises (cardio). For this reason, only the latter three phases will be on-the-wall, while the first phase takes place largely grounded, forming a hybrid warmup routine.

For the aerobic exercise, jumping jacks were selected because of the predictable positioning, and continued ability for the user to observe the climbing wall projection surface. The specific exercise does not make a large difference and could be replaced or updated if needed. The stretches can be moved to the wall relatively easily, though

- Grounded jumping jacks (Aerobic activity)
- On-the-wall controlled arm reaches to goal (Dynamic stretching)
- On-the-wall low-skill climbing route (Difficulty ramp-up)

5.2 Making the game 'fun'

With the above-mentioned constraints, and the requirements set in section 5, the ideation process can converge towards a final implementation. Again, this is done with the help of end-users, as the most important stakeholders. Using the three-phase warmup routine as the structure, an informal brainstorming session is held with a small selection of climbers, to generate a 'theme' for the gamified experience. This process follows the serious

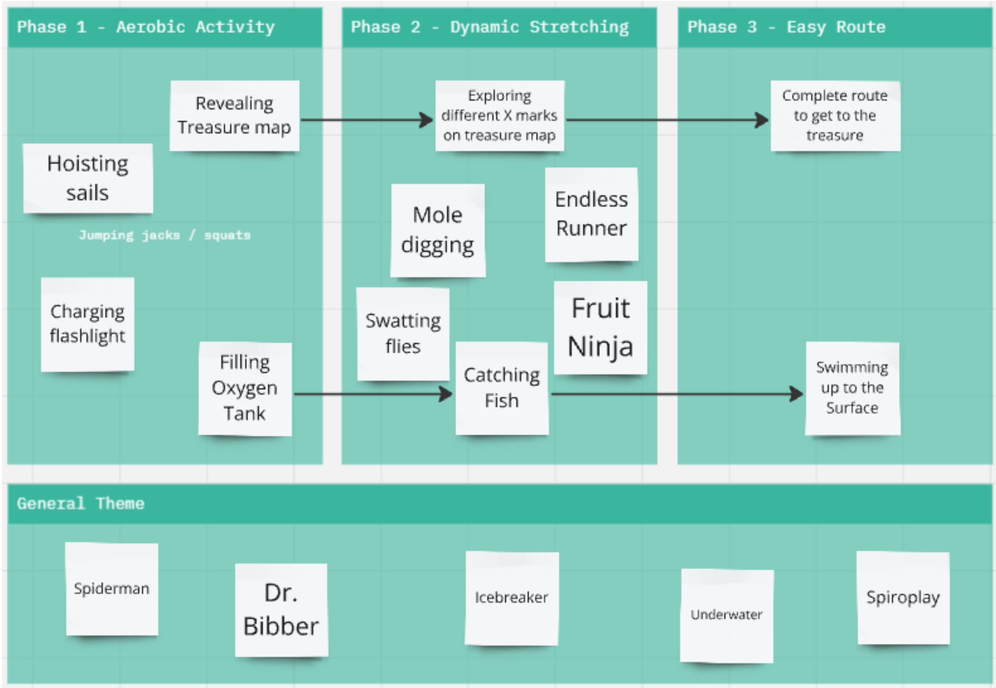


Figure 5.1: Brainstorm results for game themes

game principle of building game elements on top of a 'serious' goal [50] [93]. For the gamified elements, the instructions were kept to a minimum, giving climbers creative freedom in coming up with game elements, as long as they strictly aligned players to the provided moveset. The resulting ideas can be seen in figure 5.1, where several thematic elements are categorized in the three phases. Without much explicit guidance, the brainstorming participants tended to come up with ideas that were closer to gamification, rather than playification, taking inspiration from videogames they were familiar with from their own experiences.

From the two most cohesive game ideas, underwater and pirate themes, the pirate theme was deemed most closely aligned with the moveset, and was selected to go forward with.

5.3 Implementation

The ideated game concept and routine can now be integrated into a reliable prototype, built on the IICW platform. This section will describe its implementation into a cohesive system.

5.3.1 Motion Tracking

The selected system for the current concept, the Azure Kinect, as well as the other three pose tracking systems, are integrated into the IICW. The core of this integration is the real-time 3D engine *Unity*, which runs on the server in the climbing wall. Using this platform as a base, we can use a selection of libraries to interface with the pose tracking hardware and sdk's[1234]. Several SDK's and system-specific software have to be running for the integrations to communicate with, an overview of how these communicate can be seen in figure 5.2, and more detailed in appendix B.1. The Unity integration software layer provides direct access to real-time pose data and includes the abstraction of the pose skeleton, which can be mapped to any humanoid avatar in Unity. While the integrations function very differently, we attempt to standardize the implementation, to easily switch between different systems. A single *Avatar Controller* component is designed, to function as a two-way communication node between the pose-driven avatar, and the rest of the software stack. The following feature set is exposed:

[1] https://assetstore.unity.com/packages/3d/animations/mvn-live-animation-11338
[2] https://assetstore.unity.com/packages/tools/integration/azure-kinect-and-femto-bolt-examples-for-unity-149700
[3] https://optitrack.com/software/unity/
[4] https://github.com/creativeIKEP/BlazePoseBarracuda.git?path=Packages/BlazePoseBarracuda#v1.3.0

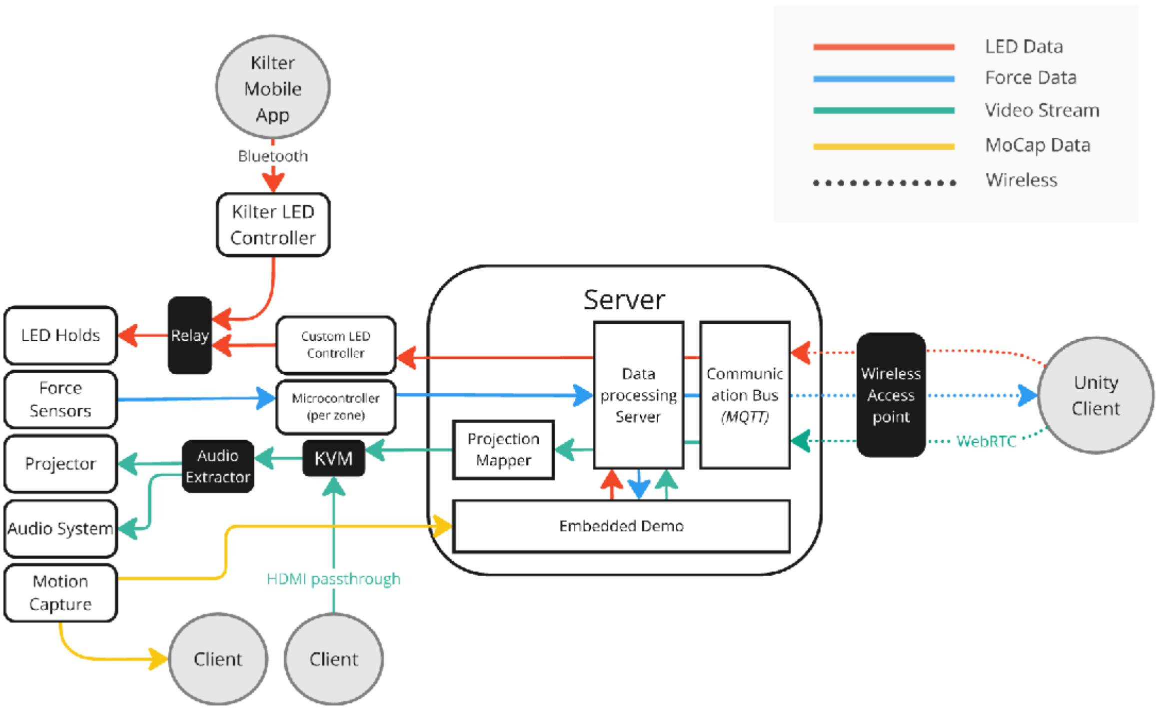


Figure 5.2: IICW component overview

- Positional & rotational calibration
- Realtime angle calculation of elbow and knee joints
- Realtime center of mass calculation & visualization
- Real-time distance to wall measurements for all limbs
- Anthropometric measurements of the climber
- Kinematics recorder, which logs joint position and angles over time to a CSV file

To compensate for the relative positional tracking of the Xsens suit, an additional calibration sequence is programmed. This ensures the position and rotation of the digital pose, relative to the climbing wall, matches the real one. This works by the climber having to stand on a marked spot, and clapping their hands together (an input method that does not require access to physical controls), which triggers the remapping of pose joint positions.

These integrations and components allow us to use the human body as game input, almost like a game controller. It's designed as a reusable platform, which can be used not only for the current concept but also the other ideated concepts, as well as beyond.

5.3.2 System Design

The package is brought together in a single unity solution, combining the tracking system with the game design. It is designed as modular as possible, with several layers of interfaces, such as the modular game, game theme, and tracking system. The entire class architecture can be seen in the appendix, figure B.2. This is not just for easily modifying or adding functionality, but also allows intuitive interfacing with the IICW hardware, as only a single wired or wireless connection from a client to the wall is required for complete control. With the complete software-hardware intervention now in place, see figure 5.3, we can start to evaluate its effectiveness in the next section.

Figure 5.3: The movement-based warm-up game in action

Chapter 6

Validating the prototype

6.1 Requirements

We are interested in two main advantages the solution could provide, compared to traditional warm-up exercises. The first is providing better incentives, stemming from the inherent entertainment value that games provide. The second is more quantitative, namely the supposed improved effectiveness of the novel warm-up procedure, compared to warm-up exercises that take place off the climbing wall. Reformulating these goals to research questions gives us the following:

- Does the novel solution provide adequate warm-up compared to a traditional warm-up routine?
- Does the novel solution incentivize climbers to warm up more frequently?

This section aims to evaluate the proposed intervention, by finding useful metrics and practical means of conducting experiments around them.

6.2 Metrics

In the previous section, we set out two different hypotheses, which we are aiming to evaluate. For both engagement and warm-up effectiveness, valid metrics are discussed, which aim to accurately measure the intervention on both fronts.

6.2.1 Measuring effectiveness

The effectiveness of warm-up exercises can be interpreted in different ways, especially since the three-phase warm-up routine has different goals for different phases. In general, though, these are a set of more concrete metrics for evaluating warm-up effectiveness, specifically for climbing.

- Isometric muscular endurance of finger flexors [74]
- Joint Range of Motion [74]
- Heart-rate & Heart Rate Variability (HRV)
- Grip strength through dynamometer
- Performance metrics, such as time to complete route and number of moves to complete route

6.2.2 Measuring engagement

The User Engagement Scale (UES) is a widely adopted and validated technique to measure user engagement in Human Computer Interaction (HCI) [94], with a survey measuring 6 factors among 31 questions. However, everything we know about surveys, tells us that concisiveness is key for better user understanding and accurate answers [95]. O'Brien et al recognized this when they published a revised, short-form version of the UES survey in 2018 [96], which brought the survey size down to 4 factors in 12 questions, by combining factors with maximal coherence. The four factors are *Focused Attention, Perceived Usability, Aesthetic Appeal* and *Reward*, which give an overview of overall user engagement with an interactive experience, in a relatively short survey. They recommend adjusting the questions slightly to fit the context better, which can be seen in the final list of questions in table 6.1.

Table 6.1: UES-SF scale

Factor	Question	Revised Question
FA-S.1	I lost myself in this experience.	I lost myself in this experience.
FA-S.1	The time I spent using Application X just slipped away.	The time I spent playing the warm-up game just slipped away.
FA-S.1	I was absorbed in this experience.	I was absorbed in this experience.
PU-S.1	I felt frustrated while using this Application X.*	I felt frustrated while playing the warm-up game.*
PU-S.1	I found this Application X confusing to use.*	I found the warm-up game confusing to use.*
PU-S.1	Using this Application X was taxing.*	Playing the warm-up game was taxing.*
AE-S.1	This Application X was attractive.	The warm-up game was attractive.
AE-S.1	This Application X was aesthetically appealing.	The warm-up game was aesthetically appealing.
AE-S.1	This Application X appealed to my senses.	The warm-up game appealed to my senses.
RW-S.1	Using Application X was worthwhile.	Doing the warm-up exercise was worthwhile.
RW-S.1	My experience was rewarding.	My experience was rewarding.
RW-S.1	I felt interested in this experience.	I felt interested in this experience.

*Answer scores are inversely coded

6.3 Participant profile

For recruiting participants for the experiment, we require a significant amount of people who fit our profile. Specifically, they should be of beginner to intermediate climbing level, as that is what the selected concept is targeted at, see section 3.2.

6.3.1 Inclusion & exclusion Criteria

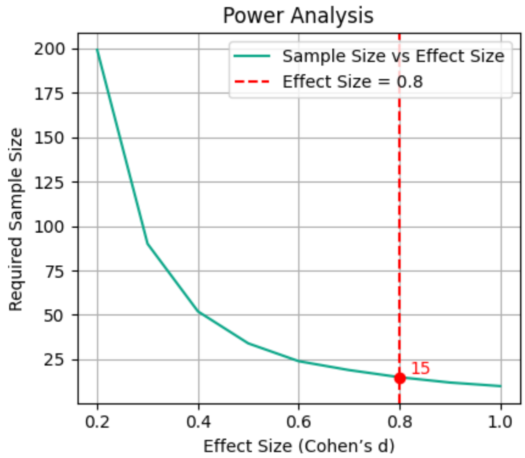
The most important aspect of the participant profile is fitting into this skill level of climbing. For classifying this, we explicitly omit differences in climbing disciplines such as indoor, outdoor, and sport climbing, as there is a large overlap in skill. For participant inclusion, the maximum skill grade is set at 7a on the Fontainebleau scale, and the minimum as 5c. Another reason for the latter is the specification of the prototype climbing wall. As the wall is built at a steep 30-degree incline angle, the strength and skill level required to use the wall are significant. To prevent participants from being unable to use the installation for an extended time, the lower inclusion skill grade cannot be set too low. Another more obvious, exclusion criterion is the health status of the participant, who should be uninjured.

6.3.2 Sample Size

While more participants generally are better for determining significant differences, diminishing returns and research scope push us to look for a manageable sample size, that is still statistically relevant. To determine the

Figure 6.1: Power Analysis for repeated measures experiment

α **(Confidence):** 0.05
β **(Power):** 0.8
r **(within-group correlation):** 0.5
d **(Effect Size):** 0.8
n **(Sample Size):** 15



amount of required participants, we have to take a closer look at the experiment's statistical power. Cohen [97], in his seminal work, described it as follows "The power of a statistical test is the probability that it will yield statistically significant results". Power is typically set to 80%, meaning there is an 80% probability of finding an effect, if it exists. Cohen describes power is affected by sample size, confidence, as well as effect size.

Specifically for repeated measures experiments, where participants are exposed to both conditions twice, the correlation is set to 0.5. The rest of the parameters and results of the power analysis can be seen in figure 6.1, which plots effect size against sample size, as effect size is one of the most important factors in designing your measurements [97]. For this specific experiment, the two conditions are very different in various ways, with a lot of potential variables affecting the result. Therefore, a larger effect size of 0.8 is well-suited. This gives us a target sample size to strive for, of 15 participants. Unfortunately, we fell short and recruited 12 participants during the final evaluation.

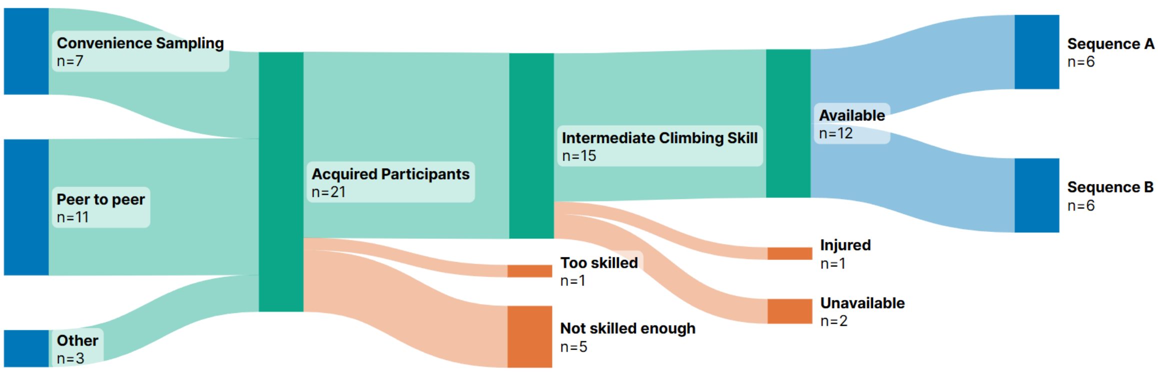


Figure 6.2: Participant recruitment process

6.4 Method

The research experiment is set up using a 'within-group' repeated measures distribution. This means that we compare our two conditions with the same participants sample, where they each will be exposed to both setups. The first and obvious is a complete play session of the prototype, with all three phases, hereby considered 'Condition A'. The second is a traditional warm-up routine for comparison, 'Condition B'. This routine consists of the same three phases, as recommended by the climbing expert, but using a simple video as instructions, see figure 6.4. The second phase shows the biggest departure from the prototype, with the stretches consisting of

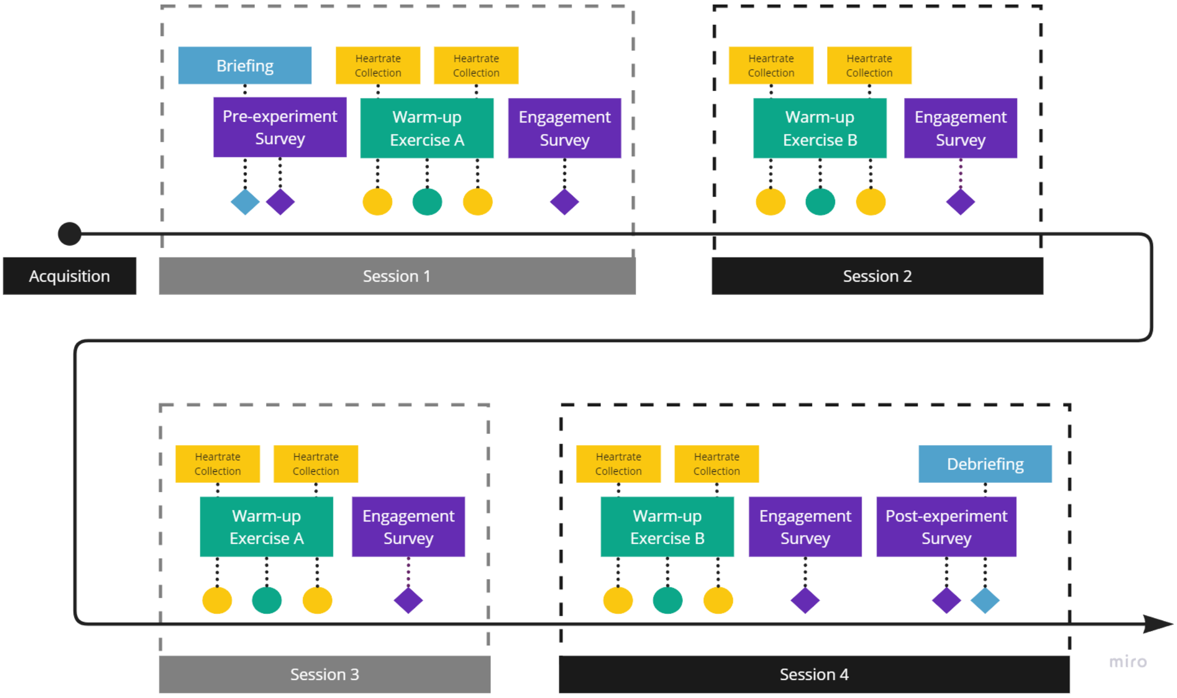


Figure 6.3: EvaluationTimeline

arm twist lunges and arm rotations.

After participants have been recruited, they are scheduled for four different sessions on different days, see timeline in figure 6.3. They are evenly distributed among the condition orders, either A-B-A-B or B-A-B-A. Naturally, every first session starts with informed consent and a briefing, but also a pre-experiment survey. This survey, see appendix C.2, gives us more insight into the demographic of the participants. Questions like 'What skill grade do you climb at?' are used to exclude participants outside our criteria, and can perhaps lead to interesting correlations.

Figure 6.4: Tradional warm-up (Condition B) with instructional video

Then the chest strap heart rate sensor is moisturized and attached to the participant. It will record heart rate and HRV during the entire session. After the three-phase routine, participants are presented with the post-session survey, see appendix C.3, consisting of the engagement questionnaire, as well as some qualitative questions about warm-up effectiveness. In the last session, a more elaborate comparison is done, by asking participants their opinion of the prototype compared to the traditional warm-up, see appendix C.4. In the debriefing after, they are also informed of the minor deception concerning motion tracking and are rewarded with (healthy) snacks.

6.5 Pilot test

Conducting a pilot test is a good way to validate our evaluation methodology, and improve upon it. Lessons can be learned by observing a 'test' participant, who is excluded from the final data processing, trying the experiment out. After the pilot had run with a preliminary version of the prototype, many imperfections were observed, in both the experiment procedure as well as technical aspects of the installation, as seen below.

Process observations

- Participant was confused on how to put on the chest strap
- During the survey, the third phase (windup route) was not considered part of the warm-up sequence by the participant
- Researcher is slightly overwhelmed by the sequence of tasks

Prototype observations

- Phases using different visualizations for target holds is confusing.
- Voice-over is difficult to hear
- Breaks feel too short
- New stretches trigger too frequently
- Cardio and stretching phase start very abruptly
- Target holds sometimes easy to miss

All mentioned issues have been addressed in the final version of the evaluation methodology. The first step was adjusting the survey, to clarify questions and explicitly mention all three phases as the warm-up routine. Also, a step-by-step cheatsheet was created for the researcher, and an instruction pamphlet was designed for the participant to put on the cheststrap, see appendix C.1.

As for the prototype, shorts breaks, stretch frequency, and voice-over volume are easy fixes. The target holds were also changed to be projected only, instead of using the LED matrix, and they are animated to increase visibility. Also, the cardio and stretch phases are improved with a short intro sequence, gradually onboarding the user with explanation. Lastly, an additional pause feature was implemented, allowing the researcher to interrupt the routine if a participant falls for example.

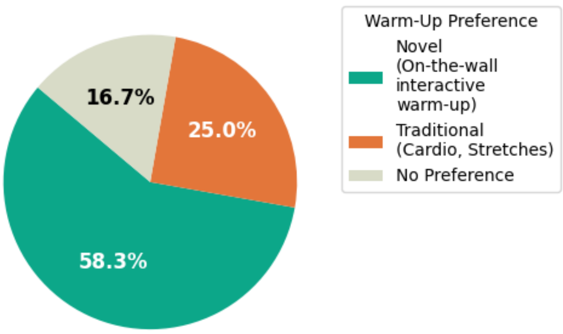
Chapter 7

Results

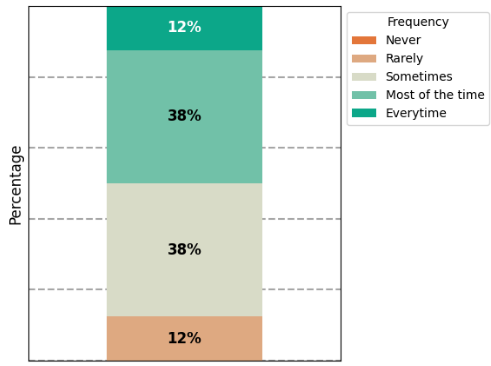
The experiments were executed in a controlled lab setting, over the course of two months, during which a large amount of user data was recorded. This contains heartrate, heart rate variability, MoCap data, a wealth of demographic information, and the results of the UES scale and post-experiment questionnaire. All data was acquired with informed consent, approved by an ethics committee, and securely stored for a maximum of 10 years. After collection, this data is processed in Python, visualized, and anonymized. Specifically, we are interested in the metrics discussed in the previous chapter 6, engagement and effectiveness.

7.1 Engagement

Starting off with the subjective opinion participants had on the two conditions *after* completing all experiment sessions. The answers to these simple comparative questions form the basis for a deeper exploration of the results and can be seen in figures 7.1a and 7.1b. Evidently, participants preferred the novel warm-up sequence more than the traditional, with most people even indicating they would incorporate the warm-up system into their own training to a degree.



(a) Participant responses to 'Which has your preference?'



(b) Participant responses to 'Would you use this in your own training? '

Figure 7.1: Questions comparing both conditions post-experiment

Before diving deeper into the data, there are factors that could disrupt the reliability of the results. Mainly the two groups of participants, that start the experiment off with different sequences of sessions, could be influenced in their opinion due to recency bias. To make sure this factor does not meddle with the outcome, we compare the two main comparative engagement questions (independent variables) with the session sequence (dependent variable) in a Chi-squared test. In appendix D.1 you can find the results of the comparison, which shows H0 to be accepted *(p=1 and p=0.45)*, meaning both sample populations can be seen as a single population with no significant differences.

While the simple answer to 'Which has your preference' seems clear, it should be backed up by more quantitative data from the different conditions to compare. Using the UES questionnaire discussed in the previous chapter, sessions are scored individually on subfactors of engagements, and compared afterward. As seen in figure 7.2, the difference in scores is positive for all subfactors, except for *Perceived Usability*. Using a Linear Mixed-effects regression model, the four subfactors were all deemed significant in their differences between conditions, and the internal consistency of the factors was acceptable, see table 7.1.

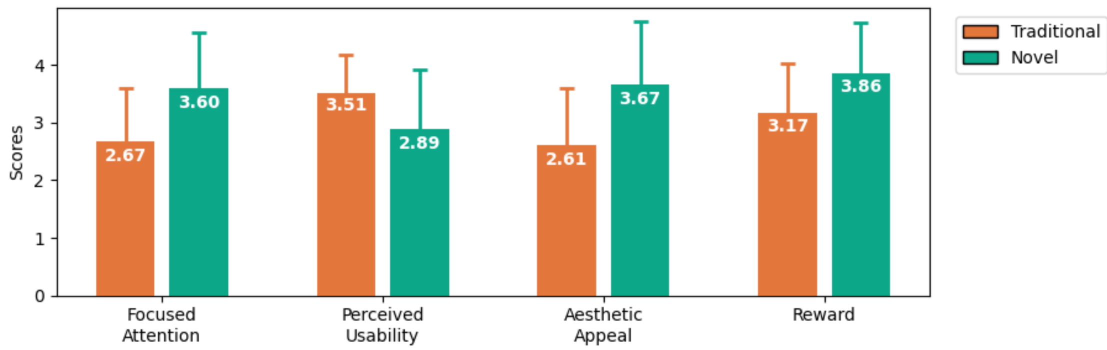


Figure 7.2: Measured Engagement Factors $(p < 0.01)$

Table 7.1: P-values and Reliability Values for the Four Factors (Linear Mixed-Effects Regression and Cronbach's Alpha).

Factor	p-value	Reliability (Cronbach's α)
Focused Attention	<0.001	0.83
Perceived Usability	<0.001	0.72
Aesthetic Appeal	<0.001	0.82
Reward	<0.001	0.7

Now diving deeper into the reasons why participants preferred the novel warm-up routine, we asked about several aspects of the installation. You can see the opinions of participants on these aspects in figure 7.3, with a clear preference for being on the wall, and overwhelming dislike of the properties of the used system board.

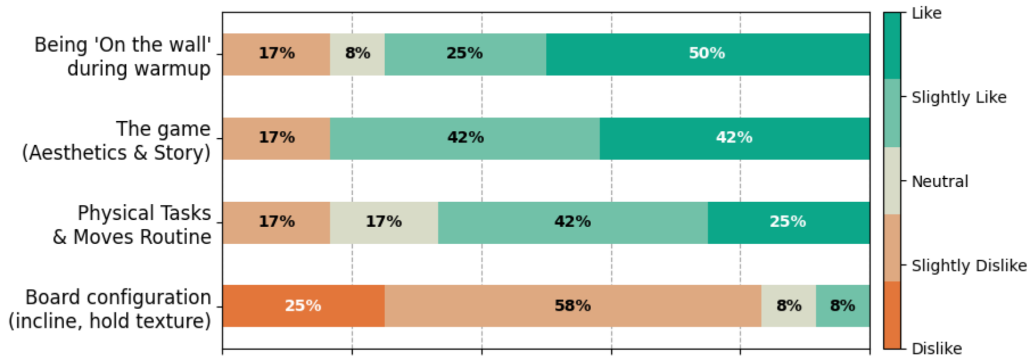


Figure 7.3: Participant's opinion on several aspects of the prototype

7.1.1 Correlations

For additional insights, the pre-experiment survey in appendix C.2, inquired participants about their demographic and climbing-specific attributes. Especially the latter is deemed interesting as it already informed the ideation and participant selection process. Now we can reflect back on this data using our post-experiment results, to see if we can find interesting relationships.

The two main comparative data points for subjective engagement measures were the questions *'Which warm-up exercise would you prefer for your own training?'* and *'If readily available, how often would you use the interactive warm-up exercise before your climbing sessions?'*. As seen in appendix D.1, initial Exploratory Data Analysis (EDA) was done first, allowing visual identification of possible relationships using scatterplots.

Determining accurate correlation numbers between factors was done using Kendall's Tau, as opposed to Pearson or Spearman correlations, due to the non-normally distributed non-linear data points and ordinal variables. The resulting heatmap can be seen in figure 7.4, and show no significant ($\alpha = 0.8$) correlations between factors. The one exception is the significant correlation between two post-experiment questions, which was to be expected.

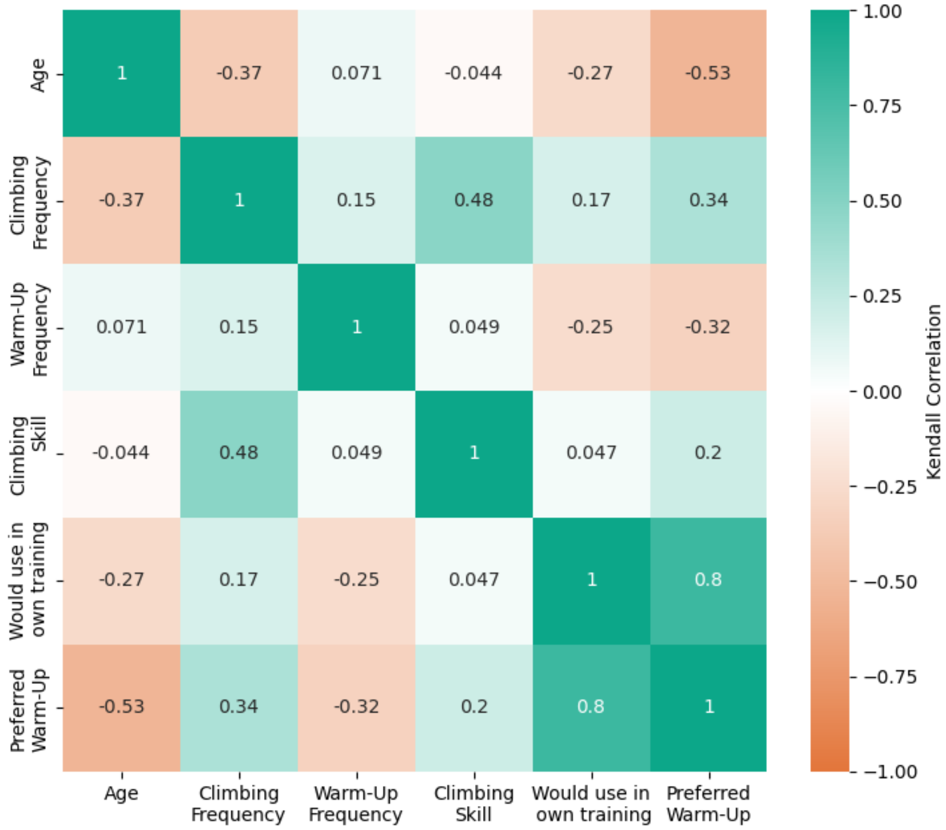


Figure 7.4: Correlations for demographic participant data

7.2 Effectiveness

Effectiveness shows mixed results. Qualitative data from the post-session questionnaire, which asked the question *"How effective do you feel the warmup was?"*, can be seen in figure 7.5. For every single participant, the Wilcoxon Signed-Rank test concludes no significant differences between conditions ($\alpha = 0.05$), see appendix D.1. The group p-value is *0.78*, meaning no significance between the two conditions in perceived effectiveness.

The intended quantitative method of analyzing Heart Rate (HR) and HRV data points, already flawed because of little academic grounding, was further complicated by frequent failure in the measurement device, resulting in several sessions with incomplete recordings. Comparing the collected data also had challenges in labelling different phases, for which there was no clear process or markers, and varied per condition. Therefore concrete results comparing the two have been omitted. Informally, we can still use the data to illustrate differences, though only for a single participant. For example, figure 7.6 clearly shows the intensity peaks of the three phases, and an overall difference in intensity between the conditions. This is confirmed by a total average across participants of *77.1% (±5.6%)* for the novel routine and *66.8% (±7.0%)* for the conventional routine.

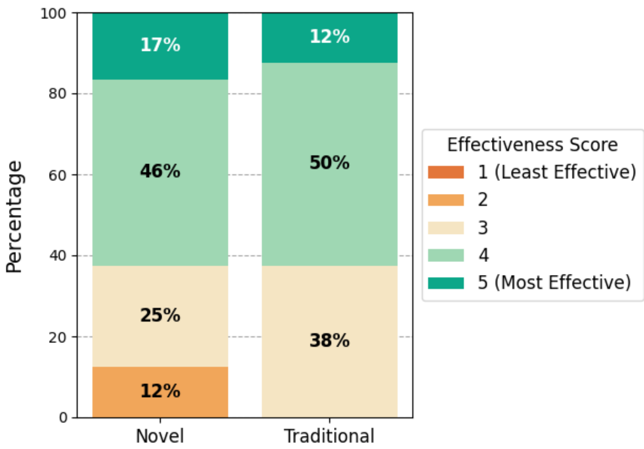


Figure 7.5: Perceived effectiveness between conditions ($p = 0.78$)

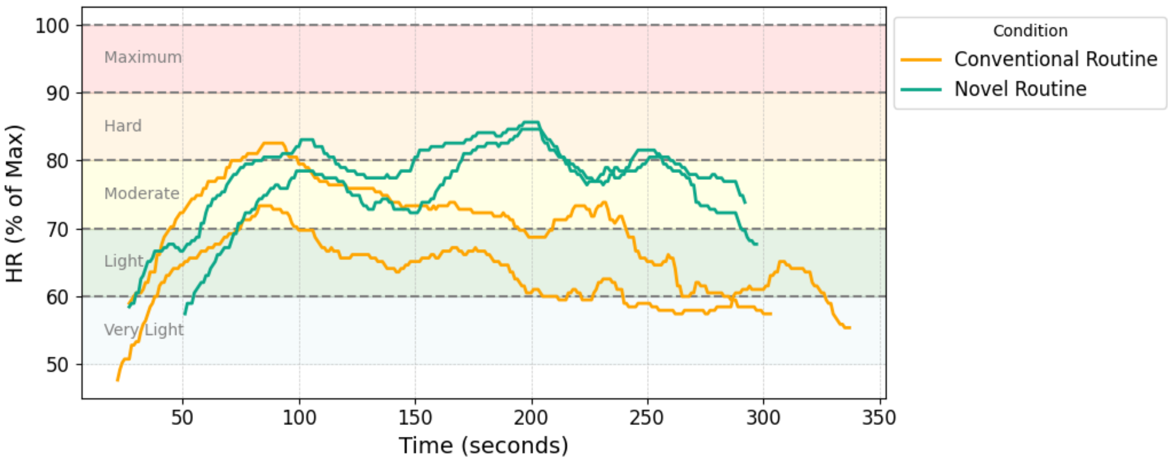


Figure 7.6: Heartrate over time, per condition, for one of the participants

Chapter 8

Final Reflections

8.1 Conclusion

Let us summarize our findings by answering the set-out research questions, starting from the ideation process;

RQ1: *How can embodied co-design methods inform the design process for in-action climbing training tools?*

- Embodied codesign allows deeper exploration, uncovering problems, opportunities and solutions not considered otherwise. Overrelying on user input risks degrading the quality of output, balancing with expert evaluation is recommended.

RQ2: *What specific climbing task-setting provides the most relevant problems & opportunities*

- The most recurring problem throughout ideation is the lack of practicing warmup, with the connected opportunity of on-the-wall warmup as an incentive for increasing warmup frequency. This is combined into a problem-opportunity-solution fit with an interactive gamified warmup concept.

RQ3: *What are the qualities of effective tracking technologies for in-action measurements?*

- Precision, latency, and invasiveness are important metrics, though several factors can influence precision, such as lighting, clothing, and wall angle. The Azure Kinect system was deemed an optimal trade-off for the novel concept, with the MVN Link being best suited for other concepts due to its high performance.

RQ4: *What are good objectives for evaluating in-action training systems on novice climbers?*

- For the novel warm-up concept, warmup **engagement** and **effectiveness** are most relevant factors to maximize impact.

The mix of post-session and post-experiment surveys shows a clear and significant improvement in engagement for the novel solution. The solution scored higher on every engagement metric except for perceived usability. The novel solution should be successfully transferable to situated practice, as most participants would prefer the solution as is in their routine. The highlight of the solution is the embodied 'in the wall' experience during warmup, with the game and moves routine closely following. The specific 'pirate' game implementation had mixed reactions, with some describing it as distracting. A clear disadvantage of the current implementation is the board configuration, with its steep 30-degree incline, lack of chalk, and rough texture, which dramatically increased difficulty and intensiveness. Smaller annoyances include obscuring the projections with the body and the discomfort of doing high-exertion cardio in climbing shoes.

The effectiveness of the novel warmup was difficult to quantify. No significant difference in heart rate patterns could be measured. However, with the amount of uncertainties and flaws in the method, I would not describe this as a clear conclusion that both warmups are of similar effectiveness. The survey answers were more clear, with participants rating the effectiveness as similar, with a slight favor of the traditional warmup for effectiveness. As difficulty was one of the described issues for perceived effectiveness, we presume an easier, flat wall could bring the perceived effectiveness to be at least on par.

Overall, gamified warmup is promising and should considered to increase warmup frequency, thus preventing injuries. With the gained knowledge we can reflect on the sub-research question ”To what extent does the final solution contribute to these objectives?”, which we further elaborated upon in the evaluation chapter;

RQ5.1: *Does the novel solution provide adequate warm-up compared to a traditional warm-up routine?*

➤ Likely; The novel warmup performs close in effectiveness to the traditional routine, based on qualitative measures only.

RQ5.2: *Does the novel solution incentivize climbers to warm up more frequently?*

➤ Yes; The novel solution is preferred over traditional warmup, and scores higher in most engagement metrics, with most participants inclined to incorporate the solution in their training to some degree.

8.2 Contributions

The field of existing climbing research is limited, creating many opportunities for this and future work to explore. As shown in the background, the state-of-the-art mapping leaves especially room in the training/in-action area, which we make use of in designing our concepts. These are all co-designed problem-solution-fits, including hardware recommendations, which we encourage future researchers in the field to explore.

The second big addition is the analysis of motion-tracking systems. While separately, some of these systems have been evaluated or even compared before in accuracy, the climbing context adds significant constraints. The context-specific outcome of a measured accuracy, latency, and accessibility overview is a valuable contribution to the field of technology-enabled climbing research.

The IICW platform, though not described in detail, was created specifically for this type of research project. It provides a solid foundation for many different technology-enabled climbing concepts, such as the four developed ones, in an easy-to-use package. This is a valuable contribution, just in the sense that it enables and accelerates future projects in the field.

Last but not least, the selected concept was evaluated and proven successful, at least in incentivizing users to warm up more frequently. Though effectiveness is slightly mixed, our evaluation shows enough promise of such a system to be applied more generally, and to be explored further.

8.3 Limitations & Future work

While the evaluation shows some promising results, quite some findings suggest knowledge gaps that can be addressed in future work. Starting with the implementation of the prototype, both the game and the IICW hardware platform, the following improvements could lift the system to a higher level.

Game Design

- Add onboarding instructions for better user understanding
- Make scoring a more central mechanic by adding granularity and showing own and other's high scores
- Decrease the focus on the 'pirate' theme narrative

Platform Design

- Use a flat wall for decreased difficulty and exertion, and better tracking accuracy
- Use LEDs or short-throw projectors to get around body projection occlusion

Perhaps more relevant, what learnings can we take from our methods? Critically analyzing our ideation and evaluation processes should offer points of improvement for research methods in any subsequent work;

Method

- Lack of quantitative measurements for warm-up effectiveness
- Lack of grip training in the conventional warm-up routine
- 'Wizard of Oz' evaluation (although participants did not notice the deception)
- Lack of quantitative measurements for tracking accuracy during comparison
- After-the-fact analysis on accuracy conditions like wall angle
- Limited scope to in-action/training framework only

8.4 Discussion

Most of the raised issues can be fairly easily addressed in future work. However let's dive deeper into a couple of the results, to place them in a broader context of the field.

8.4.1 Personalization

As discussed in the background, there is reason to believe personalization benefits climbing. However, the user-driven ideation did not end up including any personalized features in the intervention. The question remains; how could personalization play a role in this and future interventions?

The first obvious aspect is physiology, which is shown to be a KPI in climbing performance. Measures such as SMR [29], MVC [26], and foot reach [32] can be used to tailor the warm-up to the climber's body. Some biomechanical properties might be difficult to obtain, but the existing implementation of pose tracking already allows for basic anthropometric measuring such as height and arm length, without the need for additional sensing or data collection.

In addition, the warmup routine can be customized for personal preference. Not only the manual selection of different themes, but a recommendation engine can be used [33], to learn and adapt the user's moves to different climbing styles. However, for the sake of injury prevention, future research should prioritize physiology-based personalization.

8.4.2 Serious movement games

The mixed reactions to the game narrative is an interesting pain point. With the ideation not spending much time on this step, as the three-phase warmup moveset was deemed most relevant, there were limited game themes considered. The 'pirate' theme was described by some users as engaging and fun, by others as 'redundant' and 'gimmicky'. During a high-exertion on-the-wall exercise, these visuals and voice-overs were sometimes mentioned to distract users instead of motivating them. This aligns more closely with *Playification* as opposed to Gamification, according to Postma et al [15], who described different sports interaction technology methods. Toning these more explicit and narrative elements down would presumably enhance the experience, while keeping the scoring system *'Gamification'* as a motivator for players.

While tightening down the participatory ideation process could have directed the themes more toward gamification, perhaps toning down co-design, in general, would be a better solution. This is suggested by DeSmet et al [98], who analyzed 61 studies on serious digital games for health, and mentioned *"When PD [Participatory Design] is applied to game dynamics, levels, and game challenge, this was associated with higher effectiveness than when it was applied to game aesthetics"*. Looking back to our process, participatory design methods should have been constrained to these mentioned elements, while the game visuals and narrative ('theme') benefit from conventional design methods.

For future work, we suggest a more structured participatory game design process, such as Khaled et al [99] proposed. With a rigid barebones game framework, including domain [climbing] knowledge, participants can fill in the blanks to create a complete design. This 'boundary object' framework should include features to compensate for 'achiever' type players [100], and decrease focus on the narrative in favor of player agency [101].

8.4.3 Knowledge gap

Going back further in the research process, we set out our 'in/out action vs training/entertainment' framework to use as constraints. There is no literature available to support this decision, and can be considered a bias, as there might be alternative frameworks that provide new insights. Upon re-examining related work, a few patterns can be established among interventions, which function as a scale;

- Personal / Collaborative
- Entertainment / Skill acquisition
- Technical climbing / Physical climbing
- In-Action / Out-of-action
- Skill acquisition / Injury prevention

These trends can be combined into different frameworks, where related work can again be mapped onto. Two of the most promising examples can be seen in figure 8.1. Clearly, there are knowledge gaps to be found, though somewhat less pronounced. To make a more informed selection between these research directions, one could consider the SPORTS framework by Postma et al [15], to explore correlations with sports science, technology, and practice. Overall the chosen research direction still seems most relevant, though we encourage researchers to explore the alternatives.

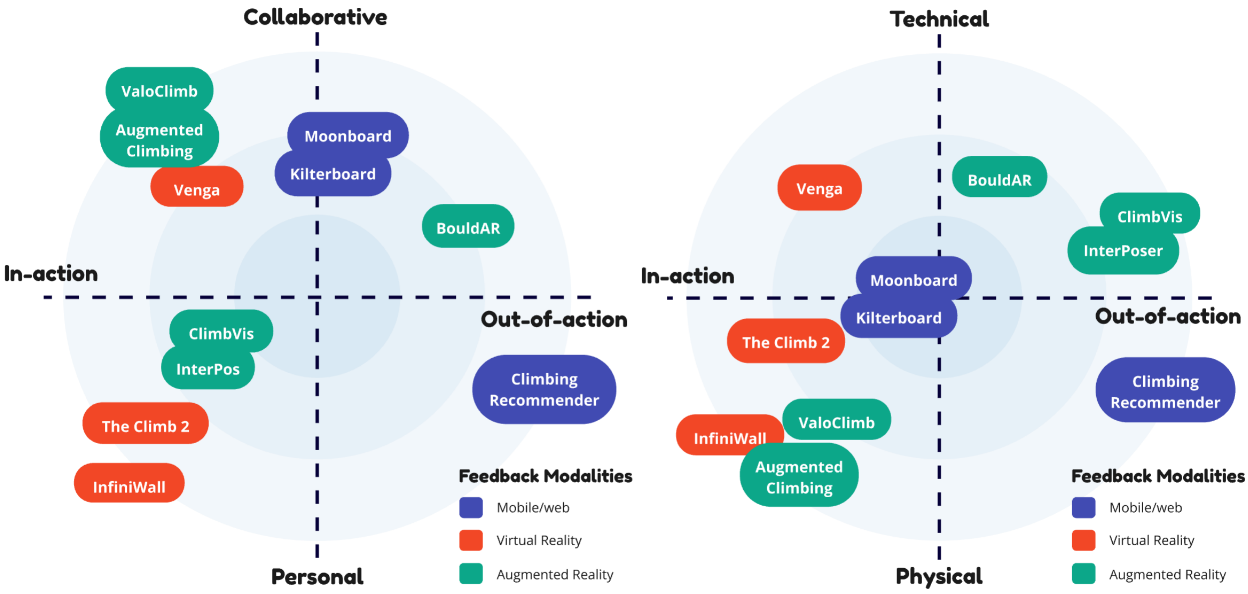


Figure 8.1: Alternative related work mappings

Bibliography

[1] R. Ali, O. Y. Tang, I. D. Connolly, H. F. Abdulrazeq, F. N. Mirza, R. K. Lim, B. R. Johnston, M. W. Groff, T. Williamson, K. Svokos, T. J. Libby, J. H. Shin, Z. L. Gokaslan, C. E. Doberstein, J. Zou, and W. F. Asaad, "Demographic Representation in 3 Leading Artificial Intelligence Text-to-Image Generators," *JAMA Surgery*, vol. 159, no. 1, pp. 87–95, 1 2024. [Online]. Available: https://jamanetwork.com/journals/jamasurgery/fullarticle/2811920

[2] N. Mehrabi, F. Morstatter, N. Saxena, K. Lerman, and A. Galstyan, "A Survey on Bias and Fairness in Machine Learning," *ACM Computing Surveys*, vol. 54, no. 6, p. 115, 7 2021.

[3] G. Shin, M. H. Jarrahi, Y. Fei, A. Karami, N. Gafinowitz, A. Byun, and X. Lu, "Wearable activity trackers, accuracy, adoption, acceptance and health impact: A systematic literature review," *Journal of Biomedical Informatics*, vol. 93, p. 103153, 5 2019.

[4] M. Fanchini, F. D. R. Violette, F. M. Impellizzeri, and N. A. Maffiuletti, "Differences in climbing-specific strength between boulder and lead rock climbers," *Journal of Strength and Conditioning Research*, vol. 27, no. 2, pp. 310–314, 2 2013.

[5] R. Magill, D. Anderson, and M. Learning, *Motor Learning and Control*, 10th ed. New York City: McGraw Hill, 2014. [Online]. Available: www.mhhe.com

[6] C. B. Wall, J. E. Starek, S. J. Fleck, and W. C. Byrnes, "Prediction of indoor climbing performance in women rock climbers," *Journal of Strength and Conditioning Research*, vol. 18, no. 1, pp. 77–83, 2004.

[7] A. Neuhof, F. F. Hennig, I. Schöffl, and V. Schöffl, "Injury risk evaluation in sport climbing," *International Journal of Sports Medicine*, vol. 32, no. 10, pp. 794–800, 2011.

[8] J. W. McDonald, A. M. Henrie, M. Teramoto, E. Medina, and S. E. Willick, "Descriptive Epidemiology, Medical Evaluation, and Outcomes of Rock Climbing Injuries," *Wilderness and Environmental Medicine*, vol. 28, no. 3, pp. 185–196, 9 2017.

[9] S. Backe, L. Ericson, S. Janson, and T. Timpka, "Rock climbing injury rates and associated risk factors in a general climbing population," *Scandinavian Journal of Medicine and Science in Sports*, vol. 19, no. 6, pp. 850–856, 12 2009.

[10] G. Jones, A. Asghar, and D. J. Llewellyn, "The epidemiology of rock-climbing injuries," *British Journal of Sports Medicine*, vol. 42, no. 9, pp. 773–778, 9 2008.

[11] E. R. Neil, Z. K. Winkelmann, and J. R. Edler, "Defining the Term "Overuse": An Evidence-Based Review of Sports Epidemiology Literature," *Journal of athletic training*, vol. 53, no. 3, pp. 279–281, 3 2018. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/29406788/

[12] D. M. Wright, T. J. Royle, and T. Marshall, "Indoor rock climbing: who gets injured?" *British Journal of Sports Medicine*, vol. 35, no. 3, p. 181, 2001. [Online]. Available: /pmc/articles/PMC1724320/?report=abstracthttps://www.ncbi.nlm.nih.gov/pmc/articles/PMC1724320/

[13] G. Jones, D. Llewellyn, and M. Asghar, "Risk Factors for Injury from Rock Climbing," *World Physical Therapy 2007*, 2007.

[14] L. M. Muratori, E. M. Lamberg, L. Quinn, and S. V. Duff, "Applying principles of motor learning and control to upper extremity rehabilitation," *Journal of Hand Therapy 26*, pp. 94–103, 2013. [Online]. Available: http://dx.doi.org/10.1016/j.jht.2012.12.007

[15] D. B. Postma, R. W. van Delden, J. H. Koekoek, W. W. Walinga, I. M. van Hilvoorde, B. F. Jan van Beijnum, F. A. Salim, D. Reidsma, and D. Rei, "A Design Space of Sports Interaction Technology," *Foundations and Trends ® in Human-Computer Interaction*, vol. 15, no. 3, pp. 132–316, 2022. [Online]. Available: http://dx.doi.org/10.1561/1100000087_app

[16] E. Horst, *Conditioning for climbers: The complete exercise guide*. The Falcon Guide, 2008. [Online]. Available: https://books.google.com/books?hl=en&lr=&id=_l9_NPu9IugC&oi=fnd&pg=PP1&dq=climbing+warm-up&ots=a07EuRiP3g&sig=Dc3BijVehiTITg-ZCbvljcb5w-k

[17] P. R. Young, R. C. Eklund, G. Tenenbaum, R. L. Glueckauf, and B. Thompson, "Not so risky business: the use of planning within rock climbing," *http://dx.doi.org/10.1080/14927713.2014.932970*, vol. 38, no. 1, pp. 21–33, 2014. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/14927713.2014.932970

[18] P. R. Young, "THE EFFECT OF ATTENTIONAL INTERFERENCE ON A ROCK CLIMBING TASK: A PILOT STUDY," *Pamukkale Jounral of Sport Sciences*, vol. 3, no. 1, pp. 10–19, 2012. [Online]. Available: https://www.researchgate.net/publication/221933099

[19] E. Hartkop, C. D. Wickens, J. Keller, and A. C. McLaughlin, "Foraging for Handholds: Attentional Scanning Varies by Expertise in Rock Climbing," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 63, no. 1, pp. 1948–1952, 11 2019.

[20] M. J. Blakely, S. L. Smith, P. N. Russell, and W. S. Helton, "The impact of cognitive load on climbing and climbing on cognitive performance," *Applied Ergonomics*, vol. 94, 7 2021.

[21] N. Draper, D. Giles, V. Schöffl, F. Konstantin Fuss, P. Watts, P. Wolf, J. Baláš, V. Espana-Romero, G. Blunt Gonzalez, S. Fryer, M. Fanchini, L. Vigouroux, L. Seifert, L. Donath, M. Spoerri, K. Bonetti, K. Phillips, U. Stöcker, F. Bourassa-Moreau, I. Garrido, S. Drum, S. Beekmeyer, J.-L. Ziltener, N. Taylor, I. Beeretz, F. Mally, A. Mithat Amca, C. Linhart, and E. Abreu, "Comparative grading scales, statistical analyses, climber descriptors and ability grouping: International Rock Climbing Research Association position statement," *Sports Technology*, vol. 8, no. 3-4, pp. 88–94, 10 2015.

[22] N. Draper, T. Dickson, G. Blackwell, S. Fryer, S. Priestley, D. Winter, and G. Ellis, "Self-reported ability assessment in rock climbing," *Journal of Sports Sciences*, vol. 29, no. 8, pp. 851–858, 5 2011.

[23] M. D. Hughes and R. M. Bartlett, "The use of performance indicators in performance analysis," *Journal of Sports Sciences*, pp. 739–754, 1 2002. [Online]. Available: http://www.tandf.co.uk/journals

[24] C. M. Mermier, J. M. Janot, D. L. Parker, and J. G. Swan, "Physiological and anthropometric determinants of sport climbing performance," *Br J Sports Med*, vol. 34, pp. 359–366, 2000. [Online]. Available: http://bjsm.bmj.com/

[25] P. B. Watts, D. T. Martin, and S. Durtschi, "Anthropometric profiles of elite male and female competitive sport rock climbers," *Journal of Sports Sciences*, vol. 11, no. 2, pp. 113–117, 1993.

[26] P. B. Watts, "Physiology of difficult rock climbing," *European journal of applied physiology*, vol. 91, no. 4, pp. 361–372, 4 2004. [Online]. Available: https://pubmed.ncbi.nlm.nih.gov/14985990/

[27] L. V. Giles, E. C. Rhodes, and J. E. Taunton, "The Physiology of Rock Climbing," School of Human Kinetics, University of British Columbia, Vancouver, British Columbia, Canada, Tech. Rep. 6, 2006.

[28] J. Baláš, O. Pecha, A. J. Martin, and D. Cochrane, "Hand-arm strength and endurance as predictors of climbing performance," *European Journal of Sport Science*, vol. 12, no. 1, pp. 16–25, 1 2012.

[29] D. Macleod, D. L. Sutherland, L. Buntin, A. Whitaker, T. Aitchison, I. Watt, J. Bradley, and S. Grant, "Physiological determinants of climbing-specific finger endurance and sport rock climbing performance," *https://doi.org/10.1080/02640410600944550*, vol. 25, no. 12, pp. 1433–1443, 10 2007. [Online]. Available: https://www.tandfonline.com/doi/abs/10.1080/02640410600944550

[30] N. Draper, D. Giles, N. Taylor, L. Vigouroux, V. E. Na-Romero, J. Balá, I. S. Altamirano, F. Mally, I. Beeretz, J. C. Canalejo, G. Josseron, J. Kodejška, M. J. A. Téllez, and G. G. C. D. Vaca, "Performance Assessment for Rock Climbers: The International Rock Climbing Research Association Sport-Specific Test Battery," *International Journal of Sports Physiology and Performance*, vol. 16, no. 9, pp. 1242–1252, 9 2021.

[31] N. Draper, T. Dickson, G. Blackwell, and S. Fryer, "Sport-specific power assessment for rock climbing," *The Journal of sports medicine and physical fitness*, 9 2011. [Online]. Available: https://www.researchgate.net/publication/51635919

[32] N. Draper, S. Brent, C. Hodgson, and G. Blackwell, "Flexibility assessment and the role of flexibility as a determinant of performance in rock climbing," *International Journal of Performance Analysis in Sport*, vol. 9, no. 1, pp. 67–89, 4 2009.

[33] I. Ivanova, M. Andrić, and F. Ricci, "Content-Based Recommendations for Crags and Climbing Routes," in *Information and Communication Technologies in Tourism 2022*. Springer International Publishing, 2022, pp. 369–381.

[34] I. A. Ivanova and M. Wald, "Introducing Context in Climbing Crags Recommender System in Arco, Italy," *International Conference on Intelligent User Interfaces, Proceedings IUI*, pp. 12–15, 3 2023. [Online]. Available: https://dl.acm.org/doi/10.1145/3581754.3584120

[35] I. A. Ivanova, A. Buriro, and F. Ricci, "Map and Content-Based Climbing Recommender System," in *Adjunct Proceedings of the 30th ACM Conference on User Modeling, Adaptation and Personalization*. New York, NY, USA: ACM, 7 2022, pp. 41–45.

[36] K. Naderi, J. Rajamäki, and P. Hämäläinen, "Discovering and synthesizing humanoid climbing movements," in *ACM Transactions on Graphics*, vol. 36, no. 4. Association for Computing Machinery, 2017.

[37] F. Stapel, "Automated Grade Classification and Route Generation with Affordances on Climbing Training Boards," Ph.D. dissertation, University of Twente, Enschede, 2023.

[38] R. Van Delden, S. Bergsma, K. Vogel, D. Postma, R. Klaassen, and D. Reidsma, "VR4VRT: Virtual reality for virtual rowing training," *CHI PLAY 2020 - Extended Abstracts of the 2020 Annual Symposium on Computer-Human Interaction in Play*, pp. 388–392, 11 2020.

[39] M. Tiator, B. Fischer, L. Gerhardt, D. Nowottnik, H. Preu, and C. Geiger, "Cliffhanger-VR," *25th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2018 - Proceedings*, pp. 779–780, 8 2018.

[40] F. Kosmalla, F. Daiber, A. Zenner, N. Herbig, M. Speicher, and A. Krüger, "Exploring rock climbing in mixed reality environments," in *Conference on Human Factors in Computing Systems - Proceedings*, vol. Part F127655. Association for Computing Machinery, 5 2017, pp. 1787–1793.

[41] F. Kosmalla, F. Daiber, and A. Krüger, "InfinityWall - Vertical Locomotion in Virtual Reality using a Rock Climbing Treadmill," *Conference on Human Factors in Computing Systems - Proceedings*, 4 2022.

[42] M. Tiator, B. Fischer, C. Geiger, L. Gerhardt, H. Preu, B. Dewitz, and D. Nowottnik, "Venga!" in *ACM International Conference Proceeding Series*, vol. Part F137697. Association for Computing Machinery, 7 2018.

[43] F. Kosmalla, A. Zenner, C. Tasch, F. Daiber, and A. Krüger, "The importance of virtual hands and feet for virtual reality climbing," in *Conference on Human Factors in Computing Systems - Proceedings*. Association for Computing Machinery, 4 2020.

[44] H. Oh and W. Son, "Cybersickness and Its Severity Arising from Virtual Reality Content: A Comprehensive Study," *Sensors*, vol. 22, no. 4, 2 2022.

[45] R. Kajastila and P. Hämäläinen, "Augmented climbing: Interacting with projected graphics on a climbing wall," *Conference on Human Factors in Computing Systems - Proceedings*, pp. 1279–1284, 2014.

[46] R. Kajastila, L. Holsti, and P. Hamalainen, "The augmented Climbing wall: High-exertion proximity interaction on a wall-sized interactive surface," *Conference on Human Factors in Computing Systems - Proceedings*, pp. 758–769, 5 2016.

[47] F. Daiber, F. Kosmalla, and A. Krüger, "BouldAR – Using Augmented Reality to Support Collaborative Boulder Training," *Conference on Human Factors in Computing Systems - Proceedings*, vol. 2013-April, pp. 949–954, 4 2013.

[48] F. Kosmalla, F. Daiber, F. Wiehr, and A. Krüger, "Climbvis — Investigating in-situ visualizations for understanding climbing movements by demonstration," *Proceedings of the 2017 ACM International Conference on Interactive Surfaces and Spaces, ISS 2017*, pp. 270–279, 10 2017.

[49] F. Wiehr, F. Daiber, F. Kosmalla, and A. Krüger, "BetaCube - Enhancing training for climbing by a self-calibrating camera-projection unit," *Conference on Human Factors in Computing Systems - Proceedings*, vol. 07-12-May-2016, pp. 1998–2004, 5 2016. [Online]. Available: https://dl.acm.org/doi/10.1145/2851581.2892393

[50] R. van Delden, T. Spil, G. Bruinsma, K. Vogel, and D. Reidsma, "How serious is serious game design?: Exploring entertainment-oriented and goal-oriented gaming," *Proceedings of the European Conference on Games-based Learning*, vol. 2019-Octob, pp. 88–88, 1 2019. [Online]. Available: https://research.utwente.nl/en/publications/how-serious-is-serious-game-design-exploring-entertainment-orient

[51] R. Kretschmann, "Developing competencies by playing digital sports-games," University of Stuttgart, Tech. Rep. 2, 2010.

[52] A. Tóth and E. Lógó, "The Effect of Gamification in Sport Applications," *9th IEEE International Conference on Cognitive Infocommunications, CogInfoCom 2018 - Proceedings*, pp. 69–74, 2 2019.

[53] S. E. Jenny and D. P. Schary, "Virtual and "real-life" wall/rock climbing: motor movement comparisons and video gaming pedagogical perceptions," *Sports Technology*, vol. 8, no. 3-4, pp. 100–111, 10 2015.

[54] M. M. Jensen, M. K. Rasmussen, F. F. Mueller, and K. Grønbæk, "Keepin' it real: Challenges when designing sports-training games," *Conference on Human Factors in Computing Systems - Proceedings*, vol. 2015-April, pp. 2003–2012, 2015.

[55] E. Rosenzweig, "UX Thinking," in *Successful User Experience: Strategies and Roadmaps*, 2015, pp. 41–67.

[56] A. Cooper, *The Inmates are Running the Asylum*. Vieweg+Teubner Verlag, Wiesbaden, 1999. [Online]. Available: https://link.springer.com/chapter/10.1007/978-3-322-99786-9_1

[57] A. Gulz, C. Magnusson, L. Malmborg, H. Eftring, B. Jönsson, and K. Tollmar, "Personas: From Theory to Practices," in *NordiCHI*, 10 2008.

[58] R. Mahamuni, P. Khambete, R. M. Punekar, S. Lobo, S. Sharma, and U. Hirom, "Concise personas based on tacit knowledge - How representative are they?" in *ACM International Conference Proceeding Series*. Association for Computing Machinery, 12 2018, pp. 53–62.

[59] J. Salamanca, P. Desmet, A. Burbano, and G. Ludden, "learning from the positive: a structured approach to possibility-driven design," in *International Conference on Design & Emotion*. Bogota: Udiciones Ugiandes, 10 2014, pp. 607–615. [Online]. Available: http://de2014.uniandes.edu.co

[60] K. Baxter, C. Courage, and K. Caine, “Understanding Your Users: A Practical Guide to User Research Methods, Second Edition, Chapter 9: Interviews,” in *Understanding Your Users: A Practical Guide to User Research Methods, Second Edition*. Elsevier, 1 2015, pp. 219–262. [Online]. Available: http://www.sciencedirect.com:5070/book/9780128002322/understanding-your-users

[61] M. Beaudouin-Lafon and W. E. Mackay, “52 N PROTOTYPING TOOLS AND TECHNIQUES,” in *Human Computer Interaction Handbook*, 3rd ed., 5 2012, vol. 3, pp. 1018–1038.

[62] C. Heape, “The Design Space: the design process as the construction, exploration and expansion of a conceptual space,” Ph.D. dissertation, Mads Clausen Institute (MCI), 2007. [Online]. Available: https://portal.findresearcher.sdu.dk/en/publications/the-design-space-the-design-process-as-the-construction-explorati

[63] M. M. Biskjaer, P. Dalsgaard, and K. Halskov, “A constraint-based understanding of design spaces,” in *Proceedings of the Conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques, DIS*. Association for Computing Machinery, 2014, pp. 453–462.

[64] M. L. Maher and J. Poon, “Modeling design exploration as co-evolution,” *Computer-Aided Civil and Infrastructure Engineering*, vol. 11, no. 3, pp. 195–209, 1996.

[65] K. Dorst and N. Cross, “Creativity in the design process:co-evolution of problem–solution,” in *Design Studies*, 2001, vol. 22, pp. 425–437. [Online]. Available: www.elsevier.com/locate/destud

[66] E. M. Segura, L. T. Vidal, and A. Rostami, “Bodystorming for movement-based interaction design,” *Human Technology*, vol. 12, no. 2, pp. 193–251, 2016.

[67] A. Oulasvirta, E. Kurvinen, and T. Kankainen, “Understanding contexts by being there: Case studies in bodystorming,” *Personal and Ubiquitous Computing*, vol. 7, no. 2, pp. 125–134, 2003. [Online]. Available: https://link.springer.com/article/10.1007/s00779-003-0238-7

[68] C. Boletsis, A. Karahasanovic, and A. Fjuk, “Virtual Bodystorming: Utilizing Virtual Reality for Prototyping in Service Design,” in *Augmented Reality, Virtual Reality, and Computer Graphics*, ser. Lecture Notes in Computer Science, L. T. De Paolis, P. Bourdot, and A. Mongelli, Eds., vol. 10324. Cham: Springer International Publishing, 2017, pp. 279–288. [Online]. Available: http://link.springer.com/10.1007/978-3-319-60922-5

[69] P. W. Dowrick, “A review of self modeling and related interventions,” *Applied and Preventive Psychology*, vol. 8, no. 1, pp. 23 – 39, 1 1999.

[70] K. Barzouka, N. Bergeles, and D. Hatziharistos, “Effect of simultaneous model observation and self-modeling of volleyball skill acquisition,” *Perceptual and Motor Skills*, vol. 104, no. 1, pp. 32 – 42, 2 2007.

[71] B. Law and D. M. Ste-Marie, “Effects of self-modeling on figure skating jump performance and psychological variables,” *European Journal of Sport Science*, vol. 5, no. 3, pp. 143 – 152, 1 2005.

[72] Laura Ruth De Ghetaldi, “The Effect of Self-modeling on Climber Self-efficacy, Motivation, Actual and perceived Rock Climbing Skills, and knowledge in beginning rock climbers.” [Online]. Available: https://books.google.nl/books/about/The_Effect_of_Self_modeling_on_Climber_S.html?id=2RZxOAAACAAJ&redir_esc=y

[73] P. G. Marques and U. C. Corrêa, “The effect of learner’s control of self-observation strategies on learning of front crawl,” *Acta Psychologica*, vol. 164, pp. 151 – 156, 2 2016.

[74] J. I. Yu, P. Liu, and T. B. Seo, “Acute Effect of Different Warm-up Methods on Isometric Muscle Endurance of the Finger Flexors and Climbing Performance in Sport Climbers,” *Korean Journal of Sport Science*, vol. 33, no. 3, pp. 340 – 348, 9 2022.

[75] A. I. Grushko and S. V. Leonov, “ScienceDirect The usage of eye-tracking technologies in rock-climbing,” *Procedia-Social and Behavioral Sciences*, vol. 146, pp. 169–174, 2014. [Online]. Available: www.sciencedirect.com

[76] A. Kos, M. Volontar, and A. Umek, “Grip Force Measurement System in Climbing,” in *Procedia Computer Science*, vol. 202. Elsevier B.V., 2022, pp. 367–372.

[77] A. M. Valevicius, P. Y. Jun, J. S. Hebert, and A. H. Vette, “Use of optical motion capture for the analysis of normative upper body kinematics during functional upper limb tasks: A systematic review A R T I C L E I N F O,” *Journal of Electromyography and Kinesiology*, pp. 1–15, 2018. [Online]. Available: https://doi.org/10.1016/j.jelekin.2018.02.011

[78] E. Ceseracciu, Z. Sawacha, and C. Cobelli, “Comparison of Markerless and Marker-Based Motion Capture Technologies through Simultaneous Data Collection during Gait: Proof of Concept,” *PLOS ONE*, 3 2014. [Online]. Available: www.plosone.org

[79] G. Kurillo, E. Hemingway, M. L. Cheng, and L. Cheng, “Evaluating the Accuracy of the Azure Kinect and Kinect v2,” *Sensors*, vol. 22, no. 7, 4 2022.

[80] S. Johnson and M. Everingham, “Clustered pose and nonlinear appearance models for human pose estimation,” *British Machine Vision Conference, BMVC 2010 - Proceedings*, no. ii, pp. 1–11, 2010.

[81] M. Andriluka, L. Pishchulin, P. Gehler, and B. Schiele, “2D human pose estimation: New benchmark and state of the art analysis,” *Proceedings of the IEEE Computer Society Conference on Computer Vision and Pattern Recognition*, pp. 3686–3693, 2014.

[82] F. Sajjad, A. F. Ahmed, and M. A. Ahmed, “A study on the learning based human pose recognition,” *2017 9th IEEE-GCC Conference and Exhibition, GCCCE 2017*, pp. 1–8, 2018.

[83] X. Chu, W. Yang, W. Ouyang, C. Ma, A. L. Yuille, and X. Wang, “Multi-context attention for human pose estimation,” *Proceedings - 30th IEEE Conference on Computer Vision and Pattern Recognition, CVPR 2017*, vol. 2017-Janua, pp. 5669–5678, 2017.

[84] W. Deng, L. Bertoni, S. Kreiss, and A. Alahi, “Joint Human Pose Estimation and Stereo 3D Localization,” *Proceedings - IEEE International Conference on Robotics and Automation*, pp. 2324–2330, 2020.

[85] K. Shiro, K. Egawa, T. Miyaki, and J. Rekimoto, “InterPoser: Visualizing interpolated movements for bouldering training,” *26th IEEE Conference on Virtual Reality and 3D User Interfaces, VR 2019 - Proceedings*, pp. 1563–1565, 3 2019.

[86] I. Poitras, F. Dupuis, M. Bielmann, A. Campeau-Lecours, C. Mercier, L. J. Bouyer, and J. S. Roy, “Validity and reliability ofwearable sensors for joint angle estimation: A systematic review,” *Sensors (Switzerland)*, vol. 19, no. 7, pp. 1–17, 2019.

[87] J. Zhao, “A Review of Wearable IMU (Inertial-Measurement-Unit)-based Pose Estimation and Drift Reduction Technologies,” in *Journal of Physics: Conference Series*, vol. 1087, no. 4. Institute of Physics Publishing, 10 2018.

[88] T. Kitamura, H. Teshima, D. Thomas, and H. Kawasaki, “Refining OpenPose With a New Sports Dataset for Robust 2D Pose Estimation,” pp. 672–681, 2022.

[89] V. Bazarevsky, I. Grishchenko, K. Raveendran, T. Zhu, F. Zhang, and M. Grundmann, “BlazePose: On-device Real-time Body Pose tracking,” 6 2020. [Online]. Available: http://arxiv.org/abs/2006.10204

[90] E. Mencarini, C. Leonardi, A. De Angeli, and M. Zancanaro, “Design opportunities for wearable devices in learning to climb,” in *ACM International Conference Proceeding Series*, vol. 23-27-October-2016. Association for Computing Machinery, 10 2016.

[91] E. Mencarini, C. Leonardi, A. Cappelletti, D. Giovanelli, A. De Angeli, and M. Zancanaro, “Co-designing wearable devices for sports: The case study of sport climbing,” *International Journal of Human Computer Studies*, vol. 124, pp. 26–43, 4 2019.

[92] M. Claypool and K. Claypool, “Latency and Player actions in online games,” *Communications of the ACM*, vol. 49, no. 11, pp. 40–45, 11 2006.

[93] S. Nicholson, “A User-Centered Theoretical Framework for Meaningful Gamification,” in *Games+Learning+Society 8.0*, Madison, WI, 6 2012. [Online]. Available: http://becauseplaymatters.com

[94] H. L. O’Brien and E. G. Toms, “The development and evaluation of a survey to measure user engagement,” pp. 50–69, 1 2010.

[95] K. Baxter, C. Courage, and K. Caine, “Understanding Your Users: A Practical Guide to User Research Methods, Second Edition, Chapter 10: Surveys,” in *Understanding Your Users: A Practical Guide to User Research Methods, Second Edition*, 2015, pp. 264–301.

[96] H. L. O’Brien, P. Cairns, and M. Hall, “A practical approach to measuring user engagement with the refined user engagement scale (UES) and new UES short form,” *International Journal of Human Computer Studies*, vol. 112, pp. 28–39, 4 2018.

[97] J. Cohen, “Statistical Power Analysis for the Behavioral Sciences Second Edition,” New York University, New York, Tech. Rep., 1998.

[98] A. DeSmet, D. Thompson, T. Baranowski, A. Palmeira, M. Verloigne, and I. De Bourdeaudhuij, “Is participatory design associated with the effectiveness of serious digital games for healthy lifestyle promotion? A meta-analysis,” *Journal of Medical Internet Research*, vol. 18, no. 4, 4 2016.

[99] R. Khaled and A. Vasalou, “Bridging serious games and participatory design,” *International Journal of Child-Computer Interaction*, vol. 2, no. 2, pp. 93–100, 5 2014.

[100] M. Pasch, N. Bianchi-Berthouze, B. van Dijk, and A. Nijholt, “Movement-based sports video games: Investigating motivation and gaming experience,” *Entertainment Computing*, vol. 1, no. 2, pp. 49–61, 2009.

[101] S. Hammond, H. Pain, and T. J. Smith, “Player Agency in Interactive Narrative: Audience, Actor & Author,” Tech. Rep., 2007. [Online]. Available: https://www.researchgate.net/publication/294582628

Appendix A

Appendix: Ideation

A.1 Interview Questions

The exact list of questions asked to participants of the pre-ideation interview sessions. Conducted by the researcher with 3 climbers of varying skill level.

- Participant Name
- What kind of climbing do you practice? (bouldering/climbing, inside/outside)
- How often do you climb? (hrs/week)
- Participant Climbing Grade
- Have you ever participated in a climbing competition?
- Did you ever experience a climbing injury? if so, what kind of injury?
- If so, how long were you unable to climb?
- How many bouldering routes do you climb per session?
- How do you select a bouldering route?
- What does your pre-climb process look like?
- How often do you get stuck halfway a difficult route?
- If you get stuck in a difficult route, what do you do?
- Would you appreaciate help or guidance when stuck?
- Would that feel like cheating?
- Do you climb with others? what role do social interaction play in climbing, both in-situ and ex-situ?
- What is your strategy for increasing your climbing skill/grade?
- Have you ever employed the help of a climbing coach/trainer? What did you learn?
- How important is energy conservation?
- Optional extra remarks

A.2 Climbing Expert Feedback

Concept A discussion

1. What are some positive aspects about this concept?
2. What are some negative aspects about this concept?
3. How could this concept be embedded in training?
4. How does the functionality affect climbers of different skill levels?
5. Do you forsee technical or physical challenges of this concept?

Concept B discussion

1. What moves are prone to injuries?
2. What points of feedback do you give novice climbers most often?
3. What are some positive aspects about this concept?
4. What are some negative aspects about this concept?
5. How could this concept be embedded in training?
6. How does the functionality affect climbers of different skill levels?
7. Do you forsee technical or physical challenges of this concept?
8. What passive and active hints do you forsee usefull?

Concept C discussion

1. Should a climber's center of mass always be close to the wall?
2. Have you ever looked at heartrate measurements of climbers?
3. How do you measure climber energy use?
4. What are some positive aspects about this concept?
5. What are some negative aspects about this concept?
6. How could this concept be embedded in training?
7. How does the functionality affect climbers of different skill levels?
8. Do you forsee technical or physical challenges of this concept?

Concept D discussion

1. What are the goals of warm-up exercises for climbing?
2. What warm-up exercises are beneficial?
3. Are there warm-up exercises on the wall?
4. What are some positive aspects about this concept?
5. What are some negative aspects about this concept?
6. How could this concept be embedded in training?
7. How does the functionality affect climbers of different skill levels?
8. Do you forsee technical or physical challenges of this concept?

A.3 Movement Expert Feedback

1. What do you like about this concept?
2. What do you dislike about this concept?
3. How could you see this concept be embedded in training?
4. What would the academic relevance be of this concept?
5. What specific goal is the concept trying to achieve?
6. What metrics could be tested that support this goal?
7. What is the validity of these metrics?
8. What are technical challenges of this concept?
9. What are physical challenges of this concept?
10. What are human-centered challenges of this concept?
11. What concept appeals most to you?
12. Would 'Movement Scientist' describe your role and expertise regarding this feedback accurately?

Appendix B

Appendix: Prototype

B.1 IICW

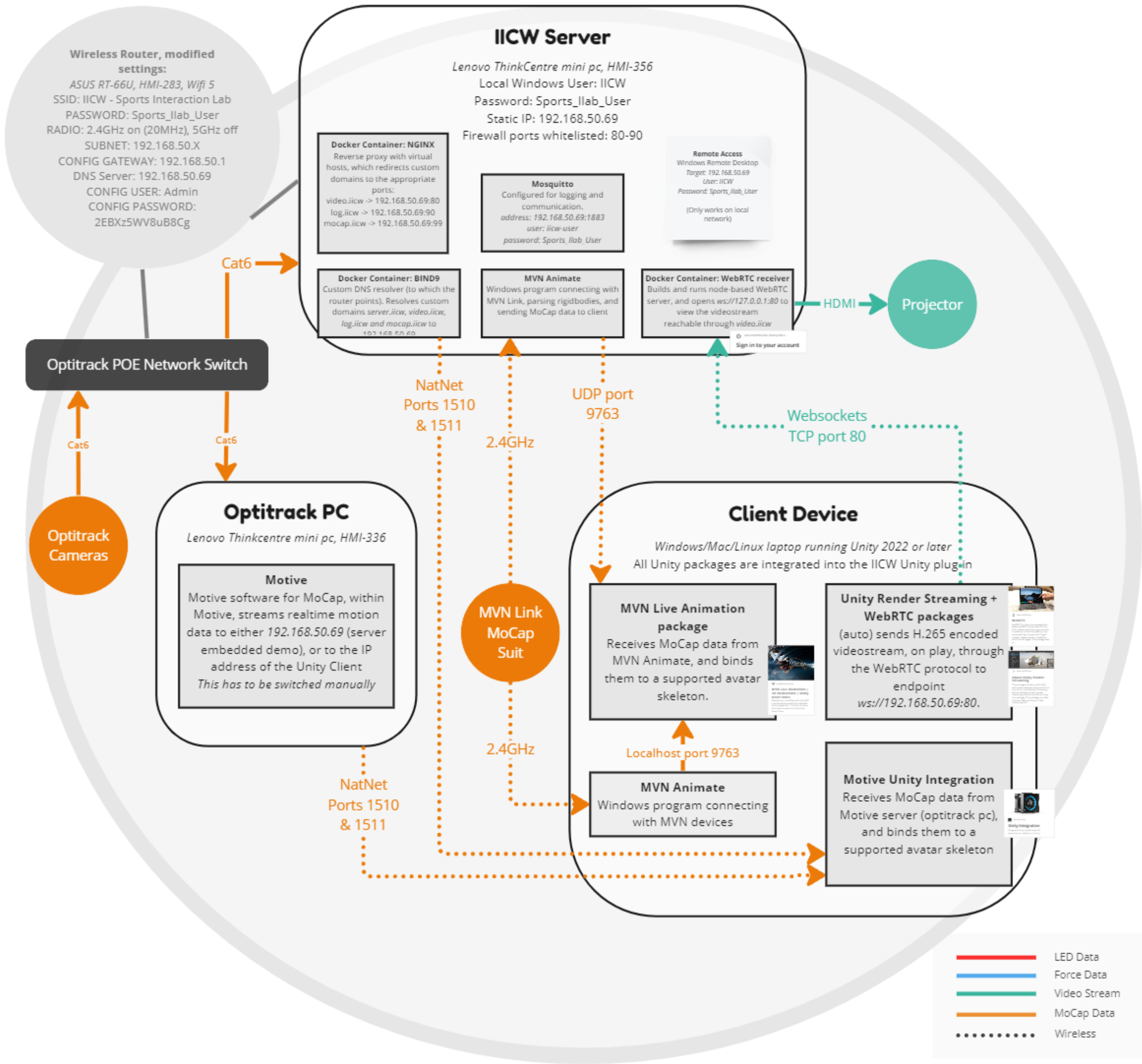


Figure B.1: Networking architecture for the IICW

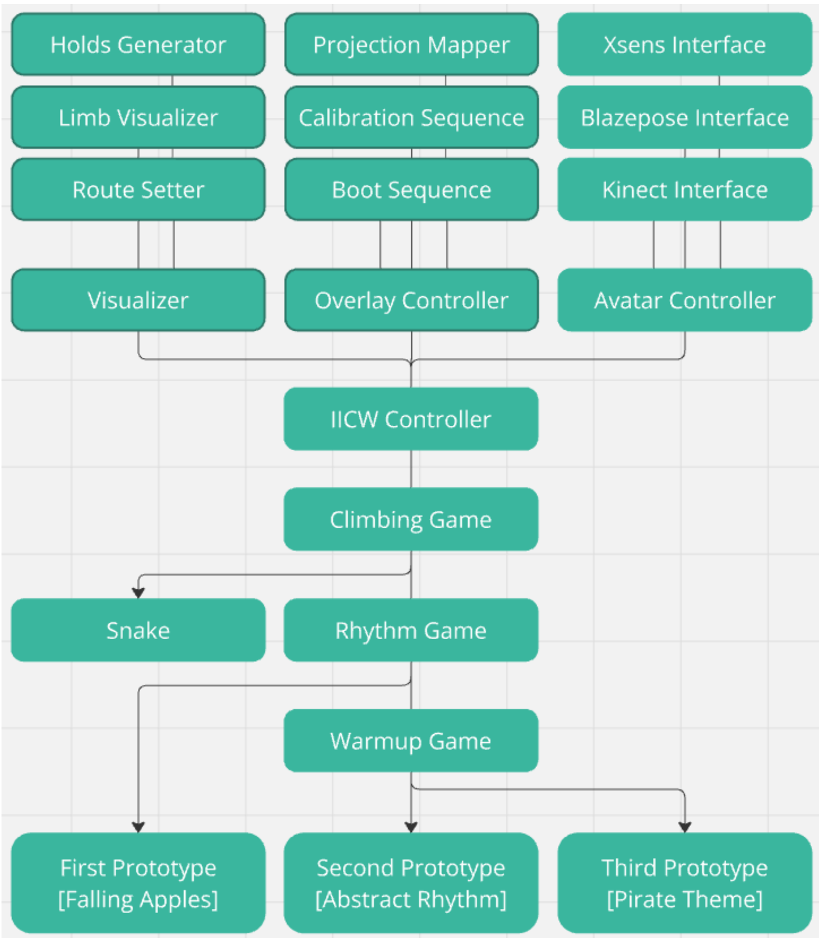


Figure B.2: Class architecture of the prototype

B.2 Assets used

Table B.1: Voice-over Assets used in prototype

Voice-over text	Warm-up phase	Intonation
”Ahoy! Get ready to set sail!”	Cardio phase	Excited
”Follow my movements!”	Cardio phase	Excited
”Well done! Let’s take a breather”	Cardio phase	Excited
”Get up into the crows nest!”	Stretching phase	Excited
”Now scour the map for treasure!”	Stretching phase	Excited
”Nicely done!”	Stretching phase	Excited
”Now again!”	Stretching phase	Excited
”Once more!”	Stretching phase	Excited
”Feel free to take a break if needed”	Stretching phase	Concerned
”Look at that score!”	Stretching phase	Excited
”Let’s take a short break”	Stretching phase	Excited
”Now go ahead and loot the treasure”	Windup phase	Excited
”Only a little further!”	Windup phase	Excited
”You did it! Now come back the way you came”	Windup phase	Excited
That concludes our adventure, thank you for playing”	Windup phase	Excited

Appendix C

Appendix: Evaluation

C.1 Usertest Instructions

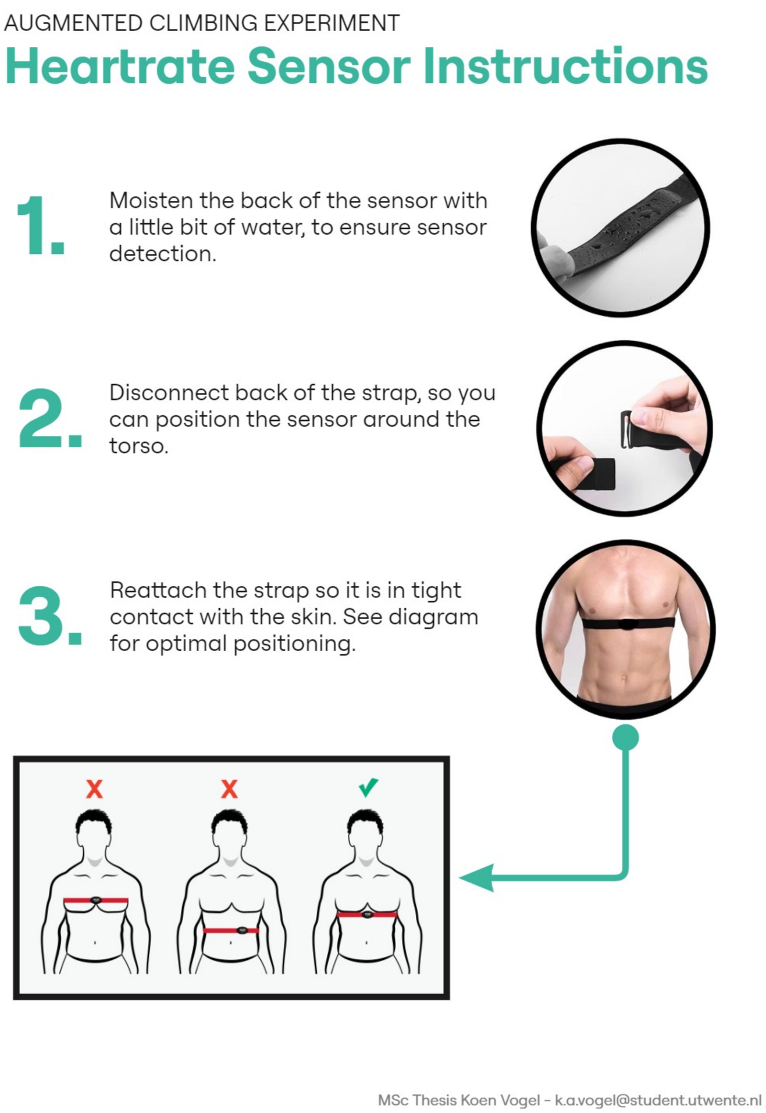


Figure C.1: Heartrate sensor Instructions

C.2 Pre-experiment survey

1. Participant Number (filled in by researcher)
2. What is your age?
3. What is your height?
4. How often do you climb?
5. What is your climbing skill grade? (highest reached route in the past 6 months)
6. How often do you warm up before climbing?
7. If so, what does your warm-up look like?

C.3 Post-session survey

1. Participant Number (filled in by researcher)
2. Session nr
3. Condition
4. How effective do you feel the warmup was?
5. What makes you feel warmed up?
6. I was absorbed in this experience.
7. Doing the warm-up exercise was worthwhile.
8. I found the warm-up exercise confusing to do.
9. I lost myself in this experience.
10. I felt frustrated while doing the warm-up experience.
11. The warm-up exercise appealed to my senses.
12. The warm-up experience was attractive.
13. The warm-up experience was aesthetically appealing.
14. The warm-up experience was mentally taxing.
15. I felt interested in this experience.
16. The time I spent doing the warm-up exercise just slipped away.
17. The warm-up experience was rewarding.

Optional Remarks about your warmup routine. What aspects contributed to a positive or negative experience?

C.4 Post-experiment survey

1. Participant Number (filled in by researcher)
2. Which warm-up exercise would you prefer for your own training?
3. If readily available, how often would you use the interactive warm-up exercise before your climbing sessions?
4. To what extend did you appreciate the following aspects of the gamified warm-up routine? [The game (Aesthetics & Story), Physical Tasks & Moves Routine, Being 'On the wall' during warmup, This board configuration (incline, hold texture, lack of chalk)]

Optional What aspects of the gamified warm-up routine improved the experience?

Optional What aspects of the gamified warm-up routine detracted the experience?

Appendix D

Appendix: Results

D.1 Statistics

Table D.1: Wilcoxon Signed-Rank Test; Condition sequence order per participant for the question 'How effective do you feel the warmup was?'

Participant	Significance ($\alpha = 0.5$)
1	- (Identical values)
2	1.0
3	1.0
4	1.0
5	1.0
6	1.0
7	1.0
8	1.0
9	1.0
10	1.0
11	1.0
12	1.0

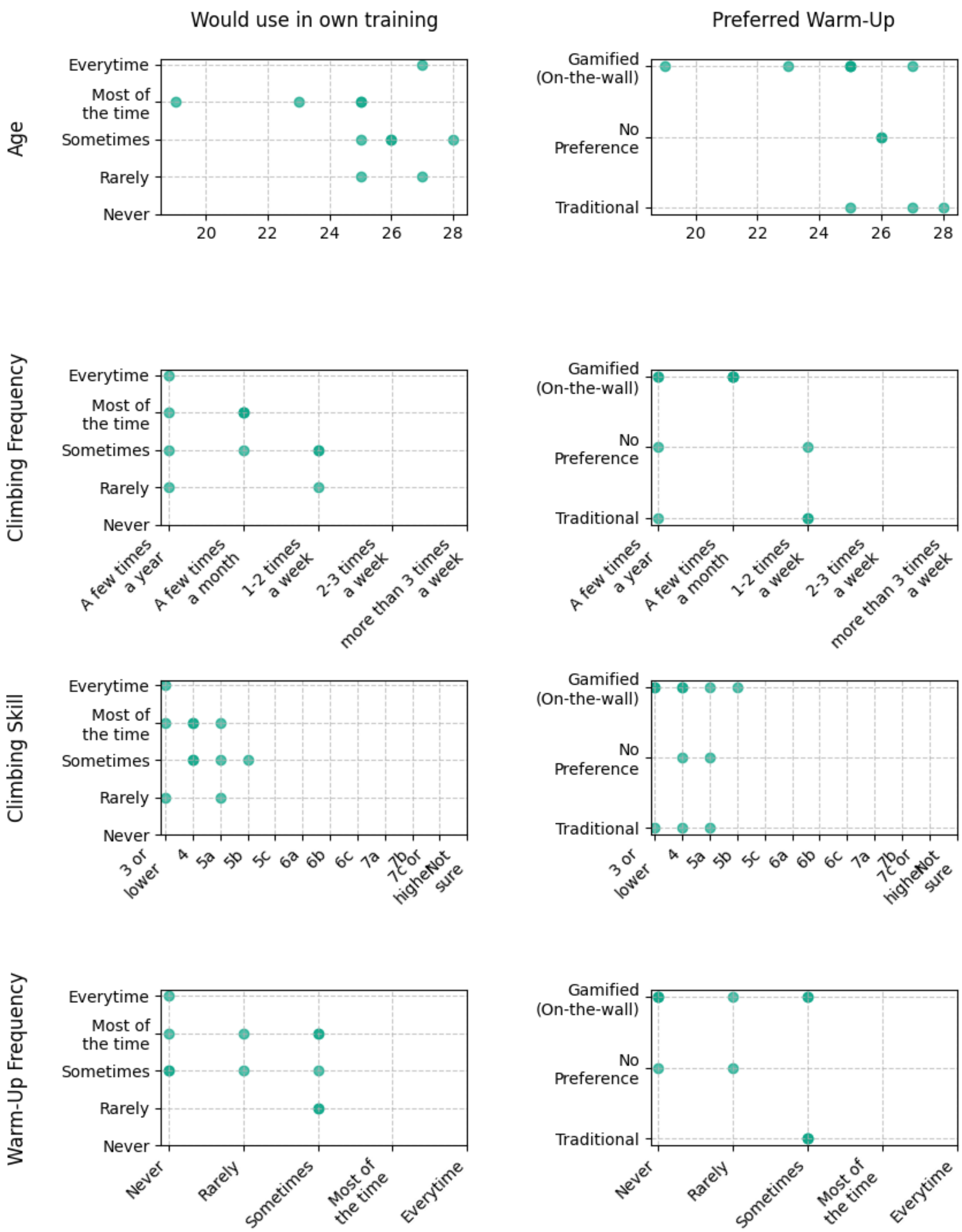


Figure D.1: EDA for finding correlations among demographic data

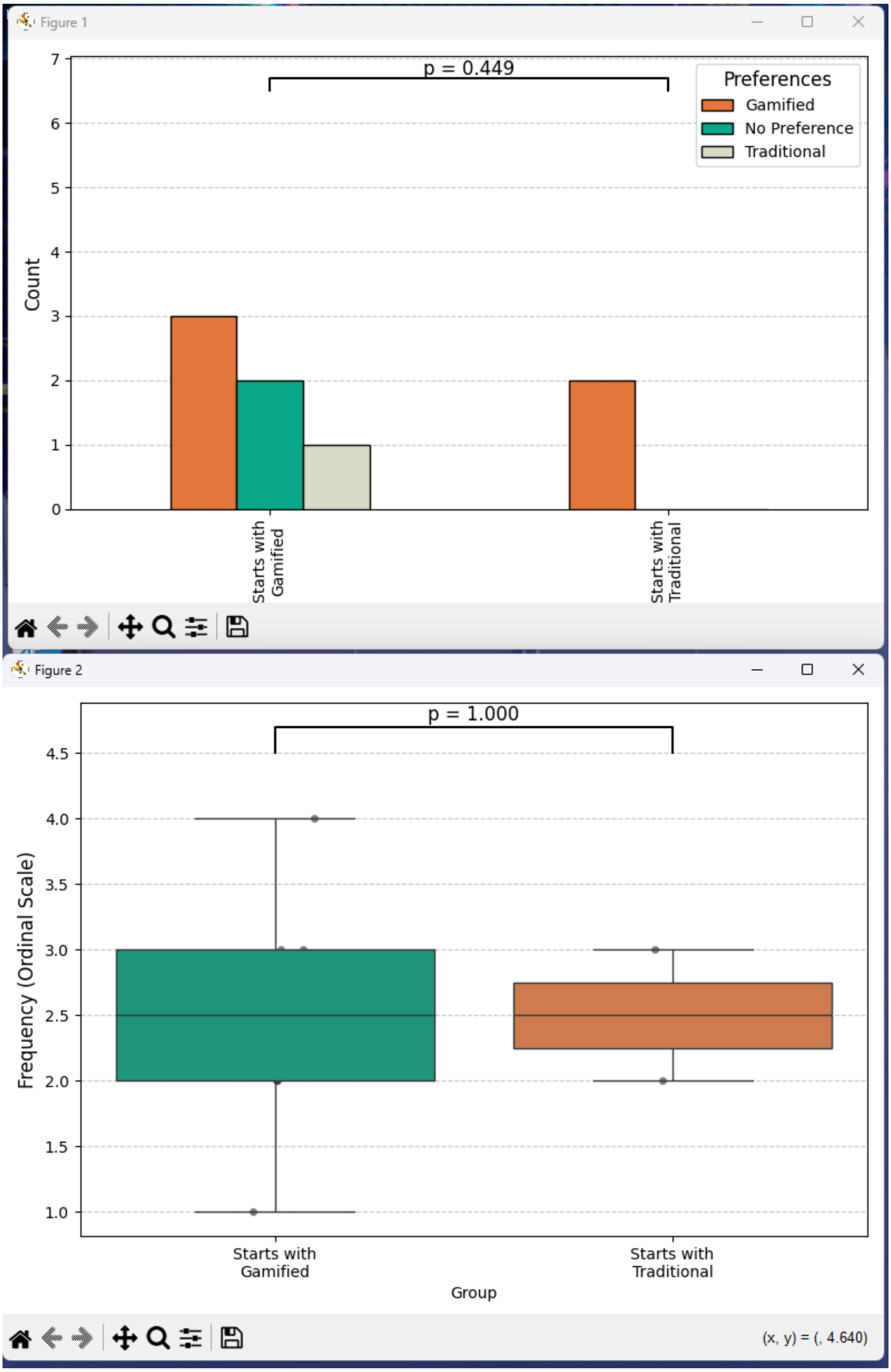


Figure D.2: Comparison of different condition sequence groups