Reetu Kontio

Exploring novel VR exergame locomotion methods with SWiP: a Supported Walk-in-Place locomotion system

Master’s Thesis
Espoo, July 29. 2023

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This thesis explores novel, physically challenging, locomotion methods within virtual reality (VR). In this work, we develop, experiment and evaluate a prototype system capable of employing multiple playing poses. We designed four different movement approaches utilizing position/orientation trackers attached to user’s limbs and waist. From these approaches, we decided to proceed further with two of the most promising ones. We conducted an user study (N=10) comparing these two approaches to receive more diverse feedback. The main themes revolving around the study were usability, simulator sickness and exercise.

We decided to name the developed movement approaches according to the playing pose: Chair, Supine, Rings and Dip Rack. The two modes chosen for the user study were Chair and Supine. In the Chair mode the player sits on a swivel chair and imitates walking or running by swinging their legs in the air. In the Supine mode the player lies on the ground on their back and swings their legs in the air.

Based on the user feedback, we can conclude that there exists potential within the experimented approaches. Due to the small size of our user study we are unable conlcude any statistical relevance, but we believe that this work can provide valuable information for future VR locomotion methods, as well as exergames.

**Keywords:** virtual reality, VR, locomotion, walk in place, supported walk in place, SWiP, exergames, games

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Käyttäjätestauksen palautteesta pystyimme päättelemään, että kehittämämme liikkumistavoissa on potentiaalia. Pienen testaajamääryn vuoksi emme voi todeta tilastollista merkityksellisyyttä havainnoilamme, mutta pyrimme siitä luonaan tällä työllä pohjaa tulevaisuuden virtuaalisen todellisuuden liikkumistavoille, sekä liikuntapeleille.

Asiasanat: virtuaalinen todellisuus, VR, liikuntapelit, liikkuminen, paikallaan käveleminen, tuettu paikallaan käveleminen

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Reetu Kontio
# Abbreviations and Acronyms

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<tr>
<td>VR</td>
<td>Virtual Reality</td>
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<td>HMD</td>
<td>Head Mounted Display</td>
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<td>WiP</td>
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<td>System Usability Scale</td>
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<td>First Person Perspective</td>
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<td>SR</td>
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Chapter 1

Introduction

1.1 Background

VR games and interactive experiences are increasingly popular. Trends show steady growth in the VR industry and it is also predicted to continue growing for the following years [1]. Gaming in VR introduces unique opportunities to create experiences that offer realism and immersion beyond the capabilities of ordinary games, with players interacting with virtual worlds in a natural and embodied manner.

However, the discrepancy between a limited real-world space and a potentially limitless virtual world remains an issue that is not fully solved. Various VR locomotion techniques have been experimented to address this problem, however they come with their own limitations and challenges. For instance, using joystick-based steering for continuous locomotion causes visuo-vestibular conflict that is a source of simulation sickness [16, 17, 49]. On the other hand, a popular locomotion method in VR, point and teleport is reported to inflict less simulation sickness [16, 17, 49]. However, it causes breaks in user immersion [5, 6, 15]. Furthermore, the instantaneous change of position leads to decreased spatial awareness [7].

In addition to the locomotion problem, present VR games and experiences are limited in that they predominantly have the users interact while standing or seated, which only represents a fraction of the full diversity of human movement. A similar "standing bias" can be observed in earlier movement-based games on platforms such as the Kinect. This is suboptimal for developing exergames that activate the whole body, and is not satisfactory from the point of view of scientific curiosity. Meanwhile, researchers have called for more work on non-standing movement in movement-based games [31]. Outside VR, there have been explorations of combining technology with
Figure 1.1: The prototype game used in our user study. The player character (on the left) is on top of the highest platform in the level. The player character does not have a visual head or torso, to only display limbs in the player’s 1st person view. The glowing green orb and the arrow above it denote a target waypoint.
non-standing physical activities such as hanging [60], trampolining [33, 50], yoga [76], climbing on an augmented reality climbing wall [40], and trying to stay on a rodeo bull simulator [53]. Specific to VR, Krekhov et al. have explored the possibilities of inhabiting non-human bodies, which can include non-conventional user movements and postures [45, 46]. For example, they experimented with controlling a quadrupedal animal in VR.

1.2 Proposed Approach: Supported Walk-in-Place Locomotion

The initial research idea was to investigate an idea of playing games while lying on one’s back, that is, in a supine pose. The user would be required to swing their legs in the air to move within the game. This would also act as a core exercise, as abdominal muscles are required to hold one’s legs up.

The problems described in the earlier Section, the need for more diverse playing poses to combat the ”standing-bias”, and the exergaming potential ultimately became our three main themes guiding our research. Based on these we designed, developed and evaluated a prototype game with four novel VR locomotion methods. We named these locomotion methods by their respective playing poses: Chair, Supine, Rings and Dip Rack, illustrated in Fig. 1.2. All these locomotion approaches tie onto the themes by utilizing two key observations:
CHAPTER 1. INTRODUCTION

1. If one’s legs are not required for support and balance, one becomes free to perform diverse locomotion movements—walking, running, jumping, strafing—*in the air*, while not moving around in the physical world. Assuming that such leg movements can be mapped to VR avatar movement naturally and reliably enough, this holds promise for flexible navigation of large virtual spaces even in a highly constrained physical space.

2. Furthermore, such in-air locomotion can be performed in non-upright orientations of the body, opening new possibilities for VR movement, and allowing gravity to provide the user with more diverse movement challenges and exercise [31]. For instance, lying supine and performing walking movements in the air requires activating abdominal muscles similar to the Pilates exercise known as the “bicycle crunch”.

This thesis describes an explorative Research through Design (RtD) [47] process of developing a prototype system for testing and evaluating non-standing VR locomotion. As the basic principle of our locomotion approaches is that we support the player’s body with some other means than the legs, we named our approach Supported Walk-in-Place (SWiP) locomotion. As an inspiration, we used the non-human embodiment experiments by Krekhov et al. [45, 46] as well as previous HCI approaches that display potential for diverse and physically demanding exercise [40, 50, 60].

We describe the design and present authors’ subjective evaluation of the four different variants of our approach illustrated in Fig. 1.2. Based on an initial evaluation by the authors, we chose the seated and supine variants to be investigated in a user study (described in the Section 4). The user study results show promise for the viability of non-standing playing poses and their exergaming potential, but we also indentified a number of issues, as well as received critical feedback, which is discussed more in detail in Section 6.

1.3 Research Methods

For this thesis, we decided to use a combination of design space analysis [52] and autobiographical design approach [62] describing the iteration process, accompanied by small qualitative user study (N=10). We documented the process of researching the design space, implementing, experimenting and iterating the prototype system. The overall process of this thesis may also be described as Research through Design, which is a valuable conceptualizing technique within the field of research [27]. For the development process, we relied on the author’s and supervisor’s experience from 10+ years of active
practicing of a variety of movement arts such as pilates, contemporary dance, parkour, and pole dancing. Acknowledging this bias in enthusiasm towards physical activity, we decided not to rely solely on the autobiographical design or other 1st person HCI research methods [19], thus including the user study to collect feedback from people who might not share our enthusiasm.

Design space analysis may be described as a coproduct of the design process itself [52]. In this thesis, design space analysis is required for multiple reasons. First reason is that we only had an vague idea of an interesting approach for VR locomotion, but no knowledge on how well it would perform, or how widely it would be applicable. Second reason for this emerged in midst of the development process, as new ways of utilizing the system were discovered. We decided to focus on two of the methods (Chair and Supine), but theorized and briefly tested two additional methods (Rings and Dip Rack), concluding that given enough time to polish them, they could be viable exergaming approaches. Further investigating and more thoroughly testing these additional methods is left out of the scope of this thesis. The speculative nature of the other possibilities in the design space still offers value for future reasearch [26]. Furthermore, to map also the already existing design space, a literature review was conducted on other novel VR locomotion approaches.

Autobiographical research stems from the need not to create for someone else, but for the researchers themselves [62]. We chose this approach for the development period of the prototype for this thesis, because we were first and foremost interested in seeing whether this novel idea had any potential at all. To iterate this a proof of concept as fast as possible, it was crucial to have fast feedback loop. For this, testing and developing the system by ourselves, for our needs and preferences, was the most convenient choice. The goal of this prototype system was to be proof of concept, to be a basis for future approaches. If potential would emerge, future development could possibly be aimed for more broad audience and user base, in which case more objective evaluation would be required.

To receive valuable feedback and further validate our own evaluation, we organized a small user study. Due to its small sample size (N=10), we opted for a mixed-methods within-subjects study, prioritizing on the qualitative data. The quantitative data we collected was only to augment and support the qualitative data, not for making strict conclusions, as we did not have enough participants to record statistically significant results.
1.4 Contributions

Our work makes an HCI artifact contribution [87], demonstrating and exploring a new possibility space for VR design, offering novel ways for navigating the tradeoffs between the range of movements possible for the user, the need for real-world space, and providing diverse physical exercise. We follow the common practice of accompanying an artifact contribution with an empirical study [87], reflecting upon the strengths, weaknesses, and future potential of our approach based on a qualitative within-subjects user study (N=10). The primary evidence we base our argumentation on stems from a qualitative thematic analysis of concurrent think-aloud and open-ended interview data. We augment this data with quantitative self-reports of physical exertion intensity using the Sickness Rating (SR) [35] and Borg CR10 [11, 32] scale. Our focus is on discovering and understanding new applications and full-body interaction styles rather than providing an interaction technique that solves an existing task more efficiently; hence, we adopted a qualitative and exploratory rather than quantitative and confirmatory research approach.

1.5 Structure of the Thesis

First, we present the related work in Section 2, discussing the state-of-the-art locomotion methods in VR, as well as other novel VR approaches that have been explored. We further present the prior exploration of exergaming research and discuss the findings regarding non-standing playing.

In Section 3 we describe the most important milestones and turning points of our iterative and exploratory design process. Towards the end, we also discuss the findings from pilot studies and finally describe the functionality of the final prototype used in the user study in more detail.

Moving on to Section 4, we present the design of the user study. We discuss details such as the reasons behind our choices for the recorded data, test tasks and collecting testers.

The Section 5 describes the results of our user study, separating qualitative and quantitative data. We present data such as the coding of the transcribed data, themes collated from these, demographics and questionnaire results.

The discussion based on the user study data is in the Section 6. We discuss the most relevant themes emerging from the results and compare them to existing research results. We also highlight shortcomings and critical feedback that we received regarding the system.

In Section 7 we conclude the most prevalent findings.
Lastly, the Section 8 discusses the potential future work and next steps that could provide further insight into our findings.
Chapter 2

Related Work

The topics discussed in this section are VR locomotion and the challenges that it is facing, exergaming and its potential in VR and use of non-standing playing poses in games. These topics are central to understanding and evaluating our work. We review experimental work done in prior studies as well as commercial products.

2.1 VR Locomotion

The locomotion methods in VR may be divided into two main categories: physical and artificial [4]. The physical methods include actual player movement, common ones being regular walking (one-to-one mapping) and walking in place (WiP). The artificial methods do not require any major physical action from the player, as they are usually initiated by controller inputs. Examples of widely used artificial locomotion methods are teleportation and joystick/trackpad/d-pad or similar controller actuated movement. According to survey done by Tseng et al. teleportation is used as the main locomotion method in as high as 67% of the top VR games, whilst joystick movement is used in 17% of the titles [75], in their paper from 2022.

2.1.1 Teleportation

As mentioned above, teleportation is one of the most popular methods for moving in VR. It is fully supported by commercial products, HTC VIVE and Oculus to name a few [9]. Teleport locomotion in VR is implemented usually in a way that the user is able to point a ray towards a location they want to move to, and then instantiate the teleportation (instantaneous change of location) by clicking a button on the controller they are using [4, 5, 9, 88].
The ray may also be presented as a parabolic curve to allow easier traversal vertically.

Teleportation is considered to be effective locomotion method in time-sensitive tasks, as it allows instantaneous traversal [5]. However, a study by Coomer et al. comparing different locomotion methods found that users used on average the most time on the trial while using teleportation method [17]. It tends to cause less VR sickness, compared to some other locomotion methods, for example controller/Joystick movement. However, the non-continuous nature of the movement causes breaks in user immersion. Furthermore, the "blinking" caused by the instantaneous change of location is straining on the users vision. [5] A literature review by Boletsis et al. shows that there is an overwhelming preference towards continuous movement within VR [4], highlighting the problems that emerge from the teleportation method.

2.1.2 Joystick Movement

This category of locomotion methods includes all typical movement actuated by regular consumer gamepads and controllers. Examples of these can be controllers used with consoles such as Xbox and Playstation. The movement speed and direction is controlled by a thumb joystick, in a similar manner as in normal (non-VR) games. An advantage to be noted with controller movement method is that due to users' prior familiarity with the controller, it might be easier to adopt than some of the more novel locomotion methods.

This is explored in a study by Boletsis et al. [5], where controller movement scored the highest System Usability Scale (SUS) score, when compared against teleportation and WiP methods. However, controller locomotion in VR suffers from simulator sickness issues [5, 8, 9, 17]. Immersion and flow are reportedly better compared to teleportation [5].

2.1.3 Walk-in-Place

Walk-in-Place methods include users performing walking-like motion with their legs, without much spatial displacement in the physical environment. Steps may be tracked via six degrees of freedom (6-DOF) trackers, e.g., VIVE trackers, which we used in our prototype as well. or a treadmill-like device [4].

Boletsis [4] compared different locomotion methods for VR. They recorded the lowest SUS scores for WiP when compared to joystick-type controller and teleportation methods. However, they also found that users had a better level of immersion into the environment while using the WiP method, due to its natural manner of moving. There also exists more dynamic approaches to
WiP systems, attempting more natural mapping of gait cycles to the user feet gestures. Examples of this are Low-Latency, Continuous-Motion Walk-in-Place (LLCM-WIP) by Feasel et al. [22] and Gait-Understanding-Driven Walk-in-Place (GUD WIP) by Wendt et al. [84]. However, even these systems also introduce certain problems, such as lack of inertia [22] and latency [84].

One limitation of WiP solutions is the lack of directional control. For example, the LLCM by Feasel et al. suffers from this [22]. They apply only forward momentum in-game, while the direction is determined by the orientation of the players themselves. This limits movement versatility, for example in scenarios where strafing or moving backwards is required. However, there also exists WiP approaches that allow strafing and backwards momentum, such as the "Gaiter" by Templeman et al. [74].

While it might not be walking in place in its purest form, there exists a number of "arm-swinging" WiP approaches. They utilize the motion of the hands instead of the feet to move the player in-game. There are both commercial games utilizing this, such as Stride by Joy Way [39], and research on this topic [55, 66, 86]. In papers by McCullough et al. [55] and Wilson et al. [86], they found that arm-swinging methods outperform common joystick movement in regards of spatial orientation. Furthermore, in exergaming study by Khundam et al., they discovered that their arm-swinging method had a good usability, as it scored a SUS score of 86.5 [43].

The most notable advantage of our approach over WiP is that the locomotion movements can be more natural, whereas WiP requires a form of stomping in place to avoid drifting around in the physical space. Additionally, WiP has limited potential for exergame applications. Similar to the more advanced WiP methods, we also support strafing and backwards locomotion, although our user study does not focus on that. Comparing the precision of omnidirectional locomotion in our and WiP approaches is a potential topic for future work.

2.1.4 Redirected Walking

Redirected walking is a VR locomotion technique that utilizes an imperceptible gain to the movement and/or rotation, allowing users to explore larger virtual spaces in confined real-life spaces. In practise, this means manipulating the in-game location, speed and/or rotation of the user in a manner that makes it easier to use VR in more confined spaces. These manipulations aim to be subtle enough for the user not to consciously notice them. Multiple different studies have implemented and evaluated different redirection techniques [2, 14, 48, 69, 73].
CHAPTER 2. RELATED WORK

While these techniques show promise, they also have limitations. To fully utilize the potential of redirection, the developers need to design the level layout to guide player in a certain manner for the redirection to work optimally. Depending on the implementation technique this might vary. For example, Azmandian et al. require the player to "reset" the orientation by spinning, while adjusting the player orientation [2]. Chen and Fuchs implemented a "distraction algorithm", guiding users gaze (and rotation) with moving objects [14]. Razzaque et al. constructed a predetermined path for the player to utilize waypoints as redirecting locations [69]. Methods like these introduce restrictions to the designers, and decrease player freedom and player experience.

Additionally, even though allowing exploring larger spaces, the physical space is still limited to some extent and it is possible for the user to walk out of the physical playing area, especially if they refuse to comply with the redirection cues supplied by the system. The size of the play areas in the experiments vary, but unrestricted motion requires still large physical spaces. Steinicke et al. argue that an area of 10 by 10 meters would suffice for a virtually infinite omnidirectional movement [73]. An unobstructed area this large is arguably quite rare in common households. Furthermore, faster locomotion, such as running, might not be as suitable for redirection techniques, as overshooting distances may become more relevant.

2.1.5 Seated VR Locomotion

For our Chair playing mode, the most similar approach for seated locomotion we discovered are the Cybershoes by Cybershoes Inc. [18]. They utilise two slippery shoes that are strapped onto the feet of the user. The shoes have cylindrical rollers attached to the bottom. Those rollers are utilized to track the speed and direction of the movement of the user. The user is required to sit in a swivel chair to be able to rotate and slide their feet on the ground. They also include an Inertial Measurement Unit (IMU) to allow tracking of orientational data.

Their approach has one major advantage over our approach. The rollers enable substantially more accurate and easier tracking of the speed and direction (forwards/backwards) compared to our tracker based system. However, the Cybershoes do not seem to allow strafing, due to the rollers rolling only on one axis. On the contrary, strafing is possible in our system. Furthermore, Cybershoes seem to not support inverse kinematic animations, that is, mapping the user's in-game feet positions accurately with the real-life feet. Usually in these situations the game does not show the legs of the user's avatar, which might decrease immersion. Our approach tries to solve this
issue by remapping the user's sitting pose to a standing in-game pose.

In a comparison of seated VR locomotion techniques by Kitson et al. the general conclusion was that joystick movement is superior to the other, more novel methods compared [44]. They compared four different seated novel locomotion methods to normal joystick locomotion. The compared methods were NaviChair, MuvMan, Head-directed and Swivel Chair. Even though their setup was rather similar to ours in the sense of the seat, their method of moving was completely different. They used leaning based gestures to move, so no actual leg movement was required to move in-game. Despite this, they found that users found the tested methods fun, engaging, more realistic and natural when comparing to the joystick locomotion [44]. Furthermore, a study focusing on the NaviChair, and its standing-up version, NaviBoard, found multiple potential benefits in these methods, such as improving user performance and reducing simulator sickness [63].

Seated VR movement methods have also been previously studied by Kitson et al. [44]. However, in the methods they compared, locomotion was implemented without locomotion-like leg movements, mainly by leaning in different directions. Despite this, they discovered that using a swivel chair for VR locomotion is comfortable for many users [44]. Our seated variant can be viewed as an extension of theirs focused on enabling more natural foot locomotion movements.

Other methods including a chair we investigated were walking by cycling by Freiwald et al. [24] and utilizing pressure pads in a seat by Ohshima et al. [65]. In the first study, Freiwald et al. developed a system where the user sits on a chair and uses pedals to move in-game. One obstacle in this approach is due to the pedals do not rotate with the chair, they were required to develop different methods for turning. In this thesis, we took inspiration from one of their turning methods to solve our problems with turning in the Supine mode.

Ohshima et al. developed a custom chair with pressure pads. The pressure pads can be used to implement locomotion controls interpreting minor walking in place gestures. The authors claim that their system can be used by various people, for example individuals in wheelchairs, due to the minor amount of leg movement required to actuate locomotion. [65]

2.1.6 Supine VR

In concurrent work, van Gemert et al. experiment with playing popular VR games on a bed, while lying down. In line with our work, they found that the remapping of users' orientation within the virtual environment is quickly adapted by the user. They further suggest that future work should explore
locomotion methods that allow more versatile locomotion, speculating on an implementation resembling that of ours [78].

As a source of initial inspiration for our prototype, moving in VR while lying supine, prone, or crouching on the floor has also been experimented by Krekhov et al. [45, 46]. However, they mainly focus on non-human body ownership and they do not study movement mappings that allow navigating virtual spaces larger than the actual physical space.

Luo et al. [51] experimented using VR while in a reclined seat, the recline angle ranging from sitting straight up to lying down parallel to the ground. They compared different aspects, such as simulator sickness and player embodiment. They discovered that although sitting straight can be considered superior, lying parallel to the ground was the second best option. Some of our results parallel theirs—in particular, their users got used to the orientational difference quickly and were barely aware of it when playing supine.

Despite the similarities in the playing pose, our study further expands the possibilities offered by this discovery. The supine pose allows one’s legs to move unrestrained in the air, which we utilize to implement locomotion with natural leg movements. In contrast, Luo et al. [51] used d-pad/joystick movement in their tests to focus solely on the embodiment and other aspects affected by the orientation of the player.

In studies by Montoya et al. they experiment with using VR in a flotation tank. While this might be a more extraordinary setting that requires an expensive and constraining setup, it does involve using VR in a supine position. They argue that technological adaptations, such as VR, can enrich experiences, such as lying in a flotation tank. [58, 59]

### 2.1.7 Other Novel Approaches for VR Locomotion

Previous work has explored novel locomotion approaches ranging from walking by cycling [24], using one’s body leaning on a chair or a board [63], various foot-based gestures [79], using a harness to suspend the body of the player [80], pressure pads in a seat [65], omnidirectional treadmills [38, 82, 83] and using VR under water [61, 71].

While displaying potential, many of these methods do not really resemble natural movement, such as the leaning or gesture-based methods. The locomotion system utilizing a harness to suspend the player, by Walther-Franks et al. [80], allows more natural movements, but none of the testers found it easier to use than regular WiP. Furthermore, its comfortability was reported to suffer from the non-fitting harness.

Among the approaches above, perhaps the most natural and unrestricted movement is offered by the omnidirectional treadmills, although limited to
upright locomotion. However, they also require large and expensive equipment. Although some of the variants of our approach also require additional equipment, the two approaches tested in our user study, Chair and Supine, only require everyday equipment such as an office chair or a yoga mat. This should make our work easier to adopt by both other researchers and consumers who are not willing to invest in expensive equipment or large open spaces.

It should be noted that non-conventional locomotion and movement-based interaction are also researched outside of VR, in contexts such as climbing on a projection-augmented climbing wall [40], rodeo-bull riding [53] and trampoline jumping [33]. Although our focus is on VR, such non-VR work has motivated and inspired our design. The hanging off a bar experiments of Mueller et al. [60] inspired us to try our locomotion approach while hanging from gymnastic rings.

2.2 Exergaming

Exergames are video games aimed at enhancing the enjoyment of exercise [43]. Studies have shown that exercising with exergames can be as effective as normal exercise [21, 54, 57, 70]. Exergaming can add novelty into exercise, potentially increasing the motivation. However, even with gamified exercise experiences, the novelty is likely to decrease over time. Thus, the novelty of the game itself needs to be refreshed, to motivate users developing a long-lasting exercise habit [85]. This was experimented in a study by Zhao et al. [89] and they found that feature updates to the game did have positive effects regarding user retention.

Despite exergames displaying potential, there also exists challenges. In a study by Whitehead et al., they conclude that the game designers should consider following aspects to pursue effective long-term exercise goals. Players might try to cheat the system, rendering the exercise sub-optimal, thus the designers should try to implement systems to prevent that. The exercises should target large muscle groups, such as legs. The games should include incentive elements that encourage long term commitment. The incentives can utilize normal game design elements, that is, they do not need to be exercise or fitness oriented. [85]

Study by Bianchi-Berthouze et al. shows that body movement increases engagement during gameplay. When studying players playing a guitar-playing game, they discovered that players tend to start adopting movements related to the role suggested by the game (in this case, a musician), even though it is not required to able to play the game. They argue that the playing
experience itself was rewarding, instead of just overcoming the challenge of the gameplay. [3]

2.3 Non-standing Playing

Even though VR is conceived as a way to better immerse and act more naturally within virtual environments, the majority of VR interaction is limited to either standing or seated playing poses. This covers only a rather small fraction of the diversity of the human body movement. This was observable even outside VR, in movement-based game systems such as Kinect by Microsoft Corporation [56].

For exergame development, this "standing bias" is sub-optimal, as it disregards many important muscle groups and offers only limited exercise potential. Prior research has also called out for more diverse movement in movement-based games [31]. This is echoed by Khundam et al. and they further argue that more varying playing poses can decrease boredom and reduce risk of injuries [43]. Additionally, when comparing exercise intensity, Peng et al. discovered that exergames seem to provide generally worse exercise for the upper body, while lower body exercises show more intensity [68]. This was also confirmed by Whitehead et al. [85]. This further suggests that a more novel approaches on the playing poses are required to fully tackle the whole exercise spectrum.

Some exploration of this topic exists, as mentioned in sections above. For example, the augmented climbing wall Kajastila et al. [40] introduced gamification to an already existing sports, climbing. The hand-hanging exergame by Mueller et al. [60] focuses heavily on hands, which normally experience rather minor physical exertion in conventional VR games.
Chapter 3

Design process

3.1 Prototype iteration

The iteration process for our system is implemented with Research through Designs methods. Throughout the development process, we developed multiple iterations of the system. We continuously tested the system while developing it and whenever a new functioning iteration was ready, we invited other people to test it, and discuss following iterations. We took notes from the testing sessions, which were further analyzed in this thesis. The iteration process description is simplified to certain extent to make it less difficult to follow. This means that certain subsections might have multiple minor parallel iteration steps described, thus the amount of subsections is not necessarily equivalent to the amount of actual iteration steps in the project.

The development equipment includes a desktop PC (GPU: NVidia RTX 3080, CPU: Intel i7 11700, RAM: 32Gb), a HTC VIVE VR set with wireless adapter (VIVE Pro 2 head mounted display, two VIVE hand controllers and three VIVE trackers (version 3.0) with straps). One of the trackers is attached to the waist of the user and the two remaining ones are used to track the feet of the user. The trackers measure input data in 6 degrees-of-freedom (6-DOF). Additionally, we use six connectable foam mats and a swiveled office chair to test the different playing modes. The more experimental game modes are tested with a movable dip rack and gymnastics rings attached to the ceiling. The VR game environment for the prototype is made with Unity game engine by Unity Technologies [77].

3.1.1 First Conceptualizing

The original idea was suggested by the thesis supervisor. The idea considered locomotion in VR games while the players lies on the ground, on their back.
The basic idea was to let the players move their limbs freely in the air, without physically moving in the playing space. This allows the player to mimic walking and running without the limitations of the size of the physical playing area. We briefly discussed on different types of games this method could be applied to, concluding that fast paced action games might be a genre where this method has opportunities. We decided to start prototyping a proof of concept prototype to validate this idea.

At the time, we made the decision that the game has to be depicted from third person perspective (3PP). This conclusion emerged from the assumption that the player laying down in real life, but standing upright in the virtual world causes too much disembodiment. Furthermore, we were interested in further exploring the possibilities opened by 3PP VR applications such as 3PP-R by Evin et al. [20]. Ultimately, we pivoted to first person perspective (1PP), details for this are discussed later on in this Section.

3.1.2 The First Pseudo-physics Experiments

While experimenting with different methods of mapping supine leg movement to in-game locomotion, we concluded that the the best approach for fast iteration and sufficient enough accuracy could be achieved through pseudo-physical simulation.

The pseudo-physical algorithm was implemented to replicate friction of the feet touching the ground. As the feet of the player are not actually in contact with the ground, we pursued for simplification of physics. The basic principle for constructing the player velocity vector is as follows: the algorithm determines which foot is lower (relative to the playing orientation, that is, when playing in supine pose, the ”down” direction in-game is the ”forward” direction in real life). The direction velocity vector of the lower foot is then multiplied by -1 and applied as the new velocity of the player character.

The in-game upward velocity is omitted at this phase. Jumping is implemented by measuring the speed of the lower leg in the the relative downward direction. If it surpasses a threshold, the player initiates jumping, thus a scaled vertical velocity of the leg is applied on top of the planar velocity vector discussed before. If the threshold is not surpassed, the in-game upwards velocity will remain as zero. The game engine’s internal gravity force is applied in addition to our own calculations.
3.1.3 Saddle Chair

In earlier discussions, we had theorized the usage of office saddle chairs as a possible VR gaming seat, as they allow rotation around the swivel and rather unrestricted leg movement. When we started having the first successful experiments with pseudo-physics in the Supine mode, we also realized the potential for other playing poses, described in Fig. 1.2. The Chair mode in particular seemed to show promise, thus we started developing and experimenting it in parallel with the Supine mode.

In our next iteration, the game was playable also on a (saddle) chair. The movement works with the same algorithm as in the other version (Supine). However, the ground reference is in the "normal" orientation, that is, the perceived ground is in same direction than ground in real life. The player can move by imitating walking/running while sitting in the saddle chair. The player can either move their feet completely in the air, or swipe them against the floor. The player orientation in the game is represented by the player orientation on the saddle chair. Rotating the chair will rotate the player model in game.

Using these methods, we hypothesized the game mechanics being applicable to various game genres. For example, in theory, most of the 3PP action game maps could be traversed with this system. However, despite seeing potential in this new system, there existed multiple problems in the mechanics, affecting gameplay and game feel. In the next Section, we discuss the design process revolving around the problems in the movement.

3.1.4 Movement Iteration

This subsection includes descriptions from multiple minor iteration steps, which together result in more intuitive and enjoyable game mechanics. We faced issues namely in three different aspects: movement, jumping and turning. For each of those, we tested multiple different methods.

For movement, we started out with "raw input", in lack of better words. This movement mode did not filter the input received from the feet trackers, which caused occasional missteps in the movement of the player, as well as movement to unintentional direction. This emerged as an "stuttering" effect in the player in-game velocity, which substantially reduced responsiveness and accuracy of the controls. To compensate this, we tried out the following four approaches:

1. **Backstep prevention**: we prevented the player from moving backwards at all. To further explain, the game omitted any input that had
a positive dot product (player movement vector is always opposite of the foot tracker velocity) with the direction the player is facing, thus allowing velocity input vectors only within a $90^\circ$ angle from the forward direction. The algorithms can be formulated as follows:

$$V_{\text{filtered}} = \begin{cases} -V_{lf}^z, & \text{if } D_z \cdot V_{lf}^z \geq 0, \\ \vec{0}, & \text{otherwise} \end{cases} \quad (3.1)$$

where $V_{\text{filtered}}$ is the final character velocity (y-component omitted), $D_z$ is the forward direction from player character perspective and $V_{lf}$ is the velocity of current lower foot tracker (y-component omitted).

This approach works arguably well when the player only wants to move straight forward and in diagonal (forward facing) directions. However, the lack of movement directions makes this undesirable approach, as a substantial amount of games utilize strafing and back stepping in their core game play mechanics.

2. **Keep direction:** in this approach, we take a shifted dot product of the foot tracker velocity vector and the current player velocity vector. Dot product result is shifted so that it is in range $[0, 1]$. We use this value to scale the leg velocity input. In practise, this means that if the player velocity is large in certain direction, new input velocity vectors to the completely opposite direction are close to zero. Conversely, input velocity vectors to approximately parallel direction as the movement velocity are close to the actual tracker input velocity. The shifted dot product formula can be expressed as:

$$V_{\text{filtered}} = -V_{lf}^z \ast ((V_{xz} \cdot V_{lf}^z) + 1) \ast 0.5 \quad (3.2)$$

where $V_{\text{filtered}}$ is the final character velocity (y-component omitted), $V_{xz}$ is the character velocity in the xz-plane (unfiltered) and $V_{lf}$ is the velocity of current lower foot tracker (y-component omitted).

This approach also provided some utility and further insight to the problem. However it did not adequately prevent the core issue in cases where the player velocity was slow or at standstill. In those situations the stuttering effect was still present. In greater velocities, the method worked, but there existed the drawback of limiting player movement options. The player could not change from running forwards to running backwards in a timely manner.
3. **Running average**: this approach utilizes a buffer of velocities gathered from past vectors to calculate a running average of the input velocity. The method can be used in parallel with the other methods, and to an extent, still used in the current version of the algorithm. The buffer had an adjustable size, which allowed us to experiment with different average ranges of input velocities. This method was not in itself sufficient to eliminate the core problem. Lower buffer sizes were not enough to eliminate the stuttering. Higher buffer sizes were able to mitigate the stutter to a certain extent, but they made the movement feel unresponsive and sluggish.

4. **Waist tilt**: in this approach, we experimented with determining the desired direction of movement with the waist tracker. We made a system that utilizes the "Backstep prevention" method, but in both directions. The tilt angle of the waist tracker of the player determined whether or not the filtered velocities were facing backwards or forwards. In practice, this meant that the player can move only forwards when sitting straight up or leaning forward. Vice versa, the player can move backwards only when leaning back. This approach has similarities to the leaning based methods experimented by Kitson et al. [44]. However, in our implementation, the player still needed to imitate the running/walking with their feet as if they would be moving in the direction in question. The threshold in the waist tracker tilt had to be manually calibrated.

This method was the most efficient method up until this point of the development both in eliminating the stutter in movement while still keeping the player controls responsive. However, the leaning forward/backward action was a conscious effort that the player was required to perform. Additionally, the threshold required calibration on a player to player basis, thus the solution was sub-optimal. Furthermore, this method was inapplicable to the Supine playing mode.

In addition to the planar movement problems, we were required to implement logic for jumping in the game. For this, we again had multiple different modes to try out which mechanics would work the best. The next implementations were tested:

1. **Single foot**: player jumps if the lower leg velocity relative y-component surpasses a threshold

2. **Both feet**: player jumps if both of the leg velocities relative y-components surpass a threshold
3. Either single or both feet: combination of the two above, single leg jump is not as powerful as the two leg jump

In addition to these modes, we experimented with different movements for the feet to perform jumping in the game. Mainly the direction (along y-axis) in which the foot tracker was required to move was experimented. With this, we had three different jumping modes for both of the directions, totaling in six options. The player could jump either by stomping their feet down onto the ground or by lifting them up from the ground fast enough, depending on the directional mode used. Initially, we used the foot lifting method for jumping, but later on decided to change it to the stomping mode, as it more closely resembles real life jumping. The single foot jump was our choice at this point of the development. However, all of the modes were intuitive enough to be utilized if preferred.

The third problem we were facing at the time was to implement intuitive turning. At this point of development, we mainly focused on the Chair mode, so we left the Supine mode out of consideration for the turning mechanics. We reasoned that we would need to make totally separate turning system for the Supine mode, as it does not allow any physical turning. We ended up testing two methods for the Chair mode:

1. **Rotation based on HMD orientation:** The player character is rotated according to the VR headset rotation, that is, the player character is always facing the direction the player is looking in. As we were still using 3rd person camera, we utilized a slightly modified version of the 3PP-R camera behaviour by Evin et al. [20].

2. **Rotation based on waist tracker orientation:** The player character is rotated based on the waist tracker rotation. Using this method allows the player to look in different directions while the character orientation stays the same.

Ultimately, we chose the approach using rotation based on waist tracker, as it allowed the player move in different directions while looking around freely at the same time.

### 3.1.5 New Feet Tracker Filtering Approach

Up until this point, all of the methods in controlling the movement of the player have had certain issues. Most of them were caused by the underlying problem of unintentional missteps caused by the inaccuracy in determining which foot should be responsible for player movement at a certain moment.
After discussions on the topic, we decided to experiment with an algorithm that would recognize the direction of the gait cycle to determine the desired direction of movement in game. When further conceptualizing this algorithm on theory level, we discovered a substantially more simple method, which was functionally similar.

The method utilizes the distance between the feet trackers along relative z-axis (forward direction). If the distance between feet is large, the feet velocities facing direction opposite to the current movement vector are omitted. The "raw" feet tracker input is used only if the feet are close to each other in the forward direction. This logic emerged from the realization that most of the stutter in movement happens where the gait cycle of the player is in a stage where the supporting leg is changing. This is because in that stage, the perceived lower foot will change, potentially causing input velocities to unintended directions. If a correct threshold is picked, we can ignore input in the wrong direction when the distance between feet surpasses this threshold. This is because we assume that the change of supporting leg takes place when the distance between the feet is the longest in the gait cycle (or close to that value). Conversely, when the distance is small, the lower foot is most likely simple to determine, as the distance between the feet along the y-axis is more prominent. The algorithm is combination of the "raw" input method and the "keep direction" method, where the formulas are used respective to the distance between the feet trackers. If the distance is beyond a threshold, the dot product between input and current velocity scales the output vector to not counteract the movement. The algorithm logic can be formulated as:

$$
\vec{V}_{filtered} = \begin{cases} 
-\vec{V}_{lf}, & \text{if } ||\vec{P}_{lLegz} - \vec{P}_{rLegz}|| < t, \\
-\vec{V}_{lf} \ast ((\vec{V}_{xz} \cdot \vec{V}_{lf}) + 1) \ast 0.5, & \text{otherwise} 
\end{cases}
$$

where $\vec{V}_{filtered}$ is the final character velocity (y-component omitted), $\vec{V}_{xz}$ is the character velocity in the xz-plane (unfiltered), $\vec{V}_{lf}$ is the velocity of current lower foot tracker (y-component omitted), $\vec{P}_{lLegz}$ is the position of the left leg tracker, $\vec{P}_{rLegz}$ is the position of the right leg tracker and $t$ is the chosen distance threshold between individual feet trackers.

This method worked substantially better than any other method we had experimented with up until this point. There was still occasional stutter, but is was considerably less frequent, thus we decided to continue using this approach. One additional major benefit in this approach was that it could be used as is in the Supine mode as well, opposed to the prior waist tilt method being unusable in that mode.
CHAPTER 3. DESIGN PROCESS

3.1.6 Comparing the Supine and Chair Mode

After committing most of our design efforts to designing the pseudo-physics algorithm, we shifted our focus on generalizing the method for multiple game modes. Despite our efforts in making the system as generalizable as possible, the change from playing in supine pose to sitting upright (or vice versa) did not immediately function well. The main reason was the mapping of relative directions to the movement of the player character and physical limitations when turning around.

The underlying logic for our system utilizes the local coordinate system of the player, which is rotated respectively when game mode changes. For example, when playing in the Supine mode, the coordinate system is rotated 90° around the x-axis (the in-game “right” direction). To further elaborate, this means that the down-vector in the Supine pose local coordinate system is pointing forward in the global coordinate system.

Arguably the most substantial difference between the Chair and Supine mode mechanics is the turning. As it is almost impossible for the player to physically turn more than 90° whilst lying on their back, separate turning mechanics were required for the Supine mode. Two different turning approaches were proposed and tested:

1. **Tank turning:** utilizing this method, the player is able to tilt their body to left or right, initiating a turning action. The player will rotate at a constant rate in game as long as the player maintains the tilted position. As soon as the player returns to the neutral position (within certain thresholds), the turning in game will stop. This method was usable, but rather slow and inaccurate to use, as the player could not affect the turning speed nor was able to quickly stop the turning.

2. **Anchoring:** this method was used in study by Freiwald et al. (referred to as “anchor-turning”) [24]. The method works as follows: when the user desires to turn, they press and hold the trigger button of either of their hand controllers. While doing this, they can move their hand to ”drag” themselves around the center y-axis of the player character. Using this kind of ”proxy-gesture” might be sub-optimal, considering our pursuit for natural controls, but our testing revealed that it was substantially more effective turning method when turning one’s body physically was not feasible.

We decided to continue with the anchoring method, as it was more accurate and responsive. We experimented with both regular and inverted
anchoring by reversing the direction in which the character rotated in relation to the dragging. We discovered that both of the methods were viable, as it was just matter of getting accustomed to the turning direction. In 3PP, the turning can be imagined either as rotating the camera around the character or the character around it’s central y-axis, depending on the direction of turning. However, in 1PP, the idea of dragging the character around rather than the camera is more intuitive. Despite this, both the regular and inverted modes were viable in this also in 1PP. Ultimately, we decided to continue with the inverted option, that is, the view will turn into opposite direction in respect to the hand movement.

3.1.7 Switching to 1PP

Towards the end of the iteration process, we had occasionally started testing switching the player perspective between 3PP and 1PP. Our initial assumption was that the first person perspective could not work in the Supine mode due to the major difference in playing pose and the player orientation in game. At first, we wanted to experiment the 1PP in the Chair mode, as the playing pose was substantially more similar to the in-game pose. Experimenting with the 1PP for the Chair mode gave us successful results. Coincidentally, we decided to experiment the 1PP view with the Supine mode as well, purely out of curiosity. To our surprise, it worked substantially better than we had expected.

For a while, we supported both of the perspectives, in a way that the player was able to toggle between 1PP and 3PP. However, after a while we concluded that the 1PP is superior immersion-wise, thus we decided to remove the option for 3PP, to reduce system complexity. The 1PP seemed also to reduce potential for simulator sickness, making it also superior choice in that regard.

3.2 Pilot Studies and Final Iterations

As we were getting closer to the point where the user studies could have started, we decided to organize pilot studies. Ultimately, we organized pilot studies with 3 different participants. One of them participated twice, while the two other participants completed the pilot study once. Between the pilot studies, we adjusted system parameters, fixed issues and planned the questionnaires and interview questions.
3.2.1 Baseline Locomotion

Our study had one obvious issue: we did not have a baseline to compare our novel methods with. For this, we decided to implement baseline locomotion controls, using the touchpad in VIVE hand controllers. The controls were simple, moving their thumb on the touchpad, the system received a 2D vector input, which we projected to the horizontal plane to initiate velocity to that direction. Jumping could be initiated by pressing the trigger in either of the controllers. As the Supine mode had proved to be more interesting approach into this VR study, we concluded that we compare only the Supine mode to the baseline in the study.

However, after the first pilot study, we observed that the baseline we had implemented caused substantial simulator sickness. The simulator sickness caused by the baseline was severe enough to prevent the tester to complete the study, impeding objective evaluation of the Supine mode. Due to these observations, we concluded that instead of comparing to a baseline, we will compare our novel approaches against each other, that is, compare the Supine mode to the Chair mode.

3.2.2 Movement Problems

After the decision to not implement a baseline locomotion, we organized more pilot studies. We faced one difficult system issue, which resulted in rather large system re-implementation. The issue was related to how the game engine works, and how the delta time between physics updates functions. The final iteration of our movement algorithm is described in section 3.3.

In addition to these changes, we implemented a new algorithm to further filter out any potential misinterpretation of the tracker input data. These changes are also explained in detail in the section 3.3. In this phase of the development, we also tested the system substantially by ourselves, fine tuning the movement parameters. An in-game user interface for altering the parameters while playing was implemented, which was a great utility.

3.2.3 Setup Considerations

Our initial testing setup also received a number of changes based on the pilot studies. We initially had played the Chair mode with a office saddle chair, a chair without armrests or back support. This chair allowed more effortless turning due to its low mass. Furthermore, it allowed more free leg movement. However, during the pilot studies we noticed that depending on the movement style of the player, the chair might be too unstable. As we
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3.3 The Prototype Used in the User Study

This section describes the last iteration, which we concluded to be viable for the user studies. After the feedback from pilot studies, we implemented our last tweaks and then froze the features for the prototype, to ensure similar testing environment for each tester participating in the actual user study. In the following subsections, we discuss separately each main mechanic in our system, considering both Chair and Supine mode. The mechanics are: Walking, Running, Jumping and Turning. Furthermore, we present the calibration set-up interface.

wanted to prioritize safety, we decided to opt for a regular office chair with back support and armrests.

Second improvement we made for the chair was padding. We noticed that the metallic legs of the chair could sometimes cause potentially painful collisions, if the players were to swing their legs in a fast manner. We used polyurethane foam sheets to pad the legs of the chair. With the padding, the player could swing their legs without fear of hurting themselves.

Last addition we did, was to find a small pillow for the Supine mode. The pillow was tucked behind the users neck, to alleviate the stress put on neck muscles due to the combined weight of the headset and head of the user. The pillow was a ordinary decorative pillow, thus not a large one. The dimensions were approximately 40 by 40 by 17 centimeters.

Figure 3.1: Locomotion (left) and jumping movements (right) of the Supine (A1 and B1) and Chair (A2 and B2) modes. The images are from the tutorial videos that we used to communicate the intended movements in our user study. In this figure, arrows have been added to clarify the cyclic locomotion movements and the larger swings of the jumps.
3.3.1 Walking and Running

To recap from the earlier iterations, the two main principles that still remain in our final iteration are the interpretation of lower leg and the rotated local coordinate system. The system determines which foot is lower by comparing the local y-position of both foot trackers. Only the input velocity from the lower one is taken into account while calculating the player velocity. The rotation of local coordinate system is determined by the respective playing pose. In Chair mode, the local coordinate system orientation is equal to the global coordinate system. In Supine mode, the local coordinate system is rotated 90° around the x-axis (global “right” direction) in respect to the global coordinate system. In this set-up, when the players mimics walking while lying on their back, the vertical movement of the feet in real world is interpreted as horizontal movement in-game. The desired leg movement is illustrated in the Fig. 3.1 (left).

In the following calculations, we are assuming that the player character is in contact with the ground. We have implemented so called ”coyote-time” mechanic, that is, the player character is considered grounded, if either of the foot colliders have been in contact with the ground during the last 200 milliseconds. We chose this particular time frame based on our own testing and preferences. This prevents player from losing control over movement due to short intervals where both feet are in the air while running. The gravity force is automatically applied by the game engine. The gravity is higher than normal, -19.62 velocity units of the game engine, approximately equal to meters per second. We chose to increase the gravity to make the jumping feel less ”floaty”.

We measure the tracker input data at every physics update of the game engine. The positional data is used to determine the lower foot. We query the velocity form the lower foot tracker, reverse the direction by multiplying it by -1 and apply it as the velocity in-game player character, scaling it with a speed scale factor. To counteract ”stuttering” movement, caused by noise in the input, we smoothen the velocity as follows:

\[
\vec{V}_{\text{smooth}} = c^{\Delta t} \cdot \vec{V}_{xz} + (1 - c^{\Delta t}) \cdot \vec{V}_{lf}
\]

where \( \vec{V}_{\text{smooth}} \) is the smoothed character velocity (y-component omitted), \( \vec{V}_{xz} \) is the character velocity in the xz-plane (unfiltered), \( \vec{V}_{lf} \): is the velocity of current lower foot tracker (y-component omitted), \( c \) is the smoothing coefficient (range \([0,1]\)) and \( \Delta t \) is the time in seconds between the current and last physics update.

This smoothing essentially applies a portion of the velocity from the last update to the new input velocity, based on coefficient \( c \). The coefficient is
raised to the power of time delta, to take into account the varying times between updates, caused by the game engine inherent functionality. This eliminates most of the noise in the tracker data, preventing misinterpretation in the movement direction. We used coefficient $c$ value of 0.5.

To further filter out misinterpretation of the input data, we implement the same shifted dot product discussed in earlier iterations, recapped in formula 3.5. It essentially scales the input vectors based on how parallel they are compared to the current velocity direction. Scaling is in range from 0 to 1, the closer to parallel the vectors are, the closer the scale is to 1. After this, drag is applied, if the player is decelerating, that is, the input velocity is smaller than the current player velocity. In this case, the velocity is multiplied by 0.9 to simulate drag. This also prevents the player from stopping/slowing down abruptly, if their lower foot momentarily stops/slow down drastically. The formula can be expressed as:

$$
\vec{V}_{filtered} = -\vec{V}_{lf} \ast ((\text{Normalize}(-\vec{V}_{lf}) \cdot \vec{V}_{smooth}) + 1) \ast 0.5 \quad (3.5)
$$

where $\vec{V}_{filtered}$ is the final character velocity (y-component omitted), $\vec{V}_{smooth}$ is the smoothed character velocity (from Eq. 3.4) and $\vec{V}_{lf}$ is the velocity of current lower foot tracker (y-component omitted)

Before applying the processed velocity as the actual player character velocity, a running average is taken from the previous frames. To elaborate, we calculate average velocity from the latest three frames. This value is then applied as the player character velocity, normally ending the pseudophysics update loop. However, if player would initiate a jump during this update, additional calculations are made. This is further explained in the next subsection.

### 3.3.2 Jumping

If the player is grounded, as described in previous section, the player can initiate a jump by ”stomping” with great enough force. In Chair mode, this action resembles stomping the ground. However, in the Supine mode, the most effective way of jumping can be described as a reminiscent of the ”scissor crunch” abdominal exercise. Our underlying principle for this is to measure the foot tracker velocity downwards, in the local coordinate system of the player. In Chair mode, this means downwards, in global coordinate system. In Supine mode, the direction is forward in the global coordinate system. The desired leg movement is illustrated in the Fig. 3.1 (right).

For jumping, both feet trackers are measured always, no matter which one is the lower foot. If the velocity measured from either of the trackers
surpasses a threshold, the jump is initiated. The thresholds used in the user study were 1.45 and 2.20 (velocity units of the game engine, approximately equal to m/s), for Chair and Supine mode respectively. Testing done by the authors concluded that the Supine mode requires higher threshold due to there not being physical ground impeding the acceleration of the feet. When the jumping is initiated, the upwards velocity is calculated as follows:

\[
\begin{align*}
V_{f_{max}} &= \max(V_{left_y}, V_{right_y}), \\
V_{fy} &= \min(1, \max(0, V_{f_{max}} - t) \times s) \times V_{f_{max}} \times k \\
V_y &= \min(V_{max}, \max(V_{fy}, V_{current_y}) \times s)
\end{align*}
\]  

(3.6)

where \( V_{f_{max}} \) is the larger local y-velocity of the two foot trackers (downwards), \( V_{left_y} \) is the y-component of the left leg tracker velocity, \( V_{right_y} \) is the y-component of the right leg tracker velocity, \( V_{fy} \) is the calculated unfiltered jump velocity for this frame, \( t \) is the jump threshold velocity, \( s \) is the jumping sensitivity multiplier, \( k \) is the total jump velocity multiplier, \( V_{current_y} \) is the current y-velocity of the player character, \( V_{max} \) is the maximum jump velocity cap and \( V_y \) is the final y-velocity that is applied to the player character.

The basic principle in the jumping logic is to check whether the jumping threshold velocity is surpassed. In this case, the upwards momentum is based on the greater velocity between the both feet trackers. To make the system more responsive, the jumping calculations also take into account the before mentioned “coyote time”. This means that within the 200 millisecond time period, the greatest measured jump velocity is applied. This prevents the logic only applying the first value that surpasses the threshold, which is usually not the intended jump velocity, as the foot of the player usually takes time to accelerate into the intended velocity.

An alternate movement logic takes place while the player is not grounded, that is, the player is either jumping or otherwise in the air without ground contact. Each physics update, the gravity of the game engine is still applied, causing downwards force. No input from the foot trackers are applied, but the orientation of the waist tracker is still recorded. This allows the player to manipulate their flying trajectory direction mid-air by turning around. However, the initial horizontal velocity remains constant throughout the jump, that is, there exists no air resistance.

### 3.3.3 Turning Around

Turning is the game mechanic that has most drastic differences between the two modes. The Chair mode uses rather simple logic: the rotation of the waist tracker is recorded and applied as the player character rotation in-game.
However, we noticed a disorienting swaying effect when spinning around with the chair while extending one’s legs forward. This was caused by the fact that our movement algorithm does not discern between swinging legs for walking and legs moving due to the user spinning on the chair. For this, we implemented an additional calculation for subtracting the displacement caused by waist rotation from the foot tracker movement, which can be expressed as:

\[
\begin{align*}
D_{\text{foot}}^w &= P_{\text{foot}}^w - P_{\text{waist}}^w, \\
\vec{C} &= \text{Normalize}(\vec{D}_{\text{up}} \times \vec{D}_{\text{foot}}^w) \\
\vec{V}_d &= \vec{C} \ast R_{\text{waist,y}} \ast ||LP_{\text{foot}}^w||
\end{align*}
\] (3.7)

where \(P_{\text{foot}}^w\) is the world position of the foot tracker, \(P_{\text{waist}}^w\) is the world position of the waist tracker, \(D_{\text{foot}}^w\) is the direction vector from the waist to the foot tracker, \(\vec{D}_{\text{up}}\) is the world up direction (y-axis), \(R_{\text{waist,y}}\) is the waist rotation around world up direction (y-axis), \(LP_{\text{foot}}^w\) is the foot tracker position in player’s local coordinate system and \(\vec{V}_d\) is the final displacement of the foot caused by waist rotation.

The formula is applied individually for both of the foot trackers. The displacement (\(\vec{V}_d\)) is calculated and subtracted from the foot movement each physics update. Y-component is omitted from all of the position data.

For the Supine mode, turning physically is naturally impossible. As the players are lying on their back, they can only slightly tilt their body to the sides, which is completely insufficient for a game with open 3-dimensional environment. For this problem, we found an alternate turning method from study by Freiwald et al. called ”anchor-turning”. Even though this method can be seen as a proxy gesture compared to real turning, we observed it to be effective, which echoes the findings of Freiwald et al. as well [24].

The basic idea for the ”anchoring” can be thought of as ”grabbing and holding onto” an arbitrary point in the air using the trigger buttons of one of the VR hand controllers. While grabbing (anchoring), the players can rotate themselves around by moving the hand. This may be imagined as ”dragging” oneself around, while holding onto an imaginary handle floating in air. The formula for calculating the rotation can be described as:

\[
\begin{align*}
\vec{D}_{\text{anchor}}^w &= LP_{\text{hand}}^w - LP_{\text{start}}^w, \\
d &= \text{Normalize}(D_{\text{waist,right}} \cdot \vec{D}_{\text{anchor}}^w) \\
\vec{R}_y &= d \ast ||\vec{D}_{\text{anchor}}|| \ast s
\end{align*}
\] (3.8)

where \(LP_{\text{hand}}^w\) is the current local position of the hand that is anchored, \(LP_{\text{start}}^w\) is the local position where the hand initially initiated anchoring, \(D_{\text{waist,right}}\)
Figure 3.2: The calibration interface. A mirror was placed in front of the player to help with aligning with the tracker targets. The panel on the right has guide texts and buttons for choosing the desired play mode and starting either practise or challenge mode.

is the right direction in waist local coordinate system, $s$ is the turning speed multiplier and $R_y$ is the final rotation around world up direction (y-axis). The speed scale $s$ we used was 300 (degrees).

3.3.4 Calibration Interface

The basic principle of our calibration uses the object parenting feature of the game engine. We have a invisible proxy object for each tracker. The proxy objects replicate the local position of the trackers, within their respective parents. We then rotate the parent object of the proxies an amount corresponding to the current play mode (for example, if playing in Supine mode, the parent object is rotated $90^\circ$). The local positions of the trackers and proxies remain identical within their respective local coordinate systems, but the world positions of the proxies change to correspond the desired in-game pose in the global coordinate system. The calibration interface is shown in Fig. 3.2.

The calibration setup consists of three steps. First, the user needs to calibrate a normal, standing t-pose (a pose where the users stand up straight, spreading their hands to the sides, reminiscent of the letter ”T”). Then, they
calibrate the playing pose, either sitting on a chair or lying down, depending on which playing mode has been chosen. Finally, they calibrate an offset for the feet, according to the current playing mode. For Chair mode, this means that the user will rotate around 180° on the chair. If calibrating the Supine mode, feet offset is calibrated by lifting the users’ legs off the ground, tucking one’s knees in a manner that the knees are approximately bent 90°. The feet offset is used to calculate the in-game position of the feet of the player character. The purpose of the offset calculation is that displaying the player character in completely identical pose as the players themselves is not desired. For example in the Chair mode, we want to avoid presenting the in-game character in a "sitting" pose, but rather standing straight up. We use these offsets from the calibration to remap the real life pose to a sensible in-game pose.

3.4 Four Variants

At this point we also further tested the applicability of the Rings and Dip Rack mode. We did not fully implement separate calibration interface for these modes, as the interface for Chair mode was sufficient enough for preliminary testing. Based on our experiments, the four variants we developed can be summarized as follows.

- **Supine**: User lies down on the floor, on top of a yoga mat or similar padding. They can mimic walking and running by moving their legs in the air. Turning physically is not possible and is instead implemented by a grab-and-pull hand gesture.

- **Rings**: User hangs from gymnastics rings, feet barely reaching the floor. Again, mimicking walking or running can be done rather naturally without any physical locomotion. Turning works naturally in this method, as long as the user refrains from making too many consecutive rotations in the same direction, tangling up the harnesses. Hands are preoccupied, thus not usable unconstrained within the game.

- **Dip Rack**: User suspends themselves in a dip rack. This method also frees up the legs for mimicking walking or running movements. Complete turning is not possible in this method, only steering. Hands are preoccupied, thus not usable unconstrained within the game.

- **Chair**: The user sits on a regular office chair with a swivel. When the chair height is adjusted in a way that the user can barely reach
the ground with their legs, they can mimic walking and running rather naturally, without moving themselves. The swivel joint of the chair allows natural turning around.

As summarized in Table 3.1, the four variants use the same leg movements and movement mechanics that map in-place user movements to avatar locomotion in the virtual space—the only difference is in which body pose and rotation the user performs the movements. This is straightforward as the user’s leg movements are tracked in a local coordinate frame that rotates with the user. This variant-agnostic locomotion is augmented with the abovementioned hand gesture for turning around in the Supine mode.

Table 3.1: The common actions performed in our locomotion system and the corresponding movements performed by the player. Note that ”downwards” is interpreted in player-local coordinates, in the head-to-hips direction.

<table>
<thead>
<tr>
<th></th>
<th>Walk</th>
<th>Jump</th>
<th>Turn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chair</td>
<td>Imitate walking</td>
<td>Kick downwards (or stomp, depending on chair height)</td>
<td>Turn physically on swivel chair</td>
</tr>
<tr>
<td>Supine</td>
<td>Imitate walking</td>
<td>Kick downwards</td>
<td>Virtually ”dragging” using hand controller</td>
</tr>
<tr>
<td>Rings</td>
<td>Imitate walking</td>
<td>Kick downwards (or stomp, depending on height of rings)</td>
<td>Turn physically</td>
</tr>
<tr>
<td>Dip Rack</td>
<td>Imitate walking</td>
<td>Kick downwards</td>
<td>Turn physically (limited range)</td>
</tr>
</tbody>
</table>

3.5 Initial Evaluation

The internal testing of the developed playing modes revealed clear mode-specific benefits and challenges that we summarize in Table 3.2. We consider the variants to primarily differ along the dimensions below:

- **Movement diversity**: The Chair and Supine variants are more versatile and support overall more diverse movements, as they do not limit arm movement. Therefore, they allow more versatile simultaneous locomotion and interaction.
Figure 3.3: Screenshot from a session where author played Supine mode, taken from a secondary third person camera (left) and the primary first person HMD viewport (right).

- **Solving the locomotion problem**: Dip Rack and Rings are more limited, although one can certainly imagine plausible game scenarios for them. For example, Dip Rack could mimic *Iron Man*-style flying with hand thrusters, and Rings could naturally map to an action scene where the player *hangs from a helicopter*, swinging to dodge obstacles and using legs to kick enemies. The Dip Rack offers the most limited locomotion, because we did not (yet) identify a plausible way to allow 360 degree rotation around the vertical axis.

- **Exergaming potential**: Unlike the other ones, the Chair variant does not require intense exertion, although one does move the legs more than with teleport or joystick-based locomotion, and lifting the legs as part of a walk cycle does require some activation of abdominal muscles and hip flexors. For the Supine mode, the abdominal muscle strain was clear. However, the users are only required to hold their legs up, not the whole body as in Rings and Dip Rack mode. Furthermore, it is possible to rest one’s legs on the ground in this pose, thus the intensity can be moderated with ease. Note that the exercise intensity estimates in Table 3.2 are subjective evaluations by the authors; the Borg CR10 scale was only employed in the user study of Section 4.

The Chair mode was tested initially with a swivel saddle chair (an office swivel chair without armrests or backrest, designed to resemble a saddle). Both authors preferred this seat over a regular office chair. However, when getting close to the user study of Section 4, we switched to a regular office chair for safety reasons, because for an inexperienced player there would be a chance of falling due to the lack of armrests and backrests. The larger mass of the office chair caused overshooting when turning, but it was usually negligible. Moving using leg movements worked well, but we found ourselves
to be sometimes consciously moving in a way that would avoid painfully hitting the chair with our legs. Jumping worked without any major issues. Moving in the Supine mode worked without issues during our testing. We concluded that the exergaming potential is easily recognizable, as even a short (around 1 minute) session caused considerable abdominal muscle strain. The most problematic aspect during development was the turning method, as wiggling around on one’s back feels slow and cumbersome. We ultimately chose the gesture-based anchoring method inspired by Freiwald et al. [24], as it was in our opinion the most applicable for supine playing pose, without compromising responsiveness. Both authors adapted to gesture-based turning quickly (within one play session of several minutes). Jumping in the Supine mode was arguably physically intense, but worked intuitively in our opinion.

Unsurprisingly, we found the Rings mode rather exhausting, taking a quick toll on arm muscles. However, as the height of the rings could be adjusted so that one’s legs are barely touching the floor, it was possible to rest while standing still. Jumping worked rather similar to the Chair mode, by kicking downward or stomping one’s feet on the ground. Turning around was quite easy and worked as expected. However, there was an unexpected issue considering turning: If the player decides to make multiple revolutions in the same direction, the ropes connecting the rings to the ceiling would get tangled up. This causes the user to involuntarily start spinning the opposite direction if they lift their legs up in the air. This could be fixed by adding a hinge that allows spinning without tangling of the ropes.

Playing the Dip Rack mode was demanding for the arms as well. However, a short playing session was possible without too much discomfort. Running worked well, but turning was naturally very limited, as the player is required to hold tight with both arms on the bars. Minor steering was possible by tilting one’s body left and right, but to turn around completely the player needs to let go of the bars, turn around feet on the ground, and take hold of the bars again after that. Jumping worked by pushing legs downward, but it was physically straining, as one needs to counteract the momentum of legs with one’s arms.
Table 3.2: Comparison of the different playing modes. *Leg freedom of movement:* how much space does the player have to move their legs, *Hand freedom of movement:* how much space does the player have to move their hands, *Turning range:* how large rotation can player make around the in-game up-axis (both directions), *Exercise intensity:* how physically straining playing is for the player.

<table>
<thead>
<tr>
<th>Playing mode</th>
<th>Leg freedom of movement</th>
<th>Hand freedom of movement</th>
<th>Turning range</th>
<th>Exercise intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chair</td>
<td>Moderate</td>
<td>Full</td>
<td>360°</td>
<td>Minor</td>
</tr>
<tr>
<td>Supine</td>
<td>Almost full</td>
<td>Almost full</td>
<td>360° (hand gesture)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Rings</td>
<td>Full</td>
<td>None</td>
<td>360°</td>
<td>Demanding</td>
</tr>
<tr>
<td>Dip Rack</td>
<td>Almost full</td>
<td>None</td>
<td>~ 90°</td>
<td>Demanding</td>
</tr>
</tbody>
</table>
Chapter 4

User Study

Even though we had four potential variants, we ultimately chose the Supine and Chair mode to be tested. The other two variants, Dip Rack and Rings, showed potential in our initial testing, but they also posed major limitations to hand movement, as they are preoccupied for holding the player’s body up. Furthermore, they were substantially more physically demanding, which would make it difficult for us to find suitable testers.

4.1 Research Questions

We aimed to address the following exploratory and primarily qualitative research questions:

- Usability and future work: What are the benefits, challenges, and application potential of non-standing VR locomotion in general and the tested variants in particular?
- Experience: How does non-standing VR locomotion feel? What is the experience like?

4.2 Study Design

We conducted a mixed-methods, within-subjects user study (N=10) to give further indicative insight for the two experimental modes: Chair and Supine.

4.2.1 Qualitative Analyses

We primarily collected qualitative data and analyzed it with thematic analysis. Following the general progression of thematic analyses, we familiarized
ourselves with the data, coded the data, gathered the emerging themes from the codes, reviewed and refined the themes and finally reported the results using quotes that highlight the content [10]. The process we used was implemented in a manner that allowed parallel gathering and processing of the user interview data. The main author conducted the user studies and interviews, whilst another author was transcribing and coding the data already gathered. After the initial coding of the data, the codes were grouped into broader themes. This way, we were able to combine the first hand interview experience and notes to the more detached perspective of the other author doing the initial coding, getting two different perspectives into the data set. As our coding is inductive, we did not calculate inter-rater agreement between multiple independent coders.

4.2.2 Quantitative Analyses

As a secondary measure, we gathered quantitative data. As our sample size is not large enough, we do not test the statistic significance of the data, rather, describe the data using means, median and standard deviations instead. As no significant conclusions may be drawn from this data, it is used to accompany the qualitative observations and both for hypotheses and research questions for future work.

4.3 Locomotion Task Design

The virtual environment used for the user tests is shown in Fig. 4.1. The level includes 15 waypoints, indicated by green glowing spheres floating approximately a meter above the ground. The waypoints are spawned one at a time, when the player reaches the current one, the next one is spawned. The player is instructed to hit the spheres with swords they have in their in-game hands. However, it is enough that the sword is close enough to the sphere, as the hitboxes are larger than the visual objects. When a waypoint is hit, a small visual effect and a sound effect are played, to let the player know the hit was recognized. We also added a floating green arrow 5 to 15 meters above the spheres, to make it easier to find waypoints occluded by the level geometry. Once the last waypoint is reached, the game will inform the player that the game is over, however, the player is still free to move around in the level, before the level is reset manually by the instructor.

After the calibration, the player is instructed to first enter the practise mode, where there are no waypoints. In this mode, the players are displayed three video clips floating in front of them, similarly as shown in Fig. 3.1. The
videos show desired leg/hand movement for performing moving, turning and jumping in the game. The tester is free to experiment with the controls as long as they want. Once the tester feels like they have a basic understanding of the controls, the level is reset and the tester is instructed to start the challenge mode, which contains the waypoints.

The tester is instructed to attempt and reach as many waypoints as possible. However, they are informed that if at any point they feel like taking a break or giving up, they are free to do so. Additionally, they are told that there is a five minute time limit to reach all the waypoints, but a timer is not displayed to the players themselves. This being said, we noticed after all the testings that due to programming error, this time limit was actually not enforced by the system, resulting in longer play times than five minutes.

The players are encouraged to think aloud during the testing. They are instructed to tell if anything they experience is for example interesting or uncomfortable. Furthermore, they are encouraged to experiment with different methods of moving, to find the best way of moving for them.

The same level and waypoint order is used in both Chair and Supine mode testing. This may introduce a learning effect for the waypoint locations and level layout, however, we counterbalance this effect in statistical analyses by alternating the order in which the modes are introduced to each tester. Furthermore, the choice of keeping the waypoint route and level layout similar had multiple supporting reasons. First, the waypoints are set up in a progressively increasing difficulty. The testers starts with just moving forward, then introducing turning, ramps and elevation, narrow bridges, dropping from height, and finally jumping. We wanted to preserve this planned learning curve between the modes. Second, keeping the level unchanged between modes allows us, and the tester as well, better evaluate the perceived performance between the modes, as there is no risk of unintentionally altering the level difficulty between modes.

The level in itself is composed of simple geometric primitives. We did our best to avoid sharp edges in the terrain, where the player could potentially get stuck. For this reason, most of our changes in elevation happened using ramps. However, there are four platforms on top of tall pillars, which are only accessible through jumping. The last four waypoints were spawned on top of these pillars, to test how well players can control their jumping force and direction. Even though the level "floats" in air, as seen in the Fig. 4.1, the player is not able to fall off the level, as there are invisible, impassable walls on each side of the level.
Figure 4.1: A general view (top) and a top-down view (bottom) of the level. All of the waypoints (green spheres) are shown here, but for the testers, only one waypoint was shown at a time. Red triangles show a point on the route where the user is expected to fall down (downward triangle) or jump up (upward triangle). Despite this, users were free to find their own routes and jump as much as they preferred.
4.4 Participants

Participants were recruited by reaching out to different communication channels and social circles throughout the university and campus. Each participant was compensated with a gift card to a restaurant on the campus area (15 euros). We gathered 10 participants (two female, eight male).

The mean age for our participants was 27.8 years (sd. 2.78, min. 25, max. 32). All of them had at least some experience in video games and VR games: one participant plays video games occasionally, three participants play video games at least once a week, four play multiple times a week and two play almost on a daily basis. Half of our participants (5) had at least tried VR, while three reported using it occasionally and two reported using at least once a month. None of our participants reported being very susceptible to motion sickness: two users reported having never experienced motion sickness, six reported rare experiences with motion sickness and two reporting getting occasionally motion sick.

All of our participants exercise at least occasionally, but as high as 70% (seven participants) exercise two or more times a week. One user reported exercising occasionally, two reported exercising once a week, two reported that they exercise two to three times a week and five more than three times a week. We did not specifically search for people that are highly active, but we speculate the following factors to influence the relatively high percentage. Firstly, we did not specify accurately what is meant by "exercising", thus it was left up to the interpretation of the user filling the questionnaire. In hindsight, we realized that some users might interpret different activities as "exercise" (e.g. walking to work compared to going to a gym). Secondly, we advertised this study as a "VR exergaming research project", which might have appealed more to physically active people.

4.5 Data Collection

Before moving into testing the playing modes, the participants filled out a demographics form, including gender (including non-binary/prefer not to disclose), age, experience with video games, experience with VR, athleticism (how much does the participant exercise), and susceptibility to motion sickness (ordered multiple choice: "I have never experienced motion sickness", "I have experienced in some rare cases", "I get motion sick occasionally", "I tend to get motion sick in certain cases", "I get motion sick very easily"). In this questionnaire, we used the term "motion sickness" instead of simulator sickness, as we assumed that it is more familiar term for non-experts. This
form also required to users to give their informed consent. The users were further told that they are free to stop the experiment at any point if they feel too much nausea or discomfort.

During the experiment, we collected the following qualitative and quantitative self-report data:

- Before 1st playing mode: Sickness Rating (SR) [35] and Borg CR10 perceived exertion [11, 32]. The Borg CR10 is described in Table 4.1. The SR is a multiple choice between ”No symptoms”, ”Any symptoms, but no nausea”, ”Mild symptoms”, ”Moderate symptoms (stop immersion)”. To make the last item more self-evident, we changed ”stop immersion” to ”Discontinuing the test is advised”.

- During both playing modes: thinking aloud, instructed as: ”Please think aloud during this test, telling us how you feel and what you think. In particular, we appreciate if you note anything you like, dislike, or find interesting.”

- After each playing mode: SR, Borg CR10, and open questions: ”How would you describe the playing mode? You can use, for example, adjectives, such as fun/easy/hard/uncomfortable/nauseating etc.”, ”How did this way of moving around feel in your body?”, ”What positive aspects do you see in this VR movement method?”, ”What negative aspects do you see in this VR movement method?”, ”What would you like to change about this VR movement method?”.

- After all playing modes: ”How would you compare the two tested approaches?”, ”What are their pros and cons in your opinion?”, ”Thinking of the version where you lie down on the floor, how did it feel to be in a different posture in the real and virtual worlds?”, ”What are your thoughts of using movements like that as part of Virtual Reality exercise and sports?”, ”If you have any prior experience with VR games, how would you compare the movement methods they used to the methods you tested here?”

We recorded video from the virtual world as the user was playing. The users’ voice was recorded using both an external microphone as well as the microphone integrated within the VIVE headset. The audio was transcribed using primarily the external microphone, but unclear cases or lines lacking context were verified from the video recordings.

Additionally, the user study instructor also took noted observations such as different movement styles. We also collected a range of movement and
CHAPTER 4. USER STUDY

Table 4.1: The Borg CR10 scale [11]

<table>
<thead>
<tr>
<th>Score</th>
<th>Exhaustion level</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Nothing at all</td>
</tr>
<tr>
<td>0.5</td>
<td>Very, very slight (just noticeable)</td>
</tr>
<tr>
<td>1</td>
<td>Very slight</td>
</tr>
<tr>
<td>2</td>
<td>Slight</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
</tr>
<tr>
<td>4</td>
<td>Somewhat severe</td>
</tr>
<tr>
<td>5</td>
<td>Severe</td>
</tr>
<tr>
<td>6</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Very severe</td>
</tr>
<tr>
<td>8</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Very, very severe (almost maximal)</td>
</tr>
<tr>
<td>10</td>
<td>Maximal</td>
</tr>
</tbody>
</table>

task performance data during gameplay. This included player position and velocity vectors \((x, y, z)\) and rotation quaternion \((x, y, z, w)\) over time, position and rotation data of various bone joints of the in-game player avatar, position and rotation data of the VR headset, hand controllers, and all of the trackers used during the gameplay. Furthermore, we recorded timestamps for each waypoint reached and the completion time of the entire waypoint track, or the timestamp of when it was halted prematurely. Both local (within the parent object) and world positions were stored for all of the positional data.

All data stored was anonymous. We used an anonymous identifier to link together the form data, recordings and tracking data, but participant names were not stored or linked to the identifiers. The voice recording data was deleted after transcription. Screen capture video was recorded only from the virtual world and player character, no video from the participants themselves was recorded.
Chapter 5

Results

5.1 Qualitative Data

In Table 5.1 we display the most frequent codes and the Table 5.2 we present the themes collated from the codes. They are sorted by the frequency of mentions within the transcribed text segments.

To further elaborate the themes listed in the table: Control contains everything where users mention a detail about controlling the character and movement in-game. Exercise includes user mentions of physical exertion or them comparing the experience to exercise. Player adaptation covers everything where users mention changing or developing their play style as the play session proceeded. For example, a user might have found an easier foot movement pattern to move more efficiently, or they found out that jumping was easier than running. Set-up problems contains the issues mentioned with the physical set-up environment or equipment. Discomfort includes instances where users felt discomfort in a way or another. However, nausea or other symptoms due to simulator sickness were excluded from this category. Enjoyment covers mentions where user enjoyed some aspect of the gameplay. Miscellaneous was a category used for themes mentioned only once, or themes that lacked broader context. Nausea/Simulator sickness/Disorientation contains the mentions of simulator sickness and its symptoms. Immersion includes mentions of immersion within the virtual environment. Safety covers cases where users mentioned aspects that affected safety (either positively or negatively). Supine/Chair mode preferred covers the preference statements of the users, when asked to compare the two play modes to each other.

The themes contain both negative and positive feedback, which are addressed more in detail in the Section 6.
Table 5.1: The most frequent codes sorted by the number of coded text segments (N) and divided into the high-level themes of positive and negative experiences.

<table>
<thead>
<tr>
<th>Positive</th>
<th>N</th>
<th>Negative</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Supine mode feels like exercise</td>
<td>31</td>
<td>Chair mode controls not working as expected</td>
<td>23</td>
</tr>
<tr>
<td>Chair mode feels like exercise</td>
<td>12</td>
<td>Supine mode headset is uncomfortable</td>
<td>18</td>
</tr>
<tr>
<td>Supine playing pose feeling natural</td>
<td>11</td>
<td>Chair mode walking is difficult</td>
<td>17</td>
</tr>
<tr>
<td>Chair mode has intuitive movement</td>
<td>7</td>
<td>Chair mode having problems with setup</td>
<td>15</td>
</tr>
<tr>
<td>Chair mode feels easy</td>
<td>7</td>
<td>Supine mode jumping is difficult</td>
<td>15</td>
</tr>
<tr>
<td>Supine mode is fun</td>
<td>6</td>
<td>Supine mode controls not working as expected</td>
<td>13</td>
</tr>
<tr>
<td>Supine mode can be mastered</td>
<td>6</td>
<td>Supine mode looking around is difficult</td>
<td>10</td>
</tr>
<tr>
<td>Supine mode has intuitive movement</td>
<td>5</td>
<td>Chair fine movements are difficult</td>
<td>9</td>
</tr>
<tr>
<td>Chair mode is immersive</td>
<td>5</td>
<td>Supine mode having problems with setup</td>
<td>7</td>
</tr>
<tr>
<td>Supine mode feels safe</td>
<td>5</td>
<td>Chair mode feeling unsafe</td>
<td>6</td>
</tr>
</tbody>
</table>

5.2 Quantitative Data

Out of all users, seven individuals did not report any symptoms on the SR scale throughout the whole experiment. After playing Chair mode, one user reported "mild symptoms" and one user reported "moderate symptoms". Respectively, for Supine mode, two users reported "mild symptoms" and one reported "any symptoms, but no nausea". In total, three users reported any other option on the SR scale than "no symptoms". Table 5.3 provides the full SR and Borg CR10 data of all participants.

Seven out of ten users completed all the waypoints on the track in both play modes. All of the testers at least briefly tested both of the playing modes. For users that completed chair mode (seven users), the average completion time for the Chair mode was 316 seconds (median 304, sd 107, min 112, max 447). For users that completed Supine mode (eight users), the average completion time was 350 seconds (median 323 seconds, sd 95.2, min 182, max
Table 5.2: The themes gathered from transcribed data sorted by the number of mentions (N) in the coded text segments.

<table>
<thead>
<tr>
<th>Theme</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>222</td>
</tr>
<tr>
<td>Exercise</td>
<td>58</td>
</tr>
<tr>
<td>Player adaptation</td>
<td>48</td>
</tr>
<tr>
<td>Set-up problems</td>
<td>32</td>
</tr>
<tr>
<td>Discomfort</td>
<td>30</td>
</tr>
<tr>
<td>Enjoyment</td>
<td>29</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>14</td>
</tr>
<tr>
<td>Nausea/Simulator sickness/Disorientation</td>
<td>11</td>
</tr>
<tr>
<td>Immersion</td>
<td>10</td>
</tr>
<tr>
<td>Safety</td>
<td>10</td>
</tr>
<tr>
<td>Chair mode preferred</td>
<td>9</td>
</tr>
<tr>
<td>Supine mode preferred</td>
<td>8</td>
</tr>
</tbody>
</table>

479). Even though we instructed the users about the five-minute time limit, we later realized that it was not enforced properly due to a programming error in the prototype. With some users, this resulted in above five minute play times. For Chair condition, four users exceeded the five-minute time. For the Supine condition, six users exceeded the five-minute time. For the Chair condition, the mean Borg10 rating was 2.00 (median 2.00, sd 1.66). For Supine the mean was 2.25 (median 2.50, sd 1.08).

In total, three users stopped one or both playing modes prematurely (before reaching final waypoint). One of these users experienced mild nausea during both modes, stopping them prematurely. However, the user was able to try playing both modes and give feedback based on the shorter experience they had.

Another of the three users was able to almost complete the Supine mode (14 out of 15 waypoints) but decided to stop the attempt at the final check-point, as it was rather hard to reach it again if missed. The user reported "Any symptoms, but no nausea" after that. However, the user had to stop the Chair mode prematurely, reporting moderate nausea. In this case, the reason for this might have been partially due to experiment instructor error. The instructor noticed the chair getting close to the play area border and attempted to help the tester by dragging the chair closer to the center. This was, however, a mistake, as the user was still sitting on the chair while dragged, causing visual-vestibular conflict. The user reported this as feeling "weird" accompanied by symptoms of simulator sickness shortly thereafter.
Table 5.3: SR and Borg CR10 values reported during the user study, one user per row. The Chair and Supine columns alternate due to counterbalancing. One "after final questions" data-pair is missing, marked with the empty cells.

<table>
<thead>
<tr>
<th>Before testing</th>
<th>After mode 1</th>
<th>After mode 2</th>
<th>End of study</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>Borg</td>
<td>SR</td>
<td>Borg</td>
</tr>
<tr>
<td>Chair</td>
<td>Supine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>0</td>
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<tr>
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<td>Any †</td>
<td>0.5</td>
</tr>
</tbody>
</table>

* Testing finished prematurely due to nausea.
† Testing finished prematurely due to user giving up after getting close to the last waypoint, but failing.
‡ Testing finished prematurely due to exhaustion.

One of the three users was able to complete the Supine mode with no notable issues but reported mild nausea after playing. This user had to stop the Chair mode prematurely, but due to physical exhaustion, not nausea. The user reported "No symptoms" on the SR scale after this, but the highest Borg rating throughout the user study (value of six).
Chapter 6

Discussion

In this section, we discuss the feedback received from the users, focusing on a selection of the themes in Table 5.2.

6.1 Differences in Movement Style

One common observation we made was that users may have entirely different play styles compared to each other. Despite all being shown the same movement tutorial videos, they all developed their own way of interpreting the movements, thus creating rather large differences in player performance. Van Gemert et al. also reported varying playing poses among the participants in their study experimenting with playing in VR while lying down [78]. One key takeaway from this is that in the future, special attention should be given for dynamic calibration for player movement patterns. While interpreting the results, one must keep in mind that there are user opinions both for and against various aspects of the tested variants, which may be at least partially due to the differences in playing styles.

6.2 Player Adaptation

One of the most interesting observations from the supine playing mode was the quick adaptation of perspective. Eight users mentioned that they initially felt weird when the perspective shifted 90 degrees, but after playing for a while they got used to it ("At first, I was skeptical, laying on the ground, as I thought it would warp my perception of being upright, but actually laying there and getting, once you get the immersion from playing, after a few minutes, I forgot that I was lying down."). "When I was getting in the position, it felt a bit weird, but then actually once the landscape opened up behind my eyes, I could
kind of forget about it, so I didn’t really find it a problem, maybe perhaps to my surprise.”). Two users mentioned that they forgot the physical direction of gravity almost immediately when the game started. For others, the shift took longer (“maybe like one or two minutes”, ”after a few minutes”, ”I forgot quickly about it”), but universally they felt that at some point they did not consciously feel like lying down anymore. The concurrent work by van Gemert et al. [78] does report similar user experiences and is also in line with Luo et al. [51]. This observation might suggest that the visual feedback of the orientation is more important than the actual vestibular sensations and mirrors research that investigated locomotion in third-person VR [34].

### 6.3 Exercise

One of the most commonly mentioned themes was that playing felt like an exercise in both tested variants. This was expected for the Supine variant, but less so for Chair which received only a slightly lower mean Borg CR10 rating. However, the reliability of the quantitative measures is low, given our sample size, and is also affected by the users who interrupted an experimental condition prematurely due to simulator sickness. Additionally, users were able to rest when they felt like it, by remaining stationary. Thus, some players might have preserved their energy more than others. Due to these issues, the qualitative data about exercise intensity is likely more informative than the Borg CR10 ratings.

The coded transcripts indicate 31 mentions of playing feeling like exercise for the Supine mode (“Good core training, I feel my abs.”, ”Could be a fun way of doing core exercise.”), and 12 for Chair mode (“It could definitely be a good workout.”, ”This already feels like a workout.”). 9 out of 10 users mentioned the Supine mode feeling like an exercise, and 6 out of 10 mentioned the same about the Chair mode. The feedback from Supine mode aligns with the concurrent work by van Gemert et al. [78] whose testers reported playing VR in a bed feeling like ”ab workout”.

Notably, there were considerable individual differences in where users reported feeling the exertion in their bodies. Four users reported strain for the abdominal muscles while playing Supine mode, while other four users mentioned lower body muscles, such as the hamstrings, quadriceps or hips. In addition to these, one user mentioned both abdominal and lower body muscles. For the Chair mode, three users mentioned strain on the lower body muscles and one other user mentioned back strain. Players adopting different playing styles is probably part of this variance in the perceived muscle exertion. This may also be partially a reason for why there was a
conflict between users on which play mode was more physically demanding.

In their literature review, Oh and Yang find that exergames are commonly referred as "videogames that require physical activity in order to play". They further propose a new definition of exergaming as "experiential activity in which playing exergames or any videogames that require physical exertion or movements that are more than sedentary activities and also include strength, balance, and flexibility activities". [64] The feedback we received supports the exergaming potential of our prototype in light of both of these definitions.

A study by Bianchi-Berthouze et al. shows that body movement increases engagement during gameplay [3], a phenomenon we also witnessed from user feedback ("Getting a little frustrated with the jump, but that was kind of motivating in a way. It was like a challenge that I wanted to overcome. Enthusiastically kicking to get higher up that series of jumps was good.").

Prior research has discussed the need for more diverse playing poses, instead of always standing or sitting [31]. This is echoed by Khundam et al. who argue that more varying playing poses can decrease boredom and reduce risk of injuries [43]. We believe that our work does provide new opportunities for more diverse body motions in future exergames.

Additionally, when comparing exercise intensity, Peng et al. discovered that exergames seem to provide generally worse exercise for the upper body, while lower body exercises show more intensity [68]. This was also confirmed by Whitehead et al. [85]. Our Supine mode offers abdominal exercise potential, while Rings and Dip rack provide upper body exercise. We believe further exploring these playing modes could offer more diversity, by providing exercise for the core and upper body.

### 6.4 Safety

Two testers mentioned a detail considering the Supine playing mode that we had not predicted or considered ourselves: The mode prevents fear of collision with real life objects ("If you’re lying down, moving like that, the only thing you’re going to hit is the ground when you get your feet down. And even with the turning, since you turn by moving your hands upwards, you don’t have the fear of hitting anything, which is great. It gives me a lot of comfort in playing."). 

Traditionally, VR users tend to be conscious of the boundaries of the physical playing area, due to fear of colliding with walls or furniture. When playing lying down on the ground, the user does not need to be considerate about accidentally moving out of the play area, as they are statically lying on their
backs. This helped the two users to "go all out" on the moves. To put it in other words, the users felt like they had more freedom of movement. This was not true for the Chair mode, as the office chair used for playing tended to drift around. Optimally the chair would be static as well, which could introduce this freedom of movement also to the Chair mode.

6.5 Empowered/Exaggerated Movement

Both the Chair and Supine variants received comments on feeling empowered. Jumping was the main focus of this feedback. We had scaled the maximum jump height to approximately six meters, which is substantially exaggerated. Four users mentioned enjoying the jumping, such as the ability to make massive leaps ("I feel sort of supernatural", "It just goes like dude, you can do this kind of huge leap."). However, two other users mentioned that they felt slight dizziness/nausea due to falling from high up. The maximum running speed was also exaggerated to approximately 12 m/s, but the players did not mention it when discussing empowerment or enjoyment. However, one user did mention the velocity being too fast ("[-] I felt like things were moving maybe too fast").

The findings above comply with the results of Ioannou et al., as they found that exaggerated (they used the term "augmented") jumping is more unnatural, thus more noticeable, than exaggerated running [37]. Granqvist et al. have studied movement exaggeration in VR as well, however, they experimented with exaggerated human joint flexibility and found that exaggeration should be subtle [29]. Our movement scaling was not subtle, but in contrast to their study, we exaggerated movement velocity, not the flexibility of human joints. Moreover, the exaggeration Ioannou et al. implemented for running and jumping was also very substantial (running speed was up to 88km/h, which is over 24m/s) and found that it still had positive effects [37]. This is in line with our results, which might suggest that certain exaggerated features, such as velocities and exerted forces, are more naturally adopted than others, such as flexibility. Furthermore, an earlier study by Hämäläinen et al. further strengthens the argument that exaggerating jump height and movement velocity does have a positive impact on player enjoyment, even at rather large scales (jump scaled up to five-fold and movement up to two-fold) [30].
CHAPTER 6. DISCUSSION

6.6 Preferred Variants

When asked to compare the two play modes, six users preferred the Supine mode (*I think this one [supine mode] is better training, it felt like more natural and I felt that I was more in control with the movements.*) and four preferred the Chair mode (*I think overall I would prefer the first one [chair mode], because I was more free to look around and it felt more like I was actually immersed in the game*). Overall, the Supine mode seemed to be easier to learn, even though it was physically more intense. This may be because the Chair mode suffered from implementation and setup problems discussed below. For two users that preferred Supine mode, the decision between the tested modes was difficult because they felt that the preference for the mode was heavily dependent on the game being played. The most common control difficulties for Chair mode were the difficulty of walking and for Supine mode it was the difficulty of jumping.

Positive aspects mentioned for the Chair mode were for example intuitiveness, easiness, immersion, naturalness and empowerment (*"My first feeling when I started with the with the chair movement was that this feels very intuitive and natural. Sliding my feet against the ground where I can feel the ground. Pretend that I’m gripping from the ground when I’m kind of sliding against it.", "Incredibly easy and a way less strenuous.", "Sitting down is much better for taking in the scenery, as in like immersing yourself into the world."*). For the Supine mode, emerging positive themes were for example naturalness, sense of mastery (or seeing potential thereof), having fun, intuitiveness and freedom of movement (*"It didn’t feel unusual. Yeah, it didn’t feel anything unusual, it just felt kind of natural.", "[...] but I did manage to adjust the way I played the game as I went along. So, I felt like I also improved.", "But I’m enjoying the game. It’s quite fun to explore this interaction.", "First, as with laying down, the expectation of how you move, you quickly get used to it, and it becomes intuitive.", "And that’s the best aspects of this. So the freedom of the legs. I don’t think many VR games would be able to leverage."*).

6.7 Chair Mode Problems

The problems in Chair mode can be mostly concentrated into two categories: setup issues and control issues. For the setup, our office chair setup was suboptimal, as the wheels allowed the chair to drift around the play area and the legs of the chair from time to time collided with the feet of the player. We were aware of these issues before user testing, but did not consider them
as major problems. We used polyethylene foam to pad the legs of the chair, to prevent users from hurting themselves if hitting the legs. This did help, but chair legs were still at times inhibiting the freedom of movement of the players.

What we did not expect was the difference in player play styles and how much that affects the drifting of the chair. When the authors played the prototype, the chair drifting was minimal. This was also true for most of our players. However, three players adopted a play style which caused notable drifting around the play area, at times even to the point that we needed to adjust the chair position during the playing. The drifting of the chair also seemed to cause simulator sickness for one of the players, especially when the user study instructor tried to help moving the chair towards the center of the play area. This is to be expected as the movement was irregular and in conflict with the in-game movement.

We could have chosen more specific chair to better fit for our prototype. A swivel chair with a steady and flat base could have been better for allowing freedom of leg movement. For example, a certain type of "bar stool" with a swivel could have been better. The Cybershoes also appear to utilize this type of a chair [18]. Another option could have been a swivel chair statically connected to the ground. We decided to opt against these, as we saw potential in using regular office chairs that are substantially more commonplace and easily obtainable. Furthermore, we had initially tested the chair mode with a saddle chair but opted to use regular office chair with backrest and armrests, to decrease the risk of falling. This observation was also made in a study by Kitson et al. [44].

6.8 Supine Mode Problems

For the supine setup, one clear obstacle was the head pillow interfering with the VR headset. Eight users mentioned this restriction for head movement. This prevented users from looking around unrestricted, which is usually an inherent part of VR gameplay. Minor head tilts were possible, but the setup blocked any real attempts to look high up or far to the sides, despite us providing a pillow to support one’s head and provide slightly more comfort and less clunky movement as compared to resting the back of the headset on hard ground. These users reported this being a downside for the Supine mode compared to the Chair mode ("But I guess now it was harder to like look around.", "So when we have this pillow behind your head and you try to look upwards, it’s definitely more difficult because you don’t have nearly as much freedom of movement with your head."). Possibly, a more specific
pillow could alleviate this problem. A pillow with support cushion mainly for the neck and space left for the headset’s backside to move more unrestricted might let the user to look around more freely. The head movement problem also arose in the study by van Gemert et al. where they had users play VR games lying on a bed [78].

6.9 Control

In all the variants we developed and tested, both in the initial evaluation and in the user study, perhaps the hardest aspect was to allow efficient turning around the vertical axis. The Supine variant requires a specific turning gesture and the Dip Rack mode prevents turning completely. The Chair and Rings variants do allow turning quite naturally, but the rings place severe movement limitations on the arms, and with Chair, the turning does not feel as efficient as when standing. This is because the human body has considerable mass and inertia and compared to natural standing, the feet can exert less force on the ground, which easily leads to both slow movements and overshooting.

The difficulty of mapping the feet movements to the in-game movement was also a recurring challenge throughout the research process. Even if one has calibrated the parameters to allow natural and efficient movement, a new player might use different movement patterns and experience problems. Additionally, depending on the physical proportions and capabilities of particular player, the easiest way of moving in-game might vary drastically.

The control issues in the Chair mode were varying, depending yet again on the play style of the player. Running fast and jumping were intuitive enough for most of the testers to complete the waypoint track. However, most common problem was that the users had no fine control over their movement and could not move slowly. Turning around was unsurprisingly intuitive for users, as it involved physically turning around. However, the inertia caused by the mass of the chair made it slower and less accurate.

6.10 Simulator Sickness

Notably, there seemed to be no major differences between the tested playing modes (Chair and Supine) and the amount of simulator sickness they caused. three users reporting symptoms of nausea throughout the study. Two of these users had to stop the current playing mode being played due to the symptoms. Both of these were female. Despite our small sample size, it is
worth noting that prior literature reports women being more susceptible for simulator sickness symptoms [13, 25, 28, 41, 67]. The one male reporting symptoms did not prematurely stop playing.

6.11 Practical Applicability

We speculate that the most appeal from our approaches in everyday VR use could be achieved with the Chair mode, due to it requiring less intensive physical activity. However, we believe that the Supine mode could attract people who desire motivation for higher intensity exercise, or people looking for more interactive and enjoyable ways of continuing their already established exercising habits. Our locomotion approaches could also provide more options for exergame developers looking for ways to gamify a diverse set of exercises. As argued before, exergames are lacking diverse muscle exercises, thus implementing multiple playing poses in a single game could provide more full-fledged exergaming experience.

As our playing modes are physically demanding, perhaps excluding the Chair mode, games utilizing our approaches need to be well-paced, to keep them accessible. Whilst already physically active people might enjoy the challenge of the more high-intensity exercises, more novice players might be discouraged, were the games designed too difficult. We nevertheless believe that it is possible to introduce these exercises even to novice players if the game sessions are kept short enough and made progressively more challenging once player skills and fitness develop.

One user mentioned that the Chair mode is not very demanding to play, but then speculated that the mode could be used for rehabilitation (“Maybe it could be used for some kind of rehabilitation.”). While it is true that certain sorts of rehabilitation could benefit from a method of playing games while sitting, we can only speculate how viable this could be in our system. However, further exploration might be worthwhile, as there already exists a number of studies experimenting with VR applications as lower-limb rehabilitation methods, highlighted for example in a literature review by Ferreira et al. [23].

6.12 Limitations

We acknowledge our small sample size of 10 participants as a limitation. Similar sample sizes, however, are not uncommon in qualitative HCI studies [12]. Furthermore, it has been argued that 10 ± 2 participants are enough
for usability evaluation [36]—although our experiment is not a pure usability evaluation, we similarly set out to identify the key benefits and challenges of the tested systems. Even though we also collected quantitative data, we use it merely descriptively, without statistical analyses that would require a larger sample.

A further limitation of our study design is the lack of proper breaks between the playing modes. We did have short breaks between the conditions and we administered the SR and Borg questionnaires and asked the open-ended questions during these breaks. However, even though we used counterbalancing to mitigate carryover effects such as nausea from the first tested version cumulatively affecting the second, longer breaks with possibly more distracting tasks than the questionnaires and open-ended questions could have further decreased the effects.
Chapter 7

Conclusions

We have developed, described and evaluated a suite of novel non-standing VR locomotion methods. The methods are four different playing modes: Chair, Supine, Rings and Dip Rack. From these, the two most potential ones, Chair and Supine mode, were further tested by conducting a qualitative user study. Based on our own observations and the user feedback, we were able to identify a set of themes to highlight both successful aspects and shortcomings of our prototypes.

Based on the user feedback, when functioning optimally, the playing modes provide immersive, intuitive and empowering experiences. This was not always the case, but we believe that we received enough positive feedback to conclude that there lies potential in implementing these method to actual game experiences. Our methods showed promise in locomotion while navigating large and complex environments. However, we still think that the possible games utilizing our system should be developed particularly keeping in mind our system, to circumvent the shortcomings that emerged. For example, the lack of fine control could be mitigated by designing levels that do not require accurate navigation.

All the playing modes displayed potential in the exergaming domain. For Supine and Chair mode, these observations were further supported by the user study results. Especially the Supine mode offers exercise for the core muscles, while providing a versatile method for moving around in a virtual environments, allowing running, jumping and strafing, whilst leaving the user’s hands free for additional interaction. The Rings and Dip rack mode offer exercise potential as well, but they restrict hand movement, which leaves out many interaction methods, sometimes crucial to VR game design. As an additional benefit, the Supine mode prevents the user from accidentally moving around, letting the user to engage in the virtual environment with less risk of colliding with the real environment. This may further increase
immersion, as the user may play without being conscious of the surroundings of the real life playing area.

On the other hand, designing turning for the Supine mode had difficulties, but the hand gesture based method we implemented did not seem to cause major usability problems for the users. However, using regular pillow was sub-optimal, as it drastically limited users’ ability to look around. Moreover, two users reported experiencing simulator sickness during the Supine mode, although it would require larger sample size to comprehensively evaluate whether or not this is caused by individually differing susceptibilities. If issues with simulator sickness would turn out to be broader problem, the play mode could still be implemented using a ceiling mounted display, instead of head mounted one, and play the game essentially without full VR immersion.

For the Chair mode, some potential for exergaming emerged, but only to a lesser extent than for the Supine mode. The main benefit for the chair mode is arguably the more relaxed and immersive gaming experience. As the required physical exertion in the Chair mode is not as intense, the users may engage in longer sessions before exhausting themselves. This is further supported by the commercialization of the products like Cybershoes [18], as they seem to share the same level of physical intensity, based on the similarity of movements performed. Furthermore, the head movement in this mode is unrestricted, as opposed to the Supine setup, which allows the player to look around freely, similarly to common VR games.

The downsides of the Chair mode were mostly connected to set-up problems. The drifting of the chair caused some users to get close to the edges of the play area, which may cause collisions with real life objects. The inertia caused by the mass of the chair when turning restricted the responsiveness and precision of turns made by players. Additionally, the chair legs sometimes impeded the leg movement of the player. Many of these issues could be potentially fixed with a more specific chair, one without wheels and which stands more statically on the floor.
Chapter 8

Future Work

Our results echo earlier findings on the field of movement-based non-standing interaction, that is, the physical set-up may heavily influence the player experience [31]. Our goal was to make a prototype playable in a set-up with only commonplace household equipment. For the Supine mode, we hoped that a normal yoga mat and a pillow could offer viable enough setup for playing, but it turned out that a normal pillow limits the freedom of head movement substantially. This led of to theorize that it could have been beneficial to have a custom pillow, which supports the neck, but leaves space for the back of the headset to allow more flexible head movements. Respectively, our initial thought for the Chair mode was that a normal office chair would be sufficient for playing. However, during user testing, we realized that the wheels on the chair cause substantial drifting, at least when users adopts a certain play style. Furthermore, the chair legs sometimes collide with users’ legs, inhibiting freedom of movement. Finally, the mass and inertia of the chair makes turning around inaccurate. From these observations, we concluded that a steady-based swivel chair would be more optimal, similar to the ones used by Cybershoes users [18].

Regarding the problems around user movement recognition, we discussed various AI methods, such as pattern recognition, during the process of developing this prototype. They were left out of the scope of this thesis, due to time limitations and the main author’s lack of experience in the field. We hypothesized that a machine learning algorithm for interpreting the tracker input data could have offered more dynamic and adaptive system to recognize broader set of different play styles. Using a diverse data set containing different movement styles and body types could be a solution. There is a volume of existing papers and surveys on gait-recognition both with algorithms and AI [42, 72, 81]

Reflecting more on the topic of user input recognition and mapping,
we also hypothesize that non-standing movement might also successfully augment non-humanoid movement. Previously studied by Krekhov et al. [45, 46], there seems to be potential also in animal-embodiment within VR. The quadrupedal movement of an animal, for example a cat, might make it easier to naturally turn, while lying down on the ground. The anchoring method we used for our Supine mode could be replaced with more intuitive quadrupedal method of strafing with hands to a direction and with feet into the opposite direction.

Additionally, the prototype system could have been be more generalizable, in a manner that would allow any arbitrary play position and orientation, without any additional programming. It is possible to test new play poses in the current set-up, however, it requires additional tweaking and programming. In ideal scenario, the system provides a set of variables and an interface for configuring new play poses effortlessly. These features were not necessary for this thesis, as we aimed to test only two play modes more extensively and the additional modes could be validated even without perfectly calibrating the set-up.

As mentioned, in addition to the two main modes discussed in this thesis, we experimented with two additional modes: Rings and Dip Rack. These modes were interesting to experiment with, but lack of more extensive testing inhibits us from evaluating them more in detail. We can, however, conclude that they are rather intense physically, thus providing potential in the exergaming field. The preoccupation of hands in these modes remains as the largest issue. Had one developed games for these play modes, one would need to take into account the lack of hand control in the game design process.

For this prototype, we had only one game for testers. In future, it would be interesting to test out different genres of games to see in which types of games our system would be applicable. Also reinforced by the feedback from our user study, the applicability of our play modes would be heavily dependent on the type of game being played. Our prototype system enables continuous locomotion in large scale environments, which could open up new possibilities in bringing more open-world games in the VR gaming domain.
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