Kontio, Reetu; Laattala, Markus; Welsch, Robin; Hämäläinen, Perttu

"I Feel My Abs": Exploring Non-standing VR Locomotion

Published in:
Proceedings of the ACM on Human-Computer Interaction

DOI:
10.1145/3611069

Published: 04/10/2023

Document Version
Publisher's PDF, also known as Version of record

Please cite the original version:
Kontio, R., Laattala, M., Welsch, R., & Hämäläinen, P. (2023). "I Feel My Abs": Exploring Non-standing VR Locomotion. *Proceedings of the ACM on Human-Computer Interaction*, *7*(CHI PLAY), 1282–1307. Article 423. https://doi.org/10.1145/3611069

"I Feel My Abs": Exploring Non-standing VR Locomotion

REETU KONTIO, MARKUS LAATTALA, ROBIN WELSCH, and PERTTU HÄMÄLÄINEN, Aalto University, Finland

Fig. 1. Two variants of our non-standing locomotion method: Chair (left) and Supine (middle). On the right, the in-game screenshot shows the user's 1st person view of the virtual environment in our user study, with a sword in the user's hand. Additionally, we explored Dip Rack and Rings variants (Figure 3) which were not pursued further after an initial evaluation.

Virtual Reality (VR) games and experiences predominantly have the users interact while standing or seated. However, this only represents a fraction of the full diversity of human movement. In this paper, we explore a novel non-standing approach to VR locomotion where the user performs locomotion movements in the air or only slightly touching the ground with their feet. For instance, the user may lie supine on the ground, reminiscent of the Bicycle Crunch, a core training movement common in Pilates and other forms of bodyweight exercise. Although this cannot generally replace traditional VR locomotion, it provides two benefits that we believe can be of use for specific application domains such as VR exergames: First, the user's lower body movement is not impeded by a small real-life space, allowing versatile navigation of large virtual worlds using walking, running, strafing, and jumping. Second, we allow new ways to activate parts of the body that remain passive in most existing VR interactions. We describe and discuss four different variants of the approach, and investigate two prototypes further in a qualitative user study, to better understand their strengths, weaknesses, and application potential.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; **Interaction techniques**.

Additional Key Words and Phrases: virtual reality, VR, exergames, locomotion

ACM Reference Format:
Reetu Kontio, Markus Laattala, Robin Welsch, and Perttu Hämäläinen. 2023. "I Feel My Abs": Exploring Non-standing VR Locomotion. *Proc. ACM Hum.-Comput. Interact.* 7, CHI PLAY, Article 423 (November 2023), 26 pages. https://doi.org/10.1145/3611069

Authors' address: Reetu Kontio, reetu.kontio@aalto.fi; Markus Laattala, markus.laattala@aalto.fi; Robin Welsch, robin.welsch@aalto.fi; Perttu Hämäläinen, perttu.hamalainen@aalto.fi, Aalto University, Otakaari 1, Espoo, Finland, 02150.

2573-0142/2023/11-ART423
https://doi.org/10.1145/3611069

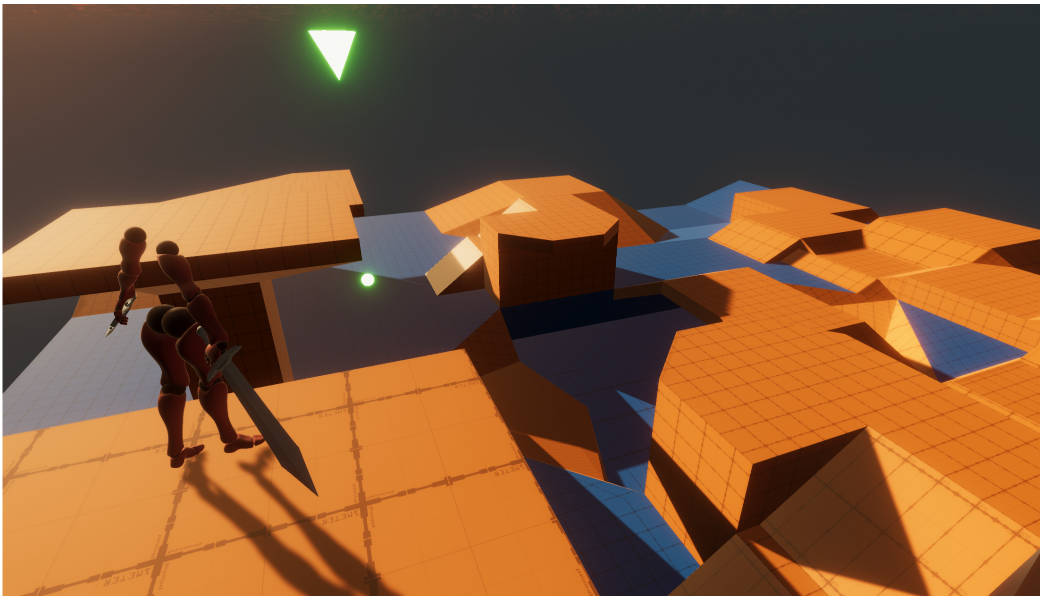

Fig. 2. The prototype game used in our user study. The player character (on the left) is on top of the highest platform in the level. The player character does not have a visual head or torso, to only display limbs in the player's 1st person view. The glowing green orb and the arrow above it denote a target waypoint.

1 INTRODUCTION

VR games and interactive experiences are increasingly popular. Trends show steady growth in the VR sector 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 with to address this problem, but they come with their own limitations and challenges. For instance, using *joystick-based steering* for continuous locomotion causes visuo-vestibular conflict that can be a source of simulator sickness [13, 14, 37]. On the other hand, *point and teleport*—a popular locomotion method in VR—is reported to inflict less simulator sickness [13, 14, 37], but may break user immersion [5, 6, 12]. Furthermore, an instantaneous change of position decreases 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 unsatisfactory from the point of view of scientific curiosity. Meanwhile, researchers have called for more work on non-standing movement in movement-based games [22] and outside VR, there have been explorations of combining technology with non-standing physical activities such as hanging [43], trampolining [24, 38], yoga [55], climbing on an Augmented Reality climbing wall [30], and trying to stay on a rodeo bull simulator

[40]. Specific to VR, Krekhov et al. have explored the possibilities of inhabiting non-human bodies, which can include non-conventional user movements and postures [33, 34].

In order to mitigate both the locomotion and movement diversity issues above, this paper describes an expansive Research through Design (RtD) exploration [35] of new forms of non-standing movement in VR. Our primary inspirations are the non-human embodiment experiments of Krekhov et al. [33, 34] and previous HCI systems that can provide both diverse and intensive physical activity [30, 38, 43]. Our focus is on settings where the user's body is supported by some other way than feet touching the ground, e.g., the user lying down supine on the floor as shown in Fig. 3. This is motivated by two key observations:

(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 [22]. 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".

We describe the design and formative evaluation of the four different variants of our approach illustrated in Fig. 3: lying supine on the ground, hanging from gymnastics rings, pushing down on a dip rack, and sitting on a saddle or swivel chair. Based on initial evaluation by the project team, the supine and swivel chair variants were deemed as the most promising ones to be evaluated in the user study we report in this paper. The user study results support the viability of non-standing playing poses and their potential for exergaming, but we also discuss the more critical feedback, highlighting general issues with calibration and specific issues related to both tested variants. We augment the user study with our own experiences and observations from the iterative design and prototyping process, leaning on the two primary authors' experience from 10+ years of active practicing of a variety of movement arts such as pilates, contemporary dance, parkour, and pole dancing. At the same time, we recognize that our own physical activity background and enthusiasm might make us less capable in designing for and empathizing with users with a wide range of movement skills and capabilities. Therefore, we do not consider an autobiographical design approach [45] or other 1st person HCI research methods [16] sufficient as such, without a user study.

Contribution: Our work makes an HCI artifact contribution [63], demonstrating and exploring a new possibility space for VR design, offering new 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 [63], 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) [26] and Borg CR10 [23] 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.

2 RELATED WORK

VR movement and locomotion techniques, in particular, are popular research topics with multiple existing in-depth surveys and comparisons [5–7, 12, 47]. Below, we focus on related approaches that go beyond the most common body postures and input devices.

2.1 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 found the lowest System Usability Scale (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 are Low-Latency, Continuous-Motion Walk-in-Place (LLCM-WIP) by Feasel et al. [17] and Gait-Understanding-Driven Walk-in-Place (GUD WIP) by Wendt et al. [61]. However, even these systems also introduce certain problems, such as lack of inertia [17] and latency [61].

One limitation of WiP solutions is the lack of directional control. For example, the LLCM by Feasel et al. suffers from this [17]. 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. [54].

The biggest advantage of our approach over WiP is that the locomotion movements can be more natural, whereas WiP requires a form of stomping to avoid drifting around in the physical space. Additionally, WiP is obviously more limited for exergame applications. Similar to the most advanced WiP methods, we also support strafing and backwards locomotion, as demonstrated in the supplemental video, 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.

2.2 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. Multiple different studies have implemented and evaluated different redirection techniques [2, 11, 36, 51, 53].

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 [11]. Razzaque et al. constructed a predetermined path for the player to utilize waypoints as redirecting locations [51]. 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 [53]. 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 might become more relevant.

The primary advantage of our approach over redirected walking is that our method requires less physical space.

2.3 Seated VR Locomotion

For the seated variant of our approach, the closest prior work relates to the Cybershoes by Cybershoes Inc. [15]. They utilise two slippery shoes that are strapped to the feet of the user. The shoes have cylindrical rollers attached to the bottom. Those rollers can be 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.

Cybershoes have one notable advantage over our approach. The rollers enable substantially more accurate and easier measurements of the speed and direction (forwards/backwards) when the feet make contact with the floor, compared to our motion-tracking -based system. However, the Cybershoes do not allow strafing, as they register only backwards/forwards movement. Our method allows foot movement in any direction, including sideways, to perform strafing. Furthermore, due to the lack of positional and rotational tracking in the Cybershoes, no inverse kinematic animations can be deployed to accurately represent the user's pose in the virtual environment.

Seated VR movement methods have also been previously studied by Kitson et al. [32]. 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 [32]. Our seated variant can be viewed as an extension of theirs focused on enabling more natural foot locomotion movements.

2.4 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 [56].

As a major inspiration for us, moving in VR while lying supine, prone, or crouching on the floor has also been explored by Krekhov et al. [33, 34]. However, their work focuses on non-human body ownership and they do not study movement mappings that allow navigating virtual spaces larger than the real space.

Luo et al. [39] 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 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.

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. [39] 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. [41, 42] 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.

2.5 Other Novel Approaches for VR Locomotion

Previous work has explored novel locomotion approaches ranging from walking by cycling [19], using one's body leaning on a chair or a board [46], various foot-based gestures [57], using a harness to suspend the body of the player [58], pressure pads in a seat [49], omnidirectional treadmills [29, 59, 60] and using VR under water [44, 52].

While displaying potential, many of these methods do not really resemble natural movement, such as the leaning or gesture-based methods. The suspended locomotion system by Walther-Franks et al. [58] 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 [30], rodeo-bull riding [40] and trampoline jumping [24]. 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. [43] inspired us to try our locomotion approach while hanging from gymnastic rings.

3 DESIGN

Our design process had two main stages:

(1) Expansion of the design space: Developing the technical movement tracking and mapping approach and exploring the four variants in Fig. 3. We first developed the supine one, inspired by performing the Bicycle Crunch move on a body-weight exercise class. We then realized that the same approach might generalize to other postures and body support methods. Throughout this exploration, we performed multiple iterations of prototyping and testing. As VR user studies are resource-consuming, this stage focused on internal testing by two of the authors (details in Section 4).
(2) Convergence: Two of the most promising variants were identified and investigated further in a user study (details in Section 5), in order to understand their pros and cons and application potential.

3.1 Design Goals

As elaborated earlier in the introduction, our work is motivated by two primary goals: 1) Increasing the diversity of movement in embodied interaction and 2) solving the key problem of VR locomotion, i.e., how to allow navigating and interacting with virtual spaces considerably larger than the physical space without resorting to techniques such as joystick-based movement or teleporting, which have limitations such as causing simulator sickness or hindering simultaneous locomotion and interaction. We primarily considered locomotion from the perspective of VR gaming, as non-VR

Fig. 3. All the four non-standing locomotion approaches we explored. All these share the design principle that one's weight is not supported by the legs. Thus, one can perform walking, running, strafing, and jumping movements in the air or only slightly touching the ground with their feet, without being limited by a small physical space.

games often utilize vast open environments. Empowering players to explore such worlds in a more natural way would offer VR game developers more freedom in their level design. An additional goal and motivation was to explore the exergaming potential of non-standing movement in VR.

3.2 Four Variants

The four variants we developed can be summarized as follows. In the rest of the paper, we will refer to them as Supine, Rings, Dip Rack, and Chair:

- 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 1 and detailed in the next section, 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 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.

	Walk	**Jump**	**Turn**
Chair	Imitate walking	Kick downwards (or stomp, depending on chair height)	Turn physically on swivel chair
Supine	Imitate walking	Kick downwards	Virtually "dragging" using hand controller
Rings	Imitate walking	Kick downwards (or stomp, depending on height of rings)	Turn physically
Dip Rack	Imitate walking	Kick downwards	Turn physically (limited range)

3.3 Movement Mechanics

The key technical and implementation challenge for our work is how to track and map the user's feet movements to the VR avatar's movement. We solve the problem by implementing a simplified virtual foot contact simulation, as detailed below.

3.3.1 Hardware and Software Environment. We use the HTC Vive Pro 2 VR headset with a wireless adapter, Vive hand trackers and 3 additional Vive 6-dof motion trackers for VR (version 3.0) attached to the player's feet and waist. The VR prototype was developed using the Unity 3D game engine.

3.3.2 Walking and Running. The basic principle is that we detect which foot tracker is the lower one in the user's local body coordinate system, i.e., the down-vector of the Supine mode points sideways in the global coordinate system, whereas it points down in the other variants. Figure 4 (left) displays these motions. At each game physics update, we query the tracker's current velocity, multiply it by -1 to reverse its direction, and apply the result as the velocity of the player character in-game, scaled by a speed scale multiplier, if the user is close to the ground, or has been close to the ground during the last 200ms (the so-called "coyote time" video game platforming mechanic). The scale multiplier was chosen based on testing done by the authors and fine-tuned to make navigating a test scene easy.

This movement mapping provides a simplified foot contact simulation where feet are "pulling" the user forwards or pushing them backwards. In a previous unpublished and failed project, we did try implementing the same simply using Unity's game physics. However, we found this highly problematic due to the lack of tactile feedback, which often makes the user think they are touching the ground while the physics doesn't detect a ground contact and lets the avatar's feet slip instead of pulling the avatar forward. Our simplified implementation including the coyote time mechanic is more forgiving in this respect.

3.3.3 Jumping. We determine that the player wants to jump if they move either of their feet downwards (in their local coordinate system) faster than a threshold value. Due to a supine pose having more space for accelerating the feet (that is, there is no physical ground blocking the foot), we ended up choosing a higher threshold for the Supine mode. If jumping is detected, the vertical velocity of the jumping leg is applied in-game with a jump boost multiplier. Otherwise, Unity's physics simulation is free to modify the vertical velocity based on physical contact and gravity.

Jumping in the seated pose may be described as "stomping the ground" with great enough velocity. In the Supine pose, the jumping is a similar move, but in this case, the "stomp" is not

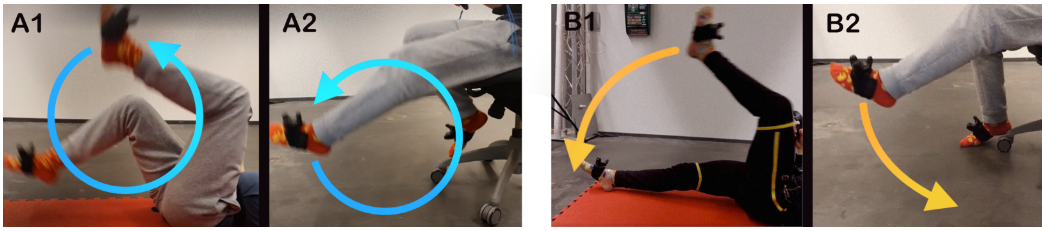

Fig. 4. Locomotion (left) and jumping movements (right) of the Supine (A1 and B1) and Chair (A2 and B2) modes. The images are from the tutorial videos that we used to communicate the intended movements in our user study. In this figure, arrows have been added to clarify the cyclic locomotion movements and the larger swings of the jumps.

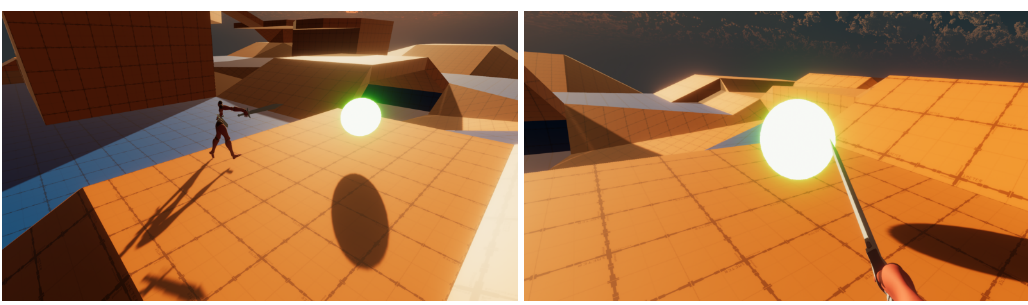

Fig. 5. Screenshot from a session where author played Supine mode, taken from a secondary third person camera (left) and the primary first person HMD viewport (right).

colliding with the physical ground. Rather, it resembles a single move of "scissors" abdominal exercise, moving the leg from high up towards the ground. Both jumping methods are shown in Figure 4 (right).

3.3.4 Turning Around. Turning around the vertical axis differs somewhat drastically between the four variants. In the Chair and Rings variants, the turning functions by mapping the swivel chair rotation one-to-one to the in-game character rotation. The rotation is measured using the tracker attached to the player’s waist.

In the Supine variant, turning around in the real world is very cumbersome. Instead, adopted a so-called "anchoring" -method, inspired by Freiwald et al. [19]. The basic principle of this method of turning is to use the hand controllers to "drag yourself" around. The player needs to "anchor" into an arbitrary position within the world by using the triggers on the hand controllers. Once anchored, the player can move their hand to rotate themselves around, by moving the hand that is anchored. The player rotates around the up-vector of their center of mass in-game. The rotation angle is determined by the distance between the initial anchoring position and the current position of the anchored hand.

For the Dip Rack variant, we have not yet devised a plausible rotation control approach, as it prevents both body rotation and hand gestures. Minor steering of the movement is possible but physically demanding.

4 INITIAL EVALUATION

Throughout the iterative design and development, we tested and evaluated prototypes internally by two authors, using early variants of the locomotion test environment utilized in the later user study (see Fig. 6). Initially, the environment was only an empty plane, but more complex geometry was gradually added as the movement mechanics evolved. Closer to the user study, three non-author pilot users were also involved in the testing, recruited from the same research group. One of them tested two different iterations of the prototype.

The internal testing of the four developed variants revealed clear variant-specific benefits and challenges that we summarize in Table 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.
- 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 2 are subjective evaluations by the authors; the Borg CR10 scale was only employed in the user study of Section 5.

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 5, we switched to a regular office chair for safety reasons, as it was the case that 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. [19], as it was in our opinion the most applicable for a 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 many revolutions in the same direction, the ropes connecting the rings to the ceiling would get tangled up. This caused the user to involuntarily start spinning the opposite way if they lifted 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 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.

	Leg freedom of movement	**Hand freedom of movement**	**Turning range**	**Exercise intensity**
Chair	Moderate	Full	360°	Minor
Supine	Almost full	Almost full	360° (hand gesture)	Moderate
Rings	Full	None	360°	Demanding
Dip Rack	Almost full	None	~90°	Demanding

5 USER STUDY

We conducted a user study to provide richer and more reliable insights about Supine and Chair, the two variants we deemed most promising based on the initial evaluation.

Supine and Chair were selected for the user study primarily because they place fewer restrictions on arm movement, increasing their application potential. Rings and Dip Rack lock the user’s arms in place, and Dip Rack also prevents one from turning around. Furthermore, using them is arguably substantially more physically demanding, increasing the risk of not finding enough suitable user study participants, or the study becoming too long and exhausting. This means we would either have to use a different test task for these approaches, making any comparisons less controlled, or we would have to artificially limit the range of movements and interactions available with the Supine and Chair variants.

5.1 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 and the tested variants in particular?
- Experience: How does non-standing VR locomotion feel? What is the experience like?

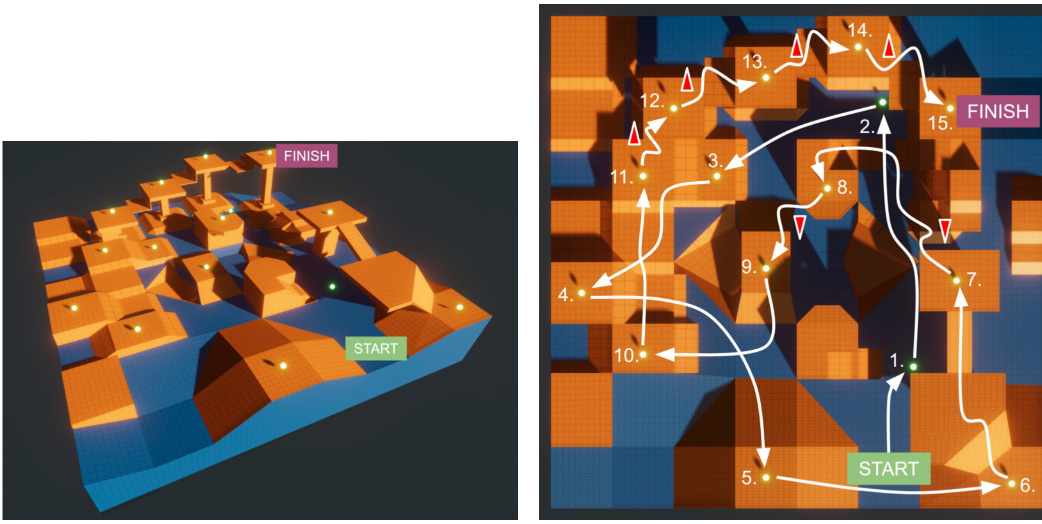

Fig. 6. A perspective view (left) and a top-down view (right) of the level. All of the waypoints are shown here, but for the testers, only one waypoint was shown at a time. Red triangles show a point on the route where the user is expected to fall down (downward triangle) or jump up (upward triangle). Despite this, users were free to find their own routes and jump as much as they preferred.

5.2 Study Design

We used a within-subjects study design with two experimental conditions: Chair and Supine. The participants perform the same locomotion task in both conditions. Learning effects were mitigated by counterbalancing the condition order.

We mainly focus on qualitative analysis of think-aloud and open-ended interview data while also collecting self-report data about exercise intensity and simulator sickness. We did not have strong a priori hypotheses about differences between conditions, except that the Supine mode was clearly the more physically intensive one in our initial testing.

5.3 Locomotion Task Design

The locomotion task used the VR scene of in Fig. 6, with a track consisting of consecutive waypoints that the user attempts to reach using forward locomotion, turning, and jumping. The desired locomotion movements were instructed as illustrated in Fig. 4, using short video clips of how moving, jumping, and turning can be performed. The waypoints were placed so that the difficulty of reaching them increases throughout the track. The first waypoints require the user to move forward in a straight line on a flat surface, then gradually introducing more turning, ramps and elevation, narrower paths and ultimately high platforms only reachable by jumping.

The users were instructed to try to reach as many waypoints as possible within a five-minute time limit. The time limit was used to ensure short enough total user study time and to minimize possible build-up of simulator sickness that might force a participant to interrupt the experiment. However, after we collected the data, we noticed that the time limit was not enforced by the system. Therefore, in practice, users could use more than five minutes. The participants were told that it is not necessary to reach all of the waypoints, or play through the whole five minutes if they feel too exhausted or uncomfortable. They were encouraged to experiment with different ways of moving and find out what works best for them. They were informed about the time limit, but they did not see a timer in-game.

The same scene and task were used in both experimental conditions. Although this may allow the user to remember the waypoint locations in the second condition, we made this design choice for a number of reasons. First, we did our best to design the waypoints and the scene so that the participants have no difficulty understanding what to do, and the main challenge would be about executing the desired movements with the two different movement mappings. Second, completing the same task twice should allow the user better reflect on the differences of the locomotion approaches, as there is no risk of having the difference in the waypoint layout change the difficulty of the task. Finally, the counterbalancing should mitigate learning effects in any statistical analyses.

5.4 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 ten 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 user played non-VR games occasionally, three roughly once a week, four multiple times per week and two almost every day. Half of our participants (five) 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 reported 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 said 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.

5.5 Data Collection

Before testing either of 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. The form also asked for the participants' informed consent. The users were further informed that they are free to stop the experiment at any point if they are feeling too much nausea or discomfort.

During the experiment, we collected the following qualitative and quantitative self-report data. The open-ended questions we used were determined based on the research questions of Section 5.1 by two of the authors:

- Before 1st experimental condition: Sickness Rating (SR) [26] and a version of Borg CR10 perceived exertion scale [9, 23]. The Borg CR10 is described in Table 3. 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 conditions: Concurrent think 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 condition: SR, Borg CR10, and open-ended questions: "How would you describe the playing mode? Was it 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?".
- Final questions: "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?"

Table 3. The Borg CR10 scale [9]

Score	**Exhaustion level**
0	Nothing at all
0.5	Very, very slight (just noticeable)
1	Very slight
2	Slight
3	Moderate
4	Somewhat severe
5	Severe
6	
7	Very severe
8	
9	Very, very severe (almost maximal)
10	Maximal

We captured video of the virtual world together with the user's voice recordings. The voice recordings were transcribed and the video was analyzed if the transcripts need further context.

Additionally, the user study facilitator also took notes about observations such as different movement styles. We also collected a range of movement and task performance data during gameplay. This included player position and velocity vectors (x,y,z) and rotation quaternions (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 was stored anonymously. The video recordings were converted to separate voice and video, and the voice was deleted after transcribing. Participants were only identified with numeric IDs, with no record kept that allows mapping an ID to a name. Video was only recorded of the anonymous virtual world and avatar, and no video was captured in the real world.

5.6 Methods

Qualitative Analyses. We analyzed the recorded and transcribed think-aloud data and open-ended question answers using qualitative thematic analysis. We followed the general thematic analysis progression of familiarizing oneself with the data, coding the data, collating codes into themes, reviewing and refining the themes, and reporting the results using illustrative quotes [8]. We implemented this process in a way that allowed two authors to work in parallel during the initial coding stages: One author facilitated the user study and data collection, observing and interviewing the participants and taking notes, while another author transcribed and coded the already collected data. After this, the authors reviewed and refined the codes and themes together, combining the close and personal perspective of the facilitator who had interacted with the participants first-hand, and the more detached perspective of the author who had only worked on the data. As our coding was open/inductive, we did not calculate any inter-rater agreement measures of multiple independent coders.

Quantitative Analyses. As our sample size is not large enough for identifying statistically significant differences between the experimental conditions, we do not perform any statistical significance testing and instead only describe the quantitative questionnaire data using means, medians, and standard deviations. Although this does not allow concluding, e.g., that condition A causes less simulator sickness than B, the results can still prompt hypotheses and research questions for future work.

6 RESULTS

Qualitative Data. Table 4 shows the most frequent codes. Here, we group the codes into the two high-level themes of positive and negative participant experiences, motivated by our research goal of understanding the benefits and challenges of our non-standing locomotion approach. In total, the coding resulted in 174 codes. We also performed an alternative grouping into more fine-grained themes such as player adaptation, control, exercise, and safety, which is how we structure the discussion of the results in the next section.

Table 4. 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.

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

Quantitative Data. Out of all users, seven 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 provides the full SR and Borg CR10 data of all participants.

Table 5. 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.

Before testing		**After testing mode 1**		**After testing mode 2**		**After final questions**	
SR	**Borg**	**SR**	**Borg**	**SR**	**Borg**	**SR**	**Borg**
		Chair		**Supine**			
None	0	None	3	None	4	None	0.5
None	0	Mild *	3	Mild *	3	Mild	0
None	0	None	2	None	1	-	-
None	0	None	0	None	1	None	0
None	0	None	1	None	3	None	1
		Supine		**Chair**			
Any	0	None	2	None	2	None	1
None	0	None	3	None	2	None	0.5
None	0	None	2	None	0.5	None	0
None	0	Mild	3	None ‡	6	None	0
Any	0	Any †	0.5	Moderate *	0.5	Mild	0

* 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.

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 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 checkpoint, 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 edges and tried 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.

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).

7 DISCUSSION

Below, we discuss a selection of the most prevalent themes, the differences in movement style between the participants, and the practical applicability of our approach.

7.1 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 [56]. One key takeaway from this is that in the future, special attention should be given for dynamic calibration for player movement patterns. While interpreting our current 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.

7.2 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 being lying down anymore. The concurrent work by van Gemert et al. does report similar user experiences [56] and is also in line with Luo et al. [39]. 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 [25].

7.3 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."*). nine out of ten users mentioned the Supine mode feeling like an exercise, and six out of ten mentioned the same about the Chair mode. The feedback from Supine mode aligns with the concurrent work by van Gemert et al. [56] 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 "experiental 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". [48] 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 [22]. This is echoed by Khundam et al. who argue that more varying playing poses can decrease boredom and reduce risk of injuries [31]. 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 [50]. This was also confirmed by Whitehead et al. [62]. 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 exercise for the core and upper body.

7.4 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 laying 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."*, "[-] *and the potential of learning how to jump very high, very fast, because you can just kick your foot as hard as you want."*). 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 back. 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.

7.5 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 6 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 [28]. 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 [20]. 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 [28]. 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) [21].

7.6 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."*).

7.7 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 sub-optimal, 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, 3 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 [15]. 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. [32].

7.8 Supine Mode Problems

For the Supine setup, one clear obstacle was the head pillow interfering with the VR headset. 8 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 in bed [56].

7.9 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 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.

7.10 Practical Applicability

We theorize 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 approach could also provide more options for exergame developers looking for ways to gamify a diverse set of exercises.

As our playing modes are physically challenging, excluding the Chair mode, games utilizing our approach 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 rehibitation."*). 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. [18].

8 LIMITATIONS

We acknowledge our small sample size of 10 participants as a limitation. Similar sample sizes, however, are not uncommon in qualitative HCI studies [10]. Furthermore, it has been argued that 10 ± 2 participants are enough for usability evaluation [27]—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.

9 CONCLUSION

We have described the design and evaluation of a novel non-standing VR locomotion approach, exemplified by four variants: Supine, Chair, Rings, and Dip Rack. Based on both our own observations and user feedback, non-standing locomotion does provide at least two key opportunities for VR. First, as the one's leg movements are not impeded by a small real-life space, one can perform diverse locomotion movements, such as walking, running, strafing and jumping, in large virtual environments. Second, especially in the Supine mode, one is able to perform movements that activate body parts that usually remain less active in the majority of VR interaction. This suggests potential for novel forms of exergaming. Although the Rings and Dip Rack variants also have obvious exercise potential, they pose heavier limitations for the user's hand movements. A further benefit of the Supine variant is that it prevents the user from accidentally moving around and colliding with objects in the physical spaces. On the other hand, the Supine mode does require using a hand gesture for turning around the vertical axis.

On the negative side, two of our users did report simulator sickness. Although the latter may be due to individual differences in susceptibility to simulator sickness, it calls for a more extensive evaluation that compares our approach to other locomotion techniques. If simulator sickness turns out to be a problem, the Supine variant could also be implemented using a ceiling-mounted screen and motion-tracking camera, instead of VR. As a further shortcoming, our work echoes earlier findings that in non-standing movement-based interaction, the design of the physical setting can have a large impact on the experience and movement [22]. We focused on the digital design and tried to increase the adoption potential of our approach by utilizing off-the-shelf physical props such as a regular pillow and an office chair, but user feedback indicates that this was not the best design decision. The pillow design should be optimized to allow unencumbered head movement in the Supine variant, and the Chair variant's chair should be designed so that it allows effortless turning but does not drift in the space, does not feature protrusions that limit feet movement, and offers enough support to prevent the user from falling. A regular swivel chair with wheels only satisfies the last of these requirements.

Perfecting the real-to-virtual movement mapping for each user also remains a challenge, as participant playstyles differed and our mapping did not work equally well for all participants. We hypothesize that instead of a rule-based system like our current approach, the best option may be a machine learning-based system that is trained on many different movement styles and body types. We also hypothesize that future work might implement supine turning both naturally and efficiently if inhabiting a quadrupedal instead of a bipedal virtual body, e.g., the tiger avatar of Krekhov et al. [33]. In this case, the turning would emerge from strafing in one direction with hands and the other direction with feet.

ACKNOWLEDGMENTS

This work has been supported by the European Commission through the Horizon 2020 FET Proactive program (grant agreement 101017779). Special thanks go to Adas Slezas for providing an IK-animation rig implementation for our prototype.

REFERENCES

[1] Alsop, Thomas. 2022. Virtual reality (VR) - statistics & facts. https://www.statista.com/topics/2532/virtual-reality-vr/. Accessed: 05.04.2023.

[2] Mahdi Azmandian, Timofey Grechkin, Mark Bolas, and Evan Suma. 2016. The redirected walking toolkit: a unified development platform for exploring large virtual environments. In *2016 IEEE 2nd Workshop on Everyday Virtual Reality (WEVR)*. 9–14. https://doi.org/10.1109/WEVR.2016.7859537

[3] Nadia Bianchi-Berthouze, Whan Woong Kim, and Darshak Patel. 2007. Does Body Movement Engage You More in Digital Game Play? and Why?. In *Affective Computing and Intelligent Interaction*, Ana C. R. Paiva, Rui Prada, and Rosalind W. Picard (Eds.). Springer Berlin Heidelberg, Berlin, Heidelberg, 102–113.

[4] Costas Boletsis. 2017. The New Era of Virtual Reality Locomotion: A Systematic Literature Review of Techniques and a Proposed Typology. *Multimodal Technologies and Interaction* 1 (09 2017), 24. https://doi.org/10.3390/mti1040024

[5] Costas Boletsis and Jarl Cedergren. 2019. VR Locomotion in the New Era of Virtual Reality: An Empirical Comparison of Prevalent Techniques. *Advances in Human-Computer Interaction* 2019 (04 2019), 1–15. https://doi.org/10.1155/2019/7420781

[6] Costas Boletsis and Dimitra Chasanidou. 2022. A Typology of Virtual Reality Locomotion Techniques. *Multimodal Technologies and Interaction* 6, 9 (2022), 72. https://doi.org/10.3390/mti6090072

[7] D.A. Bowman, D. Koller, and L.F. Hodges. 1997. Travel in immersive virtual environments: an evaluation of viewpoint motion control techniques. In *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality*. 45–52. https://doi.org/10.1109/VRAIS.1997.583043

[8] Virginia Braun and Victoria Clarke. 2006. Using thematic analysis in psychology. *Qualitative Research in Psychology* 3 (01 2006), 77–101. https://doi.org/10.1191/1478088706qp063oa

[9] Jonathan Burdon, E Juniper, Kieran Killian, F Hargreave, and E Campbell. 1982. The Perception of Breathlessness in Asthma. *The American review of respiratory disease* 126 (12 1982), 825–8. https://doi.org/10.1164/arrd.1982.126.5.825

[10] Kelly Caine. 2016. Local Standards for Sample Size at CHI. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI ’16)*. Association for Computing Machinery, New York, NY, USA, 981–992. https://doi.org/10.1145/2858036.2858498

[11] Haiwei Chen and Henry Fuchs. 2017. Towards Imperceptible Redirected Walking: Integrating a Distractor into the Immersive Experience. In *Proceedings of the 21st ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games* (San Francisco, California) *(I3D ’17)*. Association for Computing Machinery, New York, NY, USA, Article 22, 2 pages. https://doi.org/10.1145/3023368.3036844

[12] Heni Cherni, Natacha Métayer, and Nicolas Souliman. 2020. Literature review of locomotion techniques in virtual reality. *International Journal of Virtual Reality* 20 (03 2020), 1–20. https://doi.org/10.20870/IJVR.2020.20.1.3183

[13] Chris Christou and Poppy Aristidou. 2017. Steering Versus Teleport Locomotion for Head Mounted Displays. https://doi.org/10.1007/978-3-319-60928-7_37

[14] Noah Coomer, Sadler Bullard, William Clinton, and Betsy Williams-Sanders. 2018. Evaluating the Effects of Four VR Locomotion Methods: Joystick, Arm-Cycling, Point-Tugging, and Teleporting. In *Proceedings of the 15th ACM Symposium on Applied Perception* (Vancouver, British Columbia, Canada) *(SAP ’18)*. Association for Computing Machinery, New York, NY, USA, Article 7, 8 pages. https://doi.org/10.1145/3225153.3225175

[15] Cybershoes, Inc. 2020. Cybershoes. https://www.cybershoes.com/. Accessed: 10.10.2022.

[16] Audrey Desjardins, Oscar Tomico, Andrés Lucero, Marta E. Cecchinato, and Carman Neustaedter. 2021. Introduction to the Special Issue on First-Person Methods in HCI. , 12 pages. https://doi.org/10.1145/3492342

[17] Jeff Feasel, Mary C. Whitton, and Jeremy D. Wendt. 2008. LLCM-WIP: Low-Latency, Continuous-Motion Walking-in-Place. In *2008 IEEE Symposium on 3D User Interfaces*. 97–104. https://doi.org/10.1109/3DUI.2008.4476598

[18] Luara Ferreira dos Santos, Oliver Christ, Kedar Mate, Henning Schmidt, Jörg Krüger, and Christian Dohle. 2016. Movement visualisation in virtual reality rehabilitation of the lower limb: a systematic review. *Biomedical engineering online* 15, 3 (2016), 75–88. https://doi.org/10.1186/s12938-016-0289-4

[19] Jann Philipp Freiwald, Oscar Ariza, Omar Janeh, and Frank Steinicke. 2020. Walking by Cycling: A Novel In-Place Locomotion User Interface for Seated Virtual Reality Experiences. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI ’20)*. Association for Computing Machinery, New York, NY, USA, 1–12. https://doi.org/10.1145/3313831.3376574

[20] Antti Granqvist, Tapio Takala, Jari Takatalo, and Perttu Hämäläinen. 2018. Exaggeration of Avatar Flexibility in Virtual Reality. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play* (Melbourne, VIC, Australia) *(CHI PLAY ’18)*. Association for Computing Machinery, New York, NY, USA, 201–209. https://doi.org/10.1145/3242671.3242694

[21] Perttu Hämäläinen, Tommi Ilmonen, Johanna Höysniemi, Mikko Lindholm, and Ari Nykänen. 2005. Martial Arts in Artificial Reality. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Portland, Oregon, USA) *(CHI ’05)*. Association for Computing Machinery, New York, NY, USA, 781–790. https://doi.org/10.1145/1054972.1055081

[22] Perttu Hämäläinen, Joe Marshall, Raine Kajastila, Richard Byrne, and Florian "Floyd" Mueller. 2015. Utilizing Gravity in Movement-Based Games and Play. In *Proceedings of the 2015 Annual Symposium on Computer-Human Interaction in*

Play (London, United Kingdom) *(CHI PLAY '15)*. Association for Computing Machinery, New York, NY, USA, 67–77. https://doi.org/10.1145/2793107.2793110

[23] Asha Hareendran, Nancy Leidy, Brigitta Monz, Randall Winnette, Karin Becker, and Donald Mahler. 2012. Proposing a standardized method for evaluating patient report of the intensity of dyspnea during exercise testing in COPD. *International journal of chronic obstructive pulmonary disease* 7 (05 2012), 345–55. https://doi.org/10.2147/COPD.S29571

[24] Leo Holsti, Tuukka Takala, Aki Martikainen, Raine Kajastila, and Perttu Hämäläinen. 2013. Body-Controlled Trampoline Training Games Based on Computer Vision. In *CHI '13 Extended Abstracts on Human Factors in Computing Systems* (Paris, France) *(CHI EA '13)*. Association for Computing Machinery, New York, NY, USA, 1143–1148. https://doi.org/10.1145/2468356.2468560

[25] Matthias Hoppe, Andrea Baumann, Patrick Chofor Tamunjoh, Tonja-Katrin Machulla, Paweł W. Woźniak, Albrecht Schmidt, and Robin Welsch. 2022. There Is No First- or Third-Person View in Virtual Reality: Understanding the Perspective Continuum. In *Proceedings of the 2022 CHI Conference on Human Factors in Computing Systems* (New Orleans, LA, USA) *(CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 360, 13 pages. https://doi.org/10.1145/3491102.3517447

[26] P.A Howarth and M Finch. 1999. The nauseogenicity of two methods of navigating within a virtual environment. *Applied Ergonomics* 30, 1 (1999), 39–45. https://doi.org/10.1016/S0003-6870(98)00041-6

[27] Wonil Hwang and Gavriel Salvendy. 2010. Number of People Required for Usability Evaluation: The 10±2 Rule. *Commun. ACM* 53, 5 (may 2010), 130–133. https://doi.org/10.1145/1735223.1735255

[28] Christos Ioannou, Patrick Archard, Eamonn O'Neill, and Christof Lutteroth. 2019. Virtual Performance Augmentation in an Immersive Jump & Run Exergame. *CHI '19: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, 1–15. https://doi.org/10.1145/3290605.3300388

[29] Katarzyna Jochymczyk-Woźniak, Katarzyna Nowakowska-Lipiec, Jacek Polechoński, Sandra Sładczyk, and Robert Michnik. 2019. Physiological Gait versus Gait in VR on Multidirectional Treadmill-Comparative Analysis. *Medicina (Kaunas, Lithuania)* 55 (08 2019), 517. https://doi.org/10.3390/medicina55090517

[30] Raine Kajastila, Leo Holsti, and Perttu Hämäläinen. 2016. The Augmented Climbing Wall: High-Exertion Proximity Interaction on a Wall-Sized Interactive Surface. 758–769. https://doi.org/10.1145/2858036.2858450

[31] Chaowanan Khundam and Frédéric Nöel. 2021. A study of physical fitness and enjoyment on virtual running for exergames. *International Journal of Computer Games Technology* 2021 (2021), 1–16. https://doi.org/10.1155/2021/6668280

[32] Alexandra Kitson, Abraham Hashemian, Ekaterina Stepanova, Ernst Kruijff, and Bernhard Riecke. 2017. Comparing leaning-based motion cueing interfaces for virtual reality locomotion. 73–82. https://doi.org/10.1109/3DUI.2017.7893320

[33] Andrey Krekhov, Sebastian Cmentowski, and Jens Krüger. 2018. VR Animals: Surreal Body Ownership in Virtual Reality Games. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play Companion Extended Abstracts* (Melbourne, VIC, Australia) *(CHI PLAY '18 Extended Abstracts)*. Association for Computing Machinery, New York, NY, USA, 503–511. https://doi.org/10.1145/3270316.3271531

[34] Andrey Krekhov, Sebastian Cmentowski, and Jens Krüger. 2019. The Illusion of Animal Body Ownership and Its Potential for Virtual Reality Games. In *2019 IEEE Conference on Games (CoG)*. 1–8. https://doi.org/10.1109/CIG.2019.8848005

[35] Peter Gall Krogh, Thomas Markussen, and Anne Louise Bang. 2015. Ways of Drifting—Five Methods of Experimentation in Research Through Design. In *ICoRD'15 – Research into Design Across Boundaries Volume 1*, Amaresh Chakrabarti (Ed.). Springer India, New Delhi, 39–50. https://doi.org/10.1007/978-81-322-2232-3

[36] Eike Langbehn, Paul Lubos, Gerd Bruder, and Frank Steinicke. 2017. Application of redirected walking in room-scale VR. In *2017 IEEE Virtual Reality (VR)*. 449–450. https://doi.org/10.1109/VR.2017.7892373

[37] Eike Langbehn, Paul Lubos, and Frank Steinicke. 2018. Evaluation of Locomotion Techniques for Room-Scale VR: Joystick, Teleportation, and Redirected Walking. https://doi.org/10.1145/3234253.3234291

[38] Lauri Lehtonen, Maximus D. Kaos, Raine Kajastila, Leo Holsti, Janne Karsisto, Sami Pekkola, Joni Vähämäki, Lassi Vapaakallio, and Perttu Hämäläinen. 2019. Movement Empowerment in a Multiplayer Mixed-Reality Trampoline Game. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play* (Barcelona, Spain) *(CHI PLAY '19)*. Association for Computing Machinery, New York, NY, USA, 19–29. https://doi.org/10.1145/3311350.3347181

[39] Tianren Luo, Zhenxuan He, Chenyang Cai, Teng Han, Zhigeng Pan, and Feng Tian. 2022. Exploring Sensory Conflict Effect Due to Upright Redirection While Using VR in Reclining & Lying Positions. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology* (Bend, OR, USA) *(UIST '22)*. Association for Computing Machinery, New York, NY, USA, Article 79, 13 pages. https://doi.org/10.1145/3526113.3545692

[40] Joe Marshall, Duncan Rowland, Stefan Rennick Egglestone, Steve Benford, Brendan Walker, and Derek McAuley. 2011. Breath Control of Amusement Rides. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Vancouver, BC, Canada) *(CHI '11)*. Association for Computing Machinery, New York, NY, USA, 73–82. https://doi.org/10.1145/1978942.1978955

[41] Maria F. Montoya, Yuyang Ji, Sarah Jane Pell, and Florian 'Floyd' Mueller. 2023. Demonstrating Fluito: A Playful Floatation Tank Experience. In *Extended Abstracts of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI EA '23)*. Association for Computing Machinery, New York, NY, USA, Article 433, 4 pages. https://doi.org/10.1145/3544549.3583908

[42] Maria F. Montoya, Rakesh Patibanda, Christal Clashing, Sarah Jane Pell, and Florian 'Floyd' Mueller. 2022. Towards an Initial Understanding of the Design of Playful Water Experiences Through Flotation. In *Extended Abstracts of the 2022 Annual Symposium on Computer-Human Interaction in Play* (Bremen, Germany) *(CHI PLAY '22)*. Association for Computing Machinery, New York, NY, USA, 120–126. https://doi.org/10.1145/3505270.3558324

[43] Florian Mueller, Cagdas Toprak, Eberhard Graether, Wouter Walmink, Bert Bongers, and Elise van den Hoven. 2012. Hanging off a Bar. In *CHI '12 Extended Abstracts on Human Factors in Computing Systems* (Austin, Texas, USA) *(CHI EA '12)*. Association for Computing Machinery, New York, NY, USA, 1055–1058. https://doi.org/10.1145/2212776.2212384

[44] Kazuma Nagata, Denik Hatsushika, and Yuki Hashimoto. 2017. Virtual Scuba Diving System Utilizing the Sense of Weightlessness Underwater. In *Entertainment Computing – ICEC 2017*, Nagisa Munekata, Itsuki Kunita, and Junichi Hoshino (Eds.). Springer International Publishing, Cham, 205–210.

[45] Carman Neustaedter and Phoebe Sengers. 2012. Autobiographical Design in HCI Research: Designing and Learning through Use-It-Yourself. In *Proceedings of the Designing Interactive Systems Conference* (Newcastle Upon Tyne, United Kingdom) *(DIS '12)*. Association for Computing Machinery, New York, NY, USA, 514–523. https://doi.org/10.1145/2317956.2318034

[46] Thinh Nguyen-Vo, Bernhard Riecke, Wolfgang Stuerzlinger, Duc Minh Pham, and Ernst Kruijff. 2019. NaviBoard and NaviChair: Limited Translation Combined with Full Rotation for Efficient Virtual Locomotion. *IEEE Transactions on Visualization and Computer Graphics* PP (08 2019), 1–1. https://doi.org/10.1109/TVCG.2019.2935730

[47] Niels Christian Nilsson, Tabitha Peck, Gerd Bruder, Eri Hodgson, Stefania Serafin, Mary Whitton, Frank Steinicke, and Evan Suma Rosenberg. 2018. 15 Years of Research on Redirected Walking in Immersive Virtual Environments. *IEEE Computer Graphics and Applications* 38, 2 (2018), 44–56. https://doi.org/10.1109/MCG.2018.111125628

[48] Yoonsin Oh and Stephen Yang. 2010. Defining exergames & exergaming. *Proceedings of meaningful play* 2010 (2010), 21–23.

[49] Toshikazu Ohshima, Hiroki Ishihara, and Ryuki Shibata. 2016. Virtual ISU: Locomotion Interface for Immersive VR Gaming in Seated Position. In *Proceedings of the 2016 Virtual Reality International Conference* (Laval, France) *(VRIC '16)*. Association for Computing Machinery, New York, NY, USA, Article 2, 4 pages. https://doi.org/10.1145/2927929.2927941

[50] Wei Peng, Jih-Hsuan Tammy Lin, and Julia Crouse Waddell. 2011. Is Playing Exergames Really Exercising? A Meta-Analysis of Energy Expenditure in Active Video Games. *Cyberpsychology, behavior and social networking* 14 (06 2011), 681–8. https://doi.org/10.1089/cyber.2010.0578

[51] Sharif Razzaque, Zachariah Kohn, and Mary C. Whitton. 2001. Redirected Walking. In *Eurographics 2001 - Short Presentations*. Eurographics Association. https://doi.org/10.2312/egs.20011036

[52] Christian Sinnott, James Liu, Courtney Matera, Savannah Halow, Ann Jones, Matthew Moroz, Jeffrey Mulligan, Michael Crognale, Eelke Folmer, and Paul MacNeilage. 2019. Underwater Virtual Reality System for Neutral Buoyancy Training: Development and Evaluation. In *Proceedings of the 25th ACM Symposium on Virtual Reality Software and Technology* (Parramatta, NSW, Australia) *(VRST '19)*. Association for Computing Machinery, New York, NY, USA, Article 29, 9 pages. https://doi.org/10.1145/3359996.3364272

[53] Frank Steinicke, Gerd Bruder, Timo Ropinski, and Klaus Hinrichs. 2008. Moving Towards Generally Applicable Redirected Walking. *Proceedings of IEEE VRIC 2008 : 10th International Conference on Virtual Reality* (01 2008).

[54] James Templeman, Patricia Denbrook, and Linda Sibert. 1999. Virtual Locomotion: Walking in Place through Virtual Environments. *Presence* 8 (12 1999), 598–617. https://doi.org/10.1162/105474699566512

[55] Laia Turmo Vidal, Elena Márquez Segura, Luis Parrilla Bel, and Annika Waern. 2020. Training Technology Probes Across Fitness Practices: Yoga, Circus and Weightlifting. In *Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI EA '20)*. Association for Computing Machinery, New York, NY, USA, 1–8. https://doi.org/10.1145/3334480.3382862

[56] Thomas van Gemert, Kasper Hornbæk, Jarrod Knibbe, and Joanna Bergström. 2023. Towards a Bedder Future: A Study of Using Virtual Reality While Lying Down. In *Proceedings of the 2023 CHI Conference on Human Factors in Computing Systems* (Hamburg, Germany) *(CHI '23)*. Association for Computing Machinery, New York, NY, USA, Article 877, 18 pages. https://doi.org/10.1145/3544548.3580963

[57] Julius von Willich, Martin Schmitz, Florian Müller, Daniel Schmitt, and Max Mühlhäuser. 2020. Podoportation: Foot-Based Locomotion in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems* (Honolulu, HI, USA) *(CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3313831.3376626

[58] Benjamin Walther-Franks, Dirk Wenig, Jan Smeddinck, and Rainer Malaka. 2013. Suspended Walking: A Physical Locomotion Interface for Virtual Reality. 185–188. https://doi.org/10.1007/978-3-642-41106-9_27

[59] Ziyao Wang, Chiyi Liu, Jialiang Chen, Yao Yao, Dazheng Fang, Zhiyi Shi, Rui Yan, Yiye Wang, KanJian Zhang, Hai Wang, and Haikun Wei. 2022. Strolling in Room-Scale VR: Hex-Core-MK1 Omnidirectional Treadmill. https://doi.org/10.48550/ARXIV.2204.08437

[60] Lars-Ole Wehden, Felix Reer, Robin Janzik, Wai Yen Tang, and Thorsten Quandt. 2021. The Slippery Path to Total Presence: How Omnidirectional Virtual Reality Treadmills Influence the Gaming Experience. *Media and Communication* 9 (01 2021), 5–16. https://doi.org/10.17645/mac.v9i1.3170

[61] Jeremy D Wendt, Mary C Whitton, and Frederick P Brooks. 2010. Gud wip: Gait-understanding-driven walking-in-place. In *2010 IEEE Virtual Reality Conference (VR)*. IEEE, 51–58.

[62] A.D. Whitehead, Hannah Johnston, Nicole Nixon, and Jo Welch. 2010. Exergame Effectiveness: What the Numbers Can Tell Us. *Proceedings of the 5th ACM SIGGRAPH Symposium on Video Games, Association for Computing Machinery (ACM) Press* (08 2010). https://doi.org/10.1145/1836135.1836144

[63] Jacob O. Wobbrock and Julie A. Kientz. 2016. Research Contributions in Human-Computer Interaction. *Interactions* 23, 3 (apr 2016), 38–44. https://doi.org/10.1145/2907069

Received 2023-02-21; accepted 2023-07-07