Virtual Locomotion: A Survey

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Abstract—Virtual reality (VR) has enjoyed significant popularity in recent years. Where navigation has been a fundamental appeal of 3D applications for decades, facilitating this in VR has been quite a challenge. Over the past decades, various virtual locomotion techniques (VLTs) have been developed that aim to offer natural, usable and efficient ways of navigating VR without inducing VR sickness. Several studies of these techniques have been conducted in order to evaluate their performance in various study conditions and virtual contexts. Taxonomies have also been proposed to either place similar techniques in meaningful categories or decompose them to their underlying design components. In this survey, we aim to aggregate and understand the current state of the art of VR locomotion research and discuss the design implications of VLTs in terms of strengths, weaknesses and applicability.

Index Terms—Virtual reality, virtual locomotion, virtual navigation, survey, taxonomy

1 Introduction

VR has finally emerged from research labs into consumers' hands. Recent advances in VR headset technology regarding tracking, latency, refresh rate, resolution and optics have allowed for the launch of major consumer VR platforms such as HTC Vive, Oculus Rift, and Sony VR. Since the mid-twentieth century, attempts have been made to create VR systems that are natural enough to replace reality by giving the sense the illusion that what we see, hear, touch, and hopefully smell and taste is real. Though VR technology has not yet reached the stage to completely "fool" the senses, it has effectively been used in training, planning, evaluation, communication, and entertainment [1] in the fields of education, psychology, sociology, business, tourism, and journalism [2], not to mention gaming.

Among other research disciplines, Human Computer Interaction (HCI) researchers have been working on improving the utility of VR through the development and evaluation of 3D user interfaces that enable selection, manipulation and travel in virtual environments (VEs) [3]. Making or breaking the design of these interfaces could be the difference between enjoying the feeling of being present in another reality and suffering with discomfort, disorientation, or even nausea.

Finding virtual travel interfaces suitable for all possible combinations of virtual experiences, user preferences, platform capabilities, and physical space available is an endless endeavor. While tracking technology has reached a decent level of maturity to offer real walking (RW) in VR, offering a natural walking interface is not sufficient. VR travel interfaces must accommodate usage scenarios where users need to (1) navigate VEs of a space that greatly exceeds that of the physical one, (2) inspect virtual architectures at different elevations and perspectives, (3) cover great virtual distances safely with less physical exertion, or (4) travel in a way that is consistent with the experienced virtual activity (e.g., flying or surfing).

These demands motivated the emergence of *VR locomotion interfaces* that map body movements, mediated by digital sensory input, to the control of the virtual viewpoint translation, orientation and scale [3], [4]. Such mapping can vary in its fidelity from being completely natural (e.g., walking) or, on the contrary, completely artificial (e.g., using a 3D mouse). The nature of the task at hand also varies. Users could search for a target, explore a virtual scene, or maneuver obstacles [3]. Due to the variability in both mapping fidelity and the nature of the virtual task at hand, understanding the effect of the design of a VLT on the efficiency of virtual navigation has been one of the primary focus areas in VR locomotion research. Efforts to reach such understanding have been in the form of evaluations whose basis is a myriad of quality attributes that include usability, performance, naturalism, spatial abilities and cognitive abilities [5]. Another primary focus area in VR locomotion research has been concerned with the development of new VLTs or the optimization of existing ones given certain quality attributes or virtual tasks. In this paper, we aim to survey the state of the art in the field of VR locomotion and discuss the design implications of VLTs in terms of strengths, weaknesses, and applicability. Researchers can use the outcome of this effort as a bird-eye view of the VR locomotion problems that have been tackled so far. This could inspire the introduction of better solutions to problems that have been attempted already or trigger ideas of new VLTs interaction modalities. Application developers can also use this survey as a catalog of VLTs to find candidate techniques that would satisfy their application's navigation requirements.

This paper is organized as follows. Section 1 is an introduction that gives a brief history of VR and a motivation to survey VR locomotion. Section 2 gives an overview of the existing VLTs and results of their evaluations. Section 3 presents the

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existing taxonomies of VLTs proposed at different scales of generality. Finally, Section 4 discusses the strengths, the weaknesses, and the applicability of each VLTs category.

2 VR Locomotion Techniques Overview

In this section, we survey various VLTs. Similar to [4] and [3], we organize the surveyed implementations into walking-based, steering-based, selection-based and manipulation-based techniques. We further generalize walking-based techniques, similar to [6] to include all VLTs that involve repetitive motor actions. We adopt this classification criteria to survey VLTs since it is easier to relate to for users [3]. An overview of multiscale locomotion techniques is also included for completeness.

2.1 Walking-Based

The distinctive features of such techniques are that they require exertion from the user and that they have a high level of interaction fidelity [7]. Such techniques are, therefore, the closest to natural ways of moving around in VR. While some researchers thought of this category as being exclusive to walking techniques [3], it is useful to generalize these techniques to any VLT that involves repetitive motor actions [6]. Such generality allows for the inclusion of other VLTs that borrow from motions that are by-products of human walking such as head-bobbing and arm swinging.

Since the vast majority of VLTs in this category aim to mimic walking, LaViola et al. [3] subdivided these according to their degree of resemblance of the human gait cycle that consists of the stance and swing phases. The stance phase starts when the foot strikes the ground and ends when the toe is lifted off. The swing phase, on the other hand, starts with the end of the stance phase and ends when the foot strikes the ground again after a swing. In the light of this, walking-based VLTs are classified as full gait, partial gait, and gait negation techniques.

2.1.1 Full Gait Techniques

Full gait techniques include both the stance and swing phases. Common techniques in this category include RW and redirection techniques.

Real Walking. this is the most natural way to travel in VR due to its high biomechanical symmetry with respect to how humans move. Chance et al. [8] studied the effect of locomotion mode on spatial orientation through a path integration task. Among RW, joystick control and gaze-directed steering (GDS), participants were found to have significantly greater spatial orientation with RW compared to joystick control.

Usoh et al. [9] compared between RW, walking-in-place (WIP), and flying where participants were asked to move an object between two locations separated by a virtual pit. RW was found be significantly easier to use than both WIP and flying. Participants who used RW reported a significantly greater presence than those who used flying, while real walkers' sense of presence was significantly greater than those using WIP.

Zanbaka et al. [10] compared RW at room scale to three other VLTs: RW in a limited physical space complemented with joystick control; 3 degrees of freedom (DoF) head tracking with joystick positional control; and joystick control with a monitor. The goal of the study was to investigate the effect of these VLTs on cognition, categorized to knowledge, understanding and application, and high mental processes in the context of an exploration task. Information understanding and application was significantly greater in RW at room scale compared to joystick control with a monitor and limited RW with joystick control while it was notably better than joystick control with head-tracking. With respect to high mental processes, RW at room scale was significantly better than limited RW with joystick control. When participants were asked to sketch the VE they explored, those who used RW at room scale performed significantly better than those who used joystick control with a monitor. RW at room scale was also found to be significantly superior to joystick control with a monitor with respect to the sense of presence and to all other VLTs in the study with respect to comfort.

Suma et al. [11] examined the effect of travel techniques on navigation and wayfinding abilities, where participants were asked to explore a 2-story 3D maze. Results showed that the RW group significantly outperformed those who used GDS and hand-directed steering (HDS) in object placement, task completion time and collision avoidance with walls of the maze.

Suma et al. [12] compared RW, natural walking in real world, and GDS to investigate their effect on VR sickness. Participants were asked to explore a complex maze using their assigned locomotion method for 5 minutes. Results showed that RW had a significantly increased overall simulator sickness score with a significantly greater disorientation score than the other two forms of locomotion, suggesting that a VLT would be less VR sickness inducing than a natural one when navigating complex VR environments.

Ruddle et al. [13], evaluated participants' performance in terms of time, accuracy and speed in an experiment with 3 VLTs: joystick control with desktop display, GDS, and RW. Participants were asked to traverse a 24m-long route 10 times using the VLT they were assigned to. Results showed that subjects who used RW completed the task in significantly less time, with fewer collisions and less time being stationary.

Ruddle and Lessels [14] studied the effect of translational and rotational body-based information on users search abilities. Participants were evenly assigned to 3 groups: RW, GDS, and keyboard/mouse control with a monitor. Participants were asked to search for 8 targets in 16 boxes around the VE. When their performance was measured in terms of the number of times a box was rechecked (imperfect search) or not (perfect search), participants who used RW had significantly more perfect searches than the other two groups. When perfect searches were made, real walkers were found to travel paths that are closer to the shortest path than the GDS and keyboard/mouse control groups (7 versus 32 and 46 percent closer to the shortest path, respectively). Real walkers were also superior to the other two groups when imperfect searches were made in terms of the number of box rechecks. Participants who used RW also had significantly fewer collisions and missed targets. Similar results were obtained in a second experiment with a VE with less visual detail.

Nabiyouni et al. [15] compared the performance and usability of three locomotion interfaces that varied in their interaction fidelity: RW (natural interface), the Virtusphere

[16] (semi-natural interface), and gamepad control (non-natural interface). Participants were asked to follow straight and right-angled paths to measure their completion time and amount of deviation from the path. The usability of each VLT was also measured subjectively. Both RW and game-pad VLTs were found to be significantly faster, more accurate, easier to learn and less fatiguing than the Virtusphere. RW was also found to be significantly more natural than the Virtusphere.

Attempts to enable RW in VR date back to late 1960s with Sutherland's work on head tracking [17]. Several implementations followed since then and the most notable of which is the UNC Tracker Project [18] whose final product was the HiBall tracker [19] that was commercialized in late 2000s. Meyer et al. [20], Bhatnagar [21], Welch & Foxlin [22], and Baillot et al. [23] survey early implementations of VR positional tracking systems until early 2000s. The main motivation of early implementations was to improve the robustness of tracking while recent implementations were largely driven by different motivations such as reducing cost [24], [25] and improving the scalability of the tracking solution [26], [27], [28]. With the emergence of consumer VR platforms such as the Oculus Rift and the HTC Vive, RW in VR has been enabled at a relatively high quality and low cost, making VR natural travel research less concerned about robustness and cost while being more focused on the problem of scale.

Redirection Techniques. achieving a VLT that is fully natural and unrestricted by physical space has been considered as one of the grand challenges of VR travel research [3]. An attempt to realize this vision is the implementation of redirection VLTs, whose underlying goal is to keep the user within the confines of the physical space while being able to travel in a larger VE. Razzaque et al. [29] exploited the dominance of the human visual system over the vestibular system to make users walk in an unlimited straight path in the VE while actually moving on a curve in the physical environment. Users' viewpoint was manipulated by injecting imperceptible rotational distortions when they were moving in a straight path towards a waypoint. To compensate for this effect, users unknowingly moved either in or against the direction of the induced rotations. Users head rotations were also distorted to reorient them away from the boundaries of the physical environment. Since the publication of their work, research in this domain has taken off several directions that include developments of more redirection techniques, studies of viewpoint manipulation detection thresholds, and the exploration of different redirection cues.

We use both classifications by Suma et al. [30] and Steinicke et al. [31] to guide our survey of redirection VLTs. Suma et al. [30] characterize such techniques in terms of their redirection tactic, continuity, and subtlety. The used redirection tactics often depend on either controlling the user's physical *orientation* or *translation*, both having the goal of keeping the user within the limits of the tracked space. Manipulation of orientation and translation can either be applied at a certain rate (*continuous*) or just once (*discrete*). These manipulations can be either imperceptible (*subtle*) or otherwise noticeable by the user (*overt*). Steinicke et al. [31] focuses on the kinds of orientation and translation control rates, known as gains, that are applied to what they refer to as the *locomotion triple* that is composed of three vectors: the *strafe* vector s, the *up* vector u and the *direction of walking* vector w. Three gains were also identified. The translation gain scales the virtual translations with respect to the physical ones, preferably to vector w [31], [32]. Rotation gains scale rotations made by the user, where roll, pitch, and yaw rotation gains are applied to the w, s, and u vectors, respectively. Both translation and rotation gains are used to multiply the user's actual translations or rotations. Curvature gains, on the other hand, are added rotational offsets to the virtual viewpoint that make users physically walk on a curve while they are virtually walking straight. A less common form of curvature gains are added translational offsets to the virtual viewpoint while users turn their head, forcing them to compensate for these offsets by walking to the opposite direction [31]. Langbehn et al. [33] recently introduced a fourth gain, the bending gain, to include applied gains to curved virtual paths.

Nitzsche et al. [36] developed a subtle continuous redirected walking (RDW) technique, dubbed as Motion Compression, that is more generalized than Razzaque et al.'s [29] with respect to the reliance on predefined paths. Instead, Motion Compression induces curvature gains depending on the user's predicted path in the VE. Motion Compression computes curvature gains using an optimization function that minimizes the amount of deviation from the physical path for manipulations to be as imperceptible as possible. Engel et al. [40] similarly aimed to minimize the amount of dynamic rotation gains with an optimization function that considers users' discomfort and probability of collision with the walls of the tracked space. Goldfeather and Interrante [45] used subtle curvature and translation gains to minimize the amount of deviation from the physical path with the least possible collisions with the boundaries of the physical space. Zhang and Kuhl [49] proposed another redirection VLT that uses translation and rotation gains, where the latter is guided by heuristics that are based on prior knowledge about the physical environment. Bruder et al. [41] developed a redirection technique for 3D architectural model exploration named ArchExplore, where users can travel beyond the tracked space using rotation, curvature and translation gains. The implementation also uses portals for users to select a specific exploration space. Steinicke et al. [42] applied curvature gains to allow users to play a geocaching game in a virtual city larger than the tracked space. A few implementations capitalized only on translation gains. An example is the Seven-League-Boot [39] that scales the user's physical translations in the direction of their walking.

In an attempt to liberate subtle reorientation techniques from assumptions associated with the VE and the user's task, Razzaque [57] proposed a set of *generalized* steering algorithms that steers the user towards the center (steer-to-center), in circles (steer-onto-orbit) or towards given targets (steer-to-alternating-targets) by primarily applying imperceptible curvature gains. Later implementations aimed to build on these algorithms to offer RDW that works with fewer assumptions about the task and VE [58] and works in more constrained VEs [50], [59], [60].

Instead of manipulating the viewpoint rotations and translations, some research efforts considered the manipulation of the *environment's geometry*. Suma et al. [43] proposed an approach that changes the doorways' location at the VE

TABLE 1
Summary of Redirection Techniques Implementations

Implementation Features	Tactics		Subtlety		Continuity		Gains			
	Reorient.	Repos.	Subtle	Overt	Cont.	Disc.	rotation	Trans.	Curv.	Bending
Razzaque et al. [29]	■		■		■		■		■	
LaViola et al. [34]	■		■		■		■			
Razzaque et al. [35]	■		■		■		■			
Nitzsche et al. [36]	■		■		■				■	
Williams et al. [37]		■	■		■			■		
Williams et al. [38]	▲ ◆	■		■ ▲ ◆		■ ▲ ◆	◆			
Interrante et al. [39]		■	■		■			■		
Engel et al. [40]	■		■		■		■			
Bruder et al. [41]	■	▲ ◆	■ ◆	▲	■ ◆	▲	■		■	
Steinicke et al. [42]	■	▲	■ ▲		■ ▲			▲	■	
Suma et al. [43]	■		■			■				
Peck et al. [44]	■		■		■		■		■	
Goldfeather & Interrante [45]	■	▲	■ ▲		■ ▲			▲	■	
Cirio et al. [46]	■	▲		■ ▲		■ ▲				
Suma et al. [47]	■		■			■				
Vasylevska et al. [48]	■		■			■				
Zhang & Kuhl [49]	■ ◆	▲	■ ▲	◆	■ ▲	◆	■ ◆	▲		
Zmuda et al. [50]	■		■		■				■	
Lubos et al. [51]	■			■	■				■	
Freitag et al. [52]	▲	■		■ ▲		■ ▲				
Matsumoto et al. [53]	■		■		■				■	
Chen & Fuchs [54]	■		■		■		■		■	
Yu et al. [55]		■		■		■				
Langbehn et al. [33]	■		■		■					■
Sargunam et al. [56]	■		■		■		■			

Some implementations present more than one redirection technique. In those cases we use different symbols ■, ▲, or ◆ to distinguish different implementations and what methods they use.

using the change blindness illusion to keep the user within the boundaries of the tracking space. Impossible spaces [47] is a redirection technique that allows users to imperceptibly navigate a virtual environment larger than the physical tracking space using self-overlapping virtual architectures. Vasylevska et al. [48] later developed flexible spaces, an algorithm that utilizes both change blindness and self-overlapping architectures to automate redirection.

Another adopted redirection strategy is to force the user to make excess head rotations by using visual *distractors* [54], [61]. Generally, rotation gains are applied when users respond to a distractor by turning their head to either direction.

The techniques we surveyed so far use visual manipulations to achieve redirected locomotion. Matsumoto et al. [53] explored the feasibility of using *visual-haptic* feedback through the development of the unlimited corridor, where users walk in a straight path in the VE while physically walking around a physical wall. This is achieved by synchronizing haptic feedback from touching the physical wall with the virtual hand that is seen touching a corresponding virtual wall.

Due to the limitations of the current redirection techniques, chances of their failure to redirect the user away from the boundaries of the physical environment are inevitable. Users have to be instructed in such cases to "reset" their orientation and/or position before they could continue navigating the VE. To this end, Williams et al. [38] proposed three *resetting techniques*. Freeze-Backup stops the manipulation of the user's viewpoint until they make several steps backwards after which the viewpoint is unfrozen. Freeze-Turn has a similar behavior except that the user is instructed to yaw by 180 Degree. The 2:1-Turn resetting technique instructs the user to make a 180 Degree physical turn while the viewpoint is turned by 360 Degree. Further improvements were proposed [62] to make Freeze-Backup and 2:1-Turn more user-friendly and flexible in constrained physical spaces. Cirio et al. [46] proposed two resetting techniques for 3-walled CAVE environments. The goal of these techniques is to reset the user's position when they reach the boundaries of the physical space and to reset the user's orientation when they are nearly facing the CAVE's missing wall (to avoid breaking the presence). In the first technique, position reset is signalled using a no-way sign when the user approaches a wall while turn sign is used to instruct the user to move away from the missing wall. In the second technique, a virtual bird is used to deter the user from colliding against a wall by angrily flapping its wings against the user's face until they reset their position. The same technique is used when the user faces the missing wall until they reset their orientation. Having a similar goal in mind, LaViola et al. [34] proposed applying rotation gains to the VE rendered on a three-walled CAVE in a direction opposite to the user's rotation depending on the angle between their waist and the VE's forward vector as well as their distance from the CAVE's back wall. Similarly, Razzaque et al. [35] proposed redirected WIP, a subtle continuous reorientation technique that applies imperceptible rotation gains to move the user away from the CAVE's missing wall towards the front wall as they walk in place depending on their virtual speed, head orientation, and head angular velocity. Freitag et al. [52] achieved overt discrete reorientation by using portals that move the user to their desired destination in the VE while facing away from the physical environment boundaries. Users select their target location by creating a target portal. A start portal then automatically appears in a physical location that keeps users away from the CAVE walls. Bookshelf and Bird [55] are teleportation techniques that are designed to blend with the narrative of the presented VR experience. Users freely walk in the VE until they decide to move to a virtual location beyond the tracked space. Users are then teleported to the desired destination through a metaphor (e.g., bookshelf or a bird) that conforms with the narrative of the VR experience. Lubos et al. [51] proposed Safe and Round, an overt continuous reorientation technique that aims to enable RDW at room-scale. The technique works by applying overt curvature gains to the user's viewpoint when they exit a defined safe region until their re-entry. Sargunam et al. [56] proposed a continuous reorientation technique for the user's head in seated VR experiences. As rotation gains are used to allow for 360° viewpoint control without the need to physically rotate as much, the proposed technique resets the user's head to its physical forward direction by applying gradual rotation gains during travel. A summary of the surveyed redirection techniques is shown in Table 1.

Several studies focused on determining the *detection thresholds* of the induced translation, rotation, curvature and bending gains. Steinicke et al. [63] aimed to determine the limits of translation, rotation, and curvature gains in two-alternative-forced-choice tasks. Results showed that translations could be imperceptibly manipulated by 22 percent more or less than their actual translation rate while rotation gains were considered imperceptible when they were 10 less or 68 percent more than their perceived virtual rotation. It was also shown that curvature gains with radius of at least 24m made subjects perceive that they were walking straight. Another study by the same authors [64] reported translation gains thresholds to be 14 less or 26 percent more, rotation gain thresholds as 20 less or 49 percent more, and curvature gain radius of 22m. The former rotation gain thresholds were also confirmed in a follow-up study [65] that also found that the subjects were less sensitive to rotation gains as their rotation angle is larger, and vice versa. Neth et al. [66] studied the effect of walking velocity on the sensitivity to curvature gains and found that subjects were significantly less sensitive to curvature gains when they walked slower. Zhang and Kuhl [67] examined the difference between abrupt and gradual rotation gains. Participants were asked to make a 360 Degree-turn while varying the rotation gains during the turn and no difference was found between abrupt and gradual rotation gains. Grechkin et al. [68] aimed to analyze the effect of adding translation gains on curvature gains threshold and to revisit the estimation of the minimum detection threshold of curvature gains. It was found that translation gains do not cause an increase on curvature gains detection threshold and that the estimation of curvature gains threshold can be as low as 6.4m when a different threshold estimation method was used. Paludan et al. [69] examined the effect of the visual scene's density on rotation gain threshold and no difference was found between 0, 4 and 16 objects in the scene. In a recent study, Langbehn et al. [33] attempted to determine the imperceptibility threshold of the bending gain and found that a bending gain of 4.35 times the real bending radius would go unnoticed by subjects. Serfain et al. [70] aimed to estimate the detection thresholds of rotation gains when acoustic redirection cues were used. It was found that subjects can be rotated 12 more or 20 percent less than their perceived virtual rotation. A later study by Nilsson et al. [71] found no effect of adding sound cues on rotation gain detection thresholds. Schmitz et al. [72] proposed the threshold of limited immersion to establish a relationship between the amount of rotation gain and the point at which self-reported presence breaks. Rotation gains were continuously increased and decreased while participants took part in targets collection task and were asked to report breaks in presence. While the lower limit of the threshold of limited immersion was comparable to the reported detection thresholds (0.58 and 0.67, respectively) [64], a significant difference was found for the upper limits (1.85 and 1.24, respectively) [64]. It was also found that rotation gains greater than 1 had less effect on the rate of breaks in presence compared to gains less than 1.

Other studies focused on examining the *effect of gains* on users performance. Williams et al. [37] studied the effect of translation gains on the subjects' ability to orient themselves, timely and accurately, to previously seen targets in two experiments. The results showed that the amount of translation gain had no significant effect on subject's latency in both experiments with contradicting results on the effect of varying gains on the subjects' accuracy among the two experiments. Xie et al. [73] studied the effect of combining translation gain and the resetting methods implemented by Williams et al. [38] in two experiments similar to the former one by Williams et al. [37]. It was found that amount of resets had a significant effect on subjects' spatial accuracy. Bruder et al. [74] found that adding curvature gain larger than $\frac{1}{10}$, which corresponds to an arc with a diameter of 10m, had a significant effect on walking behavior by asking participants to follow a virtual sign in a 7m long straight path. Such gain was also found to have a significant effect on both spatial and verbal memories when participants were asked to perform two-back cognitive tasks. Similarly, Hodgson et al. [58] conducted a study to examine the effect on their subtle RDW technique with dynamic curvature gains on participants spatial memory and no significant effect was found. Kopper et al. [75] studied the effect of rotation gains on participant's performance in terms of visual scanning and counting abilities during head rotations. While the amount of rotation gain had no notable effect on visual scanning performance, participants counting performance significantly worsened as more rotation gain was applied. Ragan et al. [76] examined the effect of rotation gains in both head-mounted display (HMD) and CAVE platforms on performance, spatial orientation, and VR sickness in a naive search task conducted over a practice session that involved different levels of rotation amplification and an assessment session with no amplification. Rotation gains had no significant effect on search performance during practice. However, participants who practiced with the highest levels of rotation amplification found significantly more targets in the assessment session than those who practiced with lower amplification. It was also found that high rotation gains experienced with the HMD were linked to greater spatial disorientation, greater VR sickness, and less usability. Freitag et al. [77] studied the effect of a range of rotation gains (0.8 to 1.18) on spatial knowledge, VR sickness, presence, subjective cognitive load, and measured cognitive performance in a CAVE

VE. Results showed that the rotation gains under analysis had no significant effects on any of the measures except for a degrading spatial knowledge in first-time CAVE users who experienced stronger rotation gains.

Some research efforts were concerned with comparing the *effectiveness of different redirection techniques with one another*. Peck et al. [78] compared the effectiveness of 4 redirection techniques: motion compression [36], 2:1-Turn [38], the amplified rotations described in the traditional RDW by Razzaque [57], and the authors' reorientation with distractors technique. It was found that both the amplified rotations and reorientation with distractor techniques were ranked better on the scales of sensed presence, user preference, and naturalness. Suma et al. [79] compared the effects of Peck et al.'s [61] reorientation with distractors and reorientation with change blindness [80] on spatial orientation both in virtual and real world. Change blindness reorientation caused more disorientation than reorientation with distractors. The latter technique was also found to have very similar spatial orientation performance to the control condition that involved no reorientation. It was also found that reorientation with distractors had a strong influence on participant's spatial updating both in virtual and real worlds. Langbehn et al. [81] compared between RDW and teleportation along with joystick-control locomotion in pointing and spatial arrangement tasks. RDW outperformed the other two techniques in the spatial arrangement task while RDW and teleportation were comparable in terms of preference while they were both preferred over joystick-control. Except for joystick-control locomotion, neither RDW nor teleportation caused a significant increase in VR sickness and none of the locomotion techniques had a significant effect on presence. Hodgson and Bachmann [82] compared the performance of four generalized RDW algorithms. Steer-to-Center was superior to Steer-to-Orbit, Steer-to-Multiple-Targets and Steer-to-Multiple+Center in all performance measures, namely: ability to contain users in terms of mean and maximum distance traveled to the center, maximum physical distance traveled in terms of the number of wall contacts, and mean redirection rate. Steer-to-Orbit was found to have better performance than Steer-to-Center for long and straight paths. In a later study, Hodgson et al. [83] compared between Steer-to-Center and Steer-to-Orbit in a constrained VE (virtual grocery store) and the latter was found to have significantly fewer wall contacts, marginally less mean physical distance covered, and marginally better task completion time.

2.1.2 Partial Gait Techniques

The majority of partial gait techniques take advantage of the stance phase, where users step in place without making any physical translations. Slater et al. [84] proposed the first WIP implementation with the virtual treadmill. When users walk in place, their resulting head oscillations are fed to a neural network that, if a walking action was detected, translates the users' viewpoint forward in the direction they are looking. The locomotion interface was later extended to support climbing steps and ladders [85]. The virtual treadmill had four key limitations: its underlying neural net has to be trained for each user, only forward travel is supported, the direction of travel is coupled with head direction, and a proxy measure to speed (head oscillations frequency) is used. Research efforts that followed aimed to overcome some of these limitations. Templeman et al. [1] proposed the Gaiter WIP VLT that uses force and inertial sensing to transform steps in place to translation in the VE. Displacement and angle of the knee determined speed and direction of travel, respectively. The Gaiter offers forward, backward, and lateral (strafing) movements and does not require prior neural net training like the virtual treadmill. Aside from the traditional WIP gestures that resemble marching, Nilsson et al. [86] proposed two other gestures: wiping and tapping in place. With wiping in place, users move their feet alternately backwards against the floor while bending the knee of the moving leg. With tapping in place, on the other hand, users alternate the movement of each heel while having the front of their feet in contact with the ground. Similarly, Guy et al. [87] proposed two partial gait locomotion techniques. In the first technique, users step with one foot forward or backward to translate in the corresponding direction; while they bend their knees alternately for translation in the second. Rotation is enabled via upper-body gestures. Zielasko et al. [88] proposed two WIP VLTs for seated virtual experiences. In adapted WIP, users move their thigh that is attached to a smartphone upwards and downwards to translate forward in the direction of their head with a speed that corresponds to their thigh movement frequency. In the accelerator pedal technique, a heel tapping gesture of the foot attached to a smartphone is transformed to translation, where lowering the heel below a predefined zone moves the virtual viewpoint forward in the direction of the head with a speed that is derived from the distance of the heel from the predefined zone. Lifting the heel above the predefined zone translates the viewpoint backwards.

Other implementations utilized dedicated *stepping platforms* to offer WIP. Bouguila and Sato [89] developed a WIP platform that utilizes a turntable equipped with pressure sensors to detect stepping gestures. Turning in place was enabled via tracked infrared (IR) markers that can be fitted on the user's waist or head. A successor implementation enabled jumps and squats in addition to the simulation of walking over uneven terrains [90]. The walking pad [91] also uses pressure sensing, but uses switch sensors to eliminate the need for an IR camera to detect rotations in place. A similar implementation was also proposed by Lala and Nishida [92]. Zielinski et al. [93] implemented a WIP VLT, dubbed as Shadow Walking, that captures the shadow of the user's feet using an under-floor camera. Both forward and strafe movements are supported. Williams et al. [94] used a Wii balance board through which users could walk in place in the direction of their gaze. In a later implementation, a platform-less WIP technique using a Microsoft Kinect was proposed [95].

Several efforts were focused towards making WIP more natural by primarily providing *speed profiles* that are better approximations of natural walking. Fujita [96] proposed a responsive WIP technique that attempts to reduce the travel speed estimation delay. Locomotion speed is estimated as a function of hip joint difference angle, stepping frequency, stepping amplitude, and leg length. Yan and Allison [97] used data collected from the back of subjects' calf while physically walking to calibrate their WIP implementation for it to offer more realistic speeds. Kim et al. [98] used a sensor

TABLE 2
A Summary of WIP Implementations Described in Terms of the Foot Motion Pattern, Speed Control, Direction Control, Sensing Requirements, and Movements Supported

Impl. \ Features	Pattern	Speed		Direction		Sensing	Movements
		Part	Control	Part	Control		
Slater et al. [84]	marching	head	frequency	head	yawing	magnetic	forward
Slater et al. [85]	marching	head	frequency	head (walk) & hands (climb or descend)	yawing (walk) & hand position (climb or descend)	magnetic	forward, climb, descend
Templeman et al. [1]	marching	feet & knees	frequency	knees	yawing	inertial & force	forward, backward, strafe
Bouguila & Sato [89]	marching	feet	frequency	head or torso	yawing	infrared & pressure	forward
Bouguila et al. [90]	marching	feet	frequency	feet	yawing	pressure	forward, jump, squat
Bouguila et al. [91]	marching	feet	frequency	feet	yawing	pressure	forward, jump
Fujita [96]	marching	hips	frequency & amplitude	torso	yawing	bend & magnetic	forward
Yan & Allison [97]	marching	knee	knee lifting speed	torso	yawing	inertial & ultrasonic	forward
Feasel et al. [99]	marching	feet	vertical heel speed	torso	yawing	optical	forward
Kim et al. [105]	wiping	fingers	frequency & stride	fingers	rotation angle or dragging distance	haptic	forward, backward, omnidirectional
Kim et al. [106]	wiping	fingers	frequency & stride	fingers	dragging distance	haptic	forward, backward, omnidirectional
Wendt et al. [100]	marching	knee	frequency	torso	yawing	optical	forward
Lala & Nishida [92]	marching	feet	frequency	feet	yawing	pressure	forward
Zielinski et al. [93]	marching	feet	frequency	feet	yawing	optical	forward, strafe
Williams et al. [94]	marching	feet	head	frequency	yawing	pressure	forward
Terziman et al. [109]	marching	head	lateral head speed	head	tilting	optical	forward, jump, crawl, strafe
Kim et al. [98]	marching	feet	stride	torso	yawing	inertial & ultrasonic	forward
Bruno et al. [101]	marching	feet	feet height	N/A	N/A	optical	forward
Williams [95]	marching	feet	constant	head or torso	yawing	depth	forward
Nilsson et al. [86]	tapping	feet	frequency	feet	yawing	optical	forward
Guy et al. [87]	single-stepping	knee	amplitude	torso	leaning or yawing	depth	forward, backward
Guy et al. [87]	knee-bending	knee	amplitude	torso	leaning or yawing	depth	forward, backward
McCullough et al. [107]	marching	arm	frequency	head	yawing	inertial	forward
Pfeiffer et al. [111]	marching	head	frequency	head	yawing	inertial	forward, jump, backward
Tregillus & Folmer [110]	marching	head	frequency	head	yawing	inertial	forward, jump
Zielasko et al. [88]	marching	feet	frequency	head	yawing	inertial	forward
Zielasko et al. [88]	tapping	feet	tapping distance	head	yawing	inertial	forward, backward
Bruno et al. [102]	marching	feet	user height, step height & step speed	hip	yawing	depth	forward
Sarupuri et al. [108]	marching	hand	controller angle w/ frontal plane	head & hand, both hands, or head	angle b/w head & hand, angle b/w two hands, or head yaw	inertial & optical	forward

Speed and direction controls are specified in terms of the body parts involved and the control mechanism used.

fusion step detection approach that uses accelerometer and magnetometer data to offer WIP that accommodates dynamic stepping frequencies ranging from .75 Hz to 2.8 Hz. Feasel et al. [99] implemented the Low-Latency, Continuous-Motion WIP (LLCM-WIP) that aims to reduce the latency, smooth the virtual viewpoint transition between steps, and give more granular speed control of WIP locomotion by processing heel-tracking data at each movement frame. Improvements to the LLCM-WIP, such as the GUD-WIP [100] and SAS-WIP [101] were later proposed. A similar recent effort was made by Bruno et al. [102], where a WIP speed estimation model based on the lower limbs skeletal data was proposed. The range of the perceptually natural walking speeds of WIP was studied by Nilsson et al. [103], [104]. Results of these studies showed a positive trend in the relationship between stepping frequency and the speed gains perceived as natural [104]. The results also showed that perceived natural speeds were underestimated by a factor of 2 and such underestimation is inversely related to the field of view [103].

Some implementations *substitute* the use of legs with other body parts to offer WIP locomotion. Kim et al. [105] implemented the Finger Walking In Place (FWIP) technique. Users slide two of their fingers alternately to move forwards or backwards while radial sliding gestures enable virtual turning. Speed is controlled via the length of the sliding gesture. A similar implementation was proposed for multi-touch enabled smartphones [106]. McCullough et al. [107] used a wearable armband to implement an arm-swinging WIP VLT, where users swing both of their arms to travel forward in the direction of their head. Arm-swinging frequency is used to control the speed of travel. Sarupuri et al. [108] implemented Trigger Walking, a technique that mimics bipedal locomotion by having users alternate between the trigger buttons of the right and left controllers. Speed is controlled by changing the controller's angle with the frontal plane. Three methods are proposed to control travel direction: using the heading angle of one controller with respect to the user's heading, using the average bearing of both controllers, or using the user's heading. Terziman et al. [109] offered a WIP implementation using head gestures. Lateral head motions were transformed to virtual forward translations while upward and downward vertical head motions were transformed to jumping and crawling, respectively. Users roll their head to either side to change the direction of travel. Speed of horizontal and vertical travel is controlled by the lateral and vertical head oscillations amplitudes, respectively.

With the recent trend of *mobile VR*, some WIP implementations for such platform were proposed. Tregillus and Folmer [110] implemented VR-Step, a WIP implementation for mobile VR that is enabled via inertial sensing. VR-Step moves users forward in the direction of their head in a speed that is approximated by their stepping frequency. The technique has also the ability to detect vertical translation. Pfeiffer et al. [111] proposed a similar implementation with the addition of a limited ability to look around while moving forward and the ability to move backwards. A summary of the surveyed WIP implementations is shown in Table 2.

Several evaluations of WIP techniques have been concerned with their *naturalness* as proxies of natural walking. In a study by Slater et al. [112], WIP scored more subjective presence compared to flying. This finding was consistent with a later study by Usoh et al. [9], where WIP was found to score significantly greater presence than flying while being comparable with RW. WIP scored significantly less than RW in terms of ease according to that study, however. Tregillus and Folmer [110] compared WIP to auto-walking and subjects rated WIP significantly greater in terms of subjective presence and intuitiveness. In another study by Muhammad et al. [113], subjects felt more present while navigating 360 Degree videos compared to the traditional travel method. Nilsson et al. [86] compared the traditional marching WIP with two other WIP gestures, wiping and tapping, in terms of naturalness, presence and unintentional positional drift. Tapping in place was found to be significantly better than wiping with respect to naturalness. Tapping also scored significantly less than wiping and traditional WIP in terms of required effort and amount of unintentional positional drift.

Other efforts have examined the effect of WIP on *spatial abilities and understanding*. Williams et al. [94] found WIP to be comparable to RW with respect to spatial orientation. In a virtual maze navigation task, Peck et al. [114] found WIP to be significantly worse than RDW with distractors in terms of navigation and wayfinding abilities. Terziman et al. [115] conducted a spatial and temporal analyses of the trajectories made by WIP compared to those by joystick control. Results showed that subjects had greater control over their speed with WIP, but had more difficulty making natural turns while traveling compared to the joystick. Xu et al. [116] compared between WIP, joystick control, and teleportation in a spatial knowledge acquisition task and found all three methods comparable in performance.

Some studies examined the *effect of using different body parts*, e.g., fingers or arms, to implement WIP on spatial understanding and naturalness. Kim et al. [117] found that subjects had better route knowledge acquisition abilities when they walked in place with their fingers compared to flying. McCullough et al. [107] found WIP with arm swinging to be comparable to RW with respect to spatial orientation, which contradicts with a later study by Wilson et al. [118] who reported that subjects scored less than both RW and traditional (leg-based) WIP when arm swinging was used in a spatial orientation task. Nilsson et al. [119] studied the difference between traditional WIP, arm swinging, and hip movement (by swinging hips while being in place) with respect to naturalness, presence, and unintentional positional drift. Both traditional WIP and arm swinging were rated significantly more natural than hip movement. Traditional WIP, however, was found to be a significantly closer proxy to natural walking in terms of physical expenditure than arm swinging. Traditional WIP scored a comparable level of sensed presence to that of both arm swinging and hip movement while participants felt significantly more present when using arm swinging compared to hip movement. Arm swinging and hip movement were comparable in their measured unintentional positional drift, which was significantly lower than that of traditional WIP. Zielasko et al. [88] compared two seated WIP techniques (marching versus tapping), Terziman et al.'s [109] head shaking technique, LDS and gamepad control in a virtual graph analysis task. Head shaking was found slower than both gamepad control and WIP with tapping while no significant differences were found in error rates.

2.1.3 Gait Negation Techniques

These techniques aim to provide the full gait cycle while keeping the user stationary. They, therefore, overcome the room-scale issue with RW and provide a greater level of fidelity than the partial gait techniques. All of these methods depend heavily on dedicated mechanical devices which include treadmills, step-based devices, and low-friction surfaces [3].

Treadmills were first proposed by Brooks et al. to offer more natural means of virtual architectural walkthroughs [120], [121], where a custom-made treadmill utilized a bicycle handlebar for steering. Darken and Carmein [122] proposed a different implementation with their Omni-Directional Treadmill (ODT), at which two perpendicular treadmills were used, one inside the other. A qualitative evaluation with one subject compared between walking naturally and using the ODT while performing representative locomotion moves such as resting, walking, jogging, acceleration, change in direction, and maneuvering. Effects of tracking quality and user recentering criteria were found to limit the subject's ability to maneuver freely and achieve responsive locomotion experience. Further improvements to the ODT were proposed in [123]. The Torus omnidirectional treadmill [124] similarly employs two groups of treadmills to move the user along the X and Y directions. A distance perception study with 18 participants showed that the Torus resulted in significantly lower distance estimation error than joystick-control and locomotion using a motorized chair. The ATLAS [125] is another omnidirectional treadmill that dynamically adjusts its running speed according to that of the user. The Sarcos Treadport [126], [127] is a treadmill that simulates contact with physical constraints (e.g., walls), slopes, and inertial forces by manipulating the pushing and pulling forces of a tether around the user's torso. Users can walk forwards or backwards at a speed that is proportional to the user's distance from the center. The rate of turning is proportional to either the angle between head direction and torso or the amount of a sidestep to either side. With a set of ball bearings arranged around a disc, Huang et al. [128] implemented the gait sensing disc that offers omnidirectional locomotion while being stationary. This is similar to the Ball Array Treadmill [129] and the Cybercarpet [130]. A more recent implementation of an omnidirectional treadmill is the CyberWalk [131] that distinguishes itself from previous implementations by its ability to handle abrupt changes in the users' walking speed to keep them stable and close to the center of the treadmill. Cyberwalk was compared to RW in a study that evaluated participants' walking behavior and spatial updating performance while following a moving target on an arc. No notable differences were found between Cyberwalk and RW in both measures. Several research works on the development of VR treadmills focused on addressing more locomotion scenarios other than walking on flat surfaces by simulating slopes [132], [133], uneven terrains [134], [135], and stairs [136].

Step-based devices offer another alternative to provide full gait navigation while being stationary. Roston and Peurach [137] proposed a virtual locomotion device that allows users to navigate VEs by stepping over two motion platforms. Wang et al. [138] implemented a step-based locomotion device that consists of two foot boards that follow the motion of the user's foot while physically walking to move them back to their initial position. Iwata et al. [139] similarly implemented the Gait Master, a step-based locomotion device that is able to simulate uneven virtual terrains. Boian et al. [140] used a pair of robot manipulators to implement a step-based locomotion device that offers a more realistic walking experience with respect to terrains with different shapes and physical properties. A similar work was also proposed by Yoon and Ryu [141].

The Wizdish [142] is a concave *low-friction surface* at which users slide their feet in opposite direction to travel in VR, which is similar to the implementation proposed by Grant et al. [143]. The platform was made slippery for users to slide their feet back and forth similar to the wiping WIP gesture. Speed was estimated in accordance with the user's wiping magnitude. Iwata and Fuji [144] implemented the virtual perambulator that offers omnidirectional locomotion using a pair of specialized sandals with a low friction film at the middle of their soles. The naturalism of the virtual perambulator was evaluated in terms of participants' ability to perform rhythmic feet alternation and smooth change of direction. Out of the 235 participants, six participants failed to perform rhythmical walking while seven failed to turn smoothly.

Aside from treadmills, step-based, and low-friction devices, several gait negation locomotion devices were implemented. The Cybersphere [145] is a spherical projection and locomotion system that offers omnidirectional virtual travel as a result of physical walking of the user inside a sphere while being stationary, which is similar to the Virtusphere [16]. Iwata and Noma [146] developed the CirculaFloor that consists of a set of tiles that detect the user's physical walking velocity and move accordingly to pull the user back, creating an infinite walking surface. The String Walker [147] is another gait negation locomotion device that ties the user's feet with strings attached to a turntable. The pulling force of the strings is used to control a motor-pulley that is transformed to virtual omnidirectional locomotion.

2.2 Steering

The key feature associated with steering VLTs is the *continuous control of direction* [3]. Speed control can be part of a given steering technique though it's not the primary focus of its design. Steering VLTs can be categorized as spatial steering techniques (i.e., controlled using parts of the user's body) or physical steering techniques (i.e., controlled using vehicular props) [3].

2.2.1 Spatial Steering Techniques

Steering in these techniques is controlled using body gestures that are mapped to control of virtual direction. In the light of this, steering can be controlled by gaze, hand, body leaning, or torso.

In *gaze-directed* techniques, the direction of virtual travel follows that of where the user is looking. While such techniques are commonly known as gaze-directed [148], few implementations track the movement of the user's eyes [149], but rather depend on the tracked orientation of the user's head. A few studies compared between GDS and RW. Ruddle and Lessels [14] compared between RW and GDS to investigate the relationship between the amount of body-based information and navigation performance in search tasks. Participants who used GDS performed significantly worse than real walkers. Suma et al. [12] studied the effect of the VLT (RW versus GDS) on the reported VR sickness in complex virtual environments. Participants who used GDS reported significantly less VR sickness after the study compared to those who used RW. The common criticism of GDS techniques is that they limit the user's ability to look around while navigating in a certain direction [148]. This limitation is overcome by using HDS, torso-directed steering (TDS), and lean-directed steering (LDS).

Several *hand-directed steering* techniques were implemented using metaphors such as flying or skiing. Robinett [150] proposed an early implementation of VR locomotion that mimics flying, where hand input determined the direction of travel. Fairchild et al. [151] proposed flying among the possible VLTs to be used in their "Heaven and Earth" VR system, where the orientation and relative position to the user's head controls the virtual direction and velocity, respectively. A similar technique was also implemented by Boudoin et al. [152] with their FlyOver 3D HDS navigation model. Bowman et al. [153] developed a two-handed flying VLT using a pair of tracked data gloves, where the direction and speed of travel are determined based on the direction and length vector between the hands, respectively. Haydar et al. [154] implemented a HDS gesture that utilizes how tanks are steered to control the virtual direction where, for instance, turning left is achieved by moving the right hand forward and the left one backwards. Speed control, on the other hand, borrows from skiing where the angle between the hands determines the rate of translation. Cabral et al. [155] defined a set of two-handed gestures to control translation, rotation, and scaling of the virtual viewpoint as well as to switch between navigation, manipulation and visualization modes. Cirio et al. [62] implemented a HDS technique for users to be able to navigate the VE when they reach the boundaries of the physical tracking space, represented as a barrier tape in the VE. When users "push" through the barrier tape, the direction and amount of tape penetration are used to control the direction and speed of travel, respectively. Cirio et al. [46] later proposed another HDS technique through which users control the virtual viewpoint by manipulating virtual reins attached to a virtual bird. Activation, deactivation, translation rate control, and steering are achieved via 2-handed gestures as follows. Moving the arms up and down activates locomotion while crossing the arms deactivates it. Acceleration and deceleration are achieved by moving the arms forwards and backwards, respectively. Turning to the left or to the right is achieved by moving away the corresponding arm to a distance that is mapped to the desired turning rate. NuNav3D [156] is a HDS VLT that uses the offset between two recognized body poses to calculate the amount of rotation and translation updates based on offset vectors of the right and left hands, respectively. LMTravel [157] uses recognized hand gestures to determine viewpoint control activation, translation, and rotation. Viewpoint control is activated or deactivated by opening or closing both hands, respectively. Translation rate is controlled by the number of fingers stretched while rotation is controlled by the tilt angle of the right hand. Zhang et al. [158] similarly developed a set of two-handed gestures for VR locomotion. Steering left or right is done by the orienting the right thumb to the left or right, respectively. Translation, on the other hand, is achieved by pointing the left palm upwards or downwards to move forward or backward, respectively. Ferracani et al. [159] proposed two one-handed steering techniques: one that controls the direction of travel according to that the user's index finger, and another that enables steering with their fist.

Several *evaluations* compared between HDS and GDS. Bowman et al. [160] conducted two experiments to assess participants' performance in terms of time to reach the target given the VLT (HDS or GDS). No significant difference among the two techniques was found when participants were asked to move directly towards an object while HDS was found superior when they were asked to move relative to an object. The latter result, according to the authors, was due to the coupling of the user's gaze with steering control. In a target following task, Suma et al. [161] compared between GDS and HDS techniques among other VLTs when task complexity and type (single navigation or divided task) were varied. The two techniques were found comparable in terms of performance and VR sickness. Suma et al. [162] also compared between the two techniques in a multi-level 3D maze exploration task to measure participants' performance, cognitive abilities and VR sickness. While the two techniques were comparable with respect to cognitive abilities and VR sickness, GDS was superior to HDS in terms of completion time and collisions. Contrary results were reported by Christou et al. [163] when participants were asked to perform a wayfinding task, where HDS had significantly better performance than gaze in terms of task completion time and errors made. In another wayfinding task by Christou et al. [164], the two techniques were found comparable in terms of VR sickness, disorientation, and completion time while HDS resulted in significantly less success rates than GDS.

Lean-directed steering techniques varied in terms of the body parts involved and the choice of sensing platform. Among the earliest LDS techniques were the ones proposed by Fairchild et al. [151], where two LDS techniques were proposed: one that transforms head translations from a defined central point (e.g., waist) to scaled virtual translations; and another that moves the virtual viewpoint in the direction of body leaning in a speed that corresponds to the amount of leaning. The latter technique was refined by LaViola et al. [34] to reduce the chance of classifying resting postures as leaning. DeHaan et al. [165] proposed a LDS VLT using the Wii Balance Board. Leaning forward or backward causes a virtual forward or backward translation, respectively, while leaning on either side causes strafing. To turn, users press with the toe of one foot and the heel of the other. The rate of translation corresponds to the amount of leaning. A similar implementation is that of the Human Transporter [166], except that strafing is not offered and turning is activated by leaning on one of the Wii Balance Board sides. Wang and Lindemann [167] implemented a leaning interface that resembles the surfing metaphor using a Wii Balance Board for steering control and an accelerometer on one arm to control speed of travel. A later implementation [168] offered vertical travel using multitouch gestures with a touchpad on the user's leg. Carrozzino et al. [169] developed a pressure mat to offer LDS VLT whose leaning gestures are mapped similarly to those of the Human Transporter [166]. Leaning for translation and rotation was among the locomotion techniques implemented by Guy et al. [87] using depth sensing, where leaning to the right or left rotates the virtual viewpoint clockwise or anticlockwise, respectively. Translation was enabled either by body leaning or a partial gait gesture. Zielasko et al. [88] designed a LDS technique for seated virtual experiences, where leaning forwards or backwards translates the virtual viewpoint in the corresponding direction. The distance of the user's head from a predefined zone is mapped to translation speed while steering is determined based on the yaw angle of the HMD. LDS was also implemented using rotating chairs. The ChairIO [170] and NaviChair [171] appropriate a swivel stool chair to offer a leaning interface that supports moving forward, backward, upwards, downwards, sideways as well as turning. Three different chair-based leaning interfaces were compared to GDS and joystick control in a recent study that involved a search task [172]. All techniques were comparable in terms of sense of vection, spatial perception, enjoyment, engagement, presence, and physical exertion. Joystick control was found better than the rest of techniques in terms of spatial orientation, accuracy, ease-of-use, controllability, and comfort. LDS interfaces were also offered on mobile VR. Tregillus et al. [173] developed an omnidirectional leaning VLT for mobile VR via head tilt. With this interface, users could control travel direction and speed according to the direction and degree of their head tilt, respectively.

Very few research efforts have explored *torso-directed steering*, probably because it requires more sensors, compared to HDS and GDS techniques that utilize the already available sensors at most VR tracking systems [3]. TDS through tracking shoulder or hip rotation are among the recent TDS implementations by Guy et al. [87]. Bowman and Hodges [174] compared between TDS, HDS, and GDS techniques to examine their effect on cognitive load in an information gathering task while navigating a maze. All steering techniques were similar with respect to time and collisions. Similar results were obtained by Suma et al. [161]. Bowman et al. [175] compared TDS with two other steering techniques (HDS and GDS), two manipulation-based techniques (HOMER [175] and Go-Go [176]), two target selection techniques (map dragging [175] and teleportation). Participants were asked to take part in naive and primed search tasks to find targets distributed over an open space. Steering techniques were generally better than all other techniques while TDS was generally worse than the other two steering techniques in terms of both thinking and travel times. Thinking time was the time elapsed from the start of the task until the beginning of movement, while travel time was the time elapsed from the beginning of movement until the reaching the target. In a path following task [87] that involved a secondary action (e.g., holding a mug), TDS caused less physical exertion compared to LDS, but was more disruptive to secondary actions.

2.2.2 Physical Steering Techniques

These techniques utilize physical props to offer steering. The advent of consumer VR technology has made physical steering devices limited to specific scenarios such as the need to mimic the experience of a real-world vehicle. Examples of physical steering devices include the bike locomotion platforms made for the Olympic bicycle race and the Border Collie virtual environments [177], the Sarcos Uniport [6], as well as VR simulators for aircrafts, merchant ships, cars, boats, and spaceships [178]. For further discussion on physical steering techniques, readers may refer to these sources: [3], [6], [178].

2.3 Selection-Based

Also called automated VLTs [4], [5], these techniques liberate the user's mind from thinking about how to get somewhere and allow users focus on where to get to. Two known techniques in this category are target selection and route planning [3].

In *target selection*, the user selects a target destination in the VE after which the virtual viewpoint is moved to the target, which can be either a selected position [160] or scene object [175]. A widely known target selection technique is teleportation [179], which either moves the virtual viewpoint to the destination instantly [180]; or gradually at a variable [181] or fixed [182] speed. Map dragging [175] is another target selection technique through which users drag an icon that represents their current location to a new location on a miniature 2D map of the VE. While the majority of target selection techniques are activated with a controller, some implementations offer target selection control using body gestures. The Step WIM [34] is a target selection technique that enables users to move to a new destination by stepping over its corresponding location in a World-In-Miniature (WIM) projected on the floor of a CAVE. Jumper [183] allows the user to be teleported to a destination by jumping in place while looking towards the intended destination.

Several studies were conducted to examine the *effectiveness of teleportation* in different virtual tasks. Bowman [160] studied the effect of teleportation speed on the participants' spatial understanding. Four teleportation speed profiles were used: slow constant speed, fast constant speed, slow-in/slow-out, and instant teleportation. Participants were familiarized with the VE that consisted of colored boxes labeled with a given letter. Participants then moved to multiple locations in the VE and were asked after each move to locate a certain box and indicate its label. Instant teleportation was found to have the worst performance among the evaluated techniques in terms of task completion time, suggesting that instant teleportation was the most disorienting technique to the participants. Bakker et al. [184] compared between automated continuous locomotion and teleportation in a spatial memory task. Participants were periodically asked to point to previously seen objects while freely exploring the VE using one of the VLTs. Significantly more pointing delays were incurred when teleportation was used. Christou et al. [164] compared between teleportation, GDS, and HDS in a primed search task. Participants were asked to find their way to a previously seen target within a time limit and make frequent stops on the side of the way to collect tokens. Teleportation was found to be significantly the least VR sickness inducing in terms of nausea, oculomotor discomfort and disorientation. It also resulted in significantly greater task completion success rates than HDS, but comparable to that of GDS. Participants were able to complete the task in significantly less time when teleportation was used. Teleportation, however, resulted in the smallest number of collected tokens, indicating its tendency to miss spatial details.

Route-Planning VLTs offer more granular control over virtual travel than target selection techniques by providing the user with means to select the route to be navigated from the source to the destination. Few attempts have been made to implement this technique, one of which is proposed by Bowman et al. [185].

2.4 Manipulation-Based

Manipulation-based VLTs generally work by manipulating the user's position, orientation, or scale using gestures that either control the virtual viewpoint or the virtual world [3]. Ware and Osborne [186] proposed two manipulation-based VR locomotion metaphors. With the Eyeball-in-hand interaction metaphor, the position and orientation of the virtual viewpoint are updated according to changes in the position and orientation of the user's hand; while Scene-in-hand offers control of the virtual world through the manipulation of a physical prop. A qualitative study compared between the Eyeball-in-hand, the Scene-in-hand, and flying metaphors in the context of an exploration and movie making tasks. No notable differences were found between the three metaphors in terms of ease of control, ease of movie making, and ease of exploration. As suggested in [3], existing manipulation techniques can be used to control the virtual viewpoint by "grabbing the air" hand gestures. Examples are the Go-Go manipulation technique [176] that enables manipulation of remote objects by extending the user's virtual arm to unrealistic distances, and the HOMER manipulation technique [187] that similarly allows for the manipulation of remote objects when selected by ray casting. A study by Bowman et al. [175] compared between Go-Go and HOMER among other locomotion techniques. Go-Go was found significantly faster than HOMER in a naive search task while the two techniques yielded comparable search times when search was primed. The same study reported that Go-Go caused dizziness, nausea and arm-strain in some users. Manipulation-based techniques also performed generally worse than steering techniques in that study.

Several manipulation-based VLTs also utilize the WIM metaphor, where the virtual viewpoint is updated as a result of manipulating a representation of the user's virtual avatar in a 3D map of the VE [166], [188], [189], [190]. Stoakley et al. [188] conducted a qualitative evaluation of using a WIM metaphor to model a virtual office space that involved using the WIM for locomotion and object manipulation. It was observed that updating the virtual viewpoint using the WIM caused disorientation. Valkov et al. [166] explored the value of using a WIM metaphor in augmenting the capabilities of their leaning interface. Manipulation of the WIM had no effect on the primary viewpoint and were only used to assist subjects in self-orientation and wayfinding. In the study, participants were asked to explore a virtual city with and without and WIM. Using the WIM resulted in significantly better results in terms of ease of self-orientation and wayfinding. Using the WIM did not show a notable value, however, in terms of ease of navigation, locomotion speed, precision, intuitiveness, learnability, and fatigue. Wingrave et al. [190] studied the effect of the ability to change the scale of the WIM on ease of use and spatial performance. The improved WIM design (Scaled Scrolling WIM) was compared against a fixed-scale WIM design (standard WIM) in a spatial task that involved looking for and traveling to a blue sphere. No significant difference was found between the two techniques in terms of ease of use and trial completion time. The Scaled Scrolling technique, however, resulted in significantly higher accuracy than the standard WIM.

2.5 Multiscale Virtual Locomotion

Aside from grounded virtual navigation, there are use cases for which vertical navigation (e.g., flying) or multiscale exploration of the VE is required. Multiscale VLTs are designed for these purposes. Depending on how the scale is controlled, these techniques can be classified as either active or automatic scaling techniques [3]. In *active* scaling techniques, scale is manipulated using controllers [190], [191], hand [192], [193] or foot [34] gestures. *Automatic* scaling techniques aim to relieve the user from the task of controlling the scale to focus on the task at hand. Argelaguet et al. [194] classifies automatic scaling techniques according to the granularity of scaling to either discrete or continuous.

In *discrete* scaling techniques, the user moves into and out of hierarchical levels of scale. Kopper et al. [195] proposed a discrete auto scaling VLT for multiscale VEs. Users can explore different levels of scale using a virtual magnifying glass and move into or out of a new level of scale either instantly using teleportation or gradually by flying. Bacim et al. [196] later improved the aforementioned technique by adding wayfinding aids such as marked maps, WIMs, and hierarchical representation of the multiscale environment.

Scale is manipulated gradually in *continuous* scaling techniques. To ensure usability and comfort during continuous scaling, several research efforts have been made to automatically adjust other parameters such as travel speed and stereo parameters [194]. Most of the speed adjustment implementations modulate the speed depending on the distance between the virtual viewpoint and the virtual surroundings [197], [198], [199]. Other implementations also consider other criteria such as optical flow [194], [200] as well as informativeness of [201] and degree of interest in [202] the current viewpoint. Depth-based information has also been used to adjust stereo parameters (e.g., inter-pupillary distance) [203] and resolve stereo fusion issues that result from scale adjustment [204].

3 VR Locomotion Taxonomies

The majority of research work that aim to examine VR locomotion at a high level has been in the form of developing meaningful taxonomies. Taxonomies that decompose VLTs to a set of design components, similar to that of Bowman et al. [160], can serve as design palettes from which developers and interaction designers could assemble new techniques. Taxonomies that assign VLTs to clusters of techniques that share common characteristics, similar to that of Suma et al. [30], can be helpful to researchers in at least two ways. First, experiment designs of techniques that share the same category can be reused to evaluate a new VLT that belongs to the same category. This not only saves time and effort in coming up with a new study design, but also helps by making results comparable. Second, categorization of VLTs allows for "macro" comparisons between categories of VLTs. When such comparison is made at this high level, common strengths and weaknesses among categories of VLTs can be found. Existing taxonomies are either targeted towards classifying all VLTs in general or just one family of techniques in particular.

3.1 General Taxonomies

Mine [148] decomposed VLTs according to their two fundamental components: direction and speed. Direction control was subdivided into: HDS, GDS, physical control, virtual control, object-driven, and goal-driven. Speed control, on the other hand, was categorized to: constant speed, constant acceleration, hand-controlled, physically-controlled, and virtually-controlled. Bowman et al. [160] proposed a similar decomposition criteria. Along with the direction and speed controls, they added input conditions as a third decomposition component to describe how input to start and stop virtual travel could be supplied. Arns [205] similarly proposed a taxonomy that decomposes VLTs according to direction and speed control while also incorporating system factors such as the type of VR display and interaction device as additional decomposition components. Bowman et al. [185] proposed another taxonomy of travel techniques based on the amount of control that the user has over starting/stopping travel, controlling position, and controlling orientation. Aside from decomposing VLTs based on their design components, Nilsson et al. [206] proposed a classification that assumes the dimensions of metaphor plausibility, virtual movement source, and user mobility. Adopted from Slater and Usoh's VR interaction techniques classification [207], metaphor plausibility classifies travel techniques into mundane (i.e., uses a realistic metaphor) or magical (i.e., uses unrealistic metaphor). The second dimension, virtual movement source, can either be body-centric or vehicular. Similar to Wendt's classification of walking techniques [208], the dimension of user mobility classifies travel techniques into ones that require physical translation (mobile) or ones that make the user stationary. Virtual travel techniques were also classified into two broad categories: active and passive. Some researchers [6], [209] consider a travel interface as active if it closely resembles how humans walk by exerting a repetitive limb motion either using their legs or arms while others [3] classify a technique as active when it requires a body-driven motion irrespective of its pattern. Another common taxonomy [3], [4] is the one we used to organize the overview of VLTs in Section 2 which classifies VLTs as physical, steering, selection-based, and manipulation-based.

3.2 Specific Taxonomies

Another set of taxonomies were targeted to classify the VLTs that belong to a certain virtual locomotion family. Steinicke et al. [31] introduced a categorization of RDW techniques according to the type of gain applied to the virtual viewpoint in order to keep the user confined within the boundaries of the physical tracking space. Three types of gains were listed: translation, rotation, and curvature. A more generalized taxonomy for redirection techniques was proposed by Suma et al. [30] in which redirection techniques were classified into three dimensions: technique used (reorientation versus repositioning), continuity (discrete versus continuous), and imperceptibility (overt versus covert). Wendt [208] proposed a taxonomy for walking-based VLTs, represented as a decision tree. Techniques were distinguished according to design decisions such as whether or not mobility is required, body parts used to activate virtual locomotion, and the control mechanism used to implement the technique. A different specific taxonomy [210] aimed to decompose walking-based VLTs into six components: movement range, walking surface, transfer function, user support, walking movement style, and input properties sensed.

4 Discussion

The majority of the surveyed studies demonstrated the superiority of *real walking* over virtual locomotion techniques in search [14], exploration [10], and path traversal tasks [13], [15] in terms of spatial understanding [8], [10], navigation performance [13], [14], [15], VR sickness [8], presence [9], [10], and usability [9], [15]. Such superiority is mostly due to the translational and rotational body inputs that RW provides [8], [14]. Generally, RW was found mostly applicable in tasks that require problem solving, spatial understanding [10], or obstacles avoidance in complex VEs [14] where relatively little training is required [10], [13]. RW is also desirable in virtual experiences that call for a high degree of realism such as training [1]. RW, however, is not the silver bullet of VR locomotion. For it be enabled, RW requires a tracking space that is void of obstacles as well as a positional tracking system. These are costs whose benefits are not always justified [11]. While RW has high interaction fidelity [15], it is still not suitable to support some virtual scenarios such as flying or even running.

Redirection techniques' ultimate goal is to enable unlimited real walking in virtual environments in order to both reap the benefits of RW and improve the safety of virtual navigation. Redirecting users imperceptibly has been the most attractive alternative as it aims to make users walk infinitely in VR without the need to break their experience when reaching the boundaries of the physical space. With a required tracking space that varies between 12 meters [68] and 44 meters [42] in width, such techniques have been difficult to evaluate with live user testing [58] and to use in a typical home setting. It is possible to achieve redirection with perceptible gains, but such gains have showed a negative effect on walking patterns and cognitive performance [74]. RDW with distractors has also been shown to be an effective alternative for imperceptible redirection [61]. Users, however, can choose to ignore the distractor, causing the redirection to fail [54]. The distractor should also be well-blended with the narrative of the virtual experience for it be perceived as natural [78]. Imperceptible redirection through the manipulation of the VE's structure was also shown to be feasible [43], [47], [48] though it is limited to structured VEs. While redirection using this technique enables exploration of an infinite number of virtual spaces, it does not allow walking in a single virtual space that is larger than the tracking space. Resetting techniques have been proposed to mitigate the potential failure of redirection techniques. A common criticism of these techniques is the interruption of the virtual experience that may break presence. Such limitation motivated the design of active resetting techniques such as portals [52] and cell-based redirection [55].

Partial gait techniques such as WIP offer another alternative for infinite bipedal locomotion in VR especially when tracking space [94], [114] or computing power [110] (e.g., on mobile VR) are limited. Although it only covers parts of the human gait cycle, WIP has shown its effectiveness from a multitude of perspectives. Due to the proprioceptive and vestibular cues provided by the stepping gestures [112], WIP was as effective as RW in assisting participants to maintain their orientation while navigating VEs [94], [107]. These gestures also helped participants to have better sense of presence compared to virtual locomotion techniques [109], [111], [211] while some studies reported presence scores that are comparable to RW [9]. WIP was also rated as more usable than virtual techniques [110]. This can be due to the fact that WIP is hands-free, requiring no switching between interaction modes, compared to other hand-based VLTs [84]; and has better resemblance of how we walk, even in terms of the level of body exertion [119]. Despite these benefits, the design and implementation of effective WIP gestures faces a number of challenges. Marching WIP gestures often have to be exaggerated [1], making them perceived as strenuous [86]. This also has made it difficult for participants to differentiate between the physical states of walking and running [100]. Such issue motivated the design of less strenuous WIP gestures such as tapping in place [86], ones that capitalize on the by-products of walking [109], or ones that use entirely different body parts to resemble WIP [105]. While WIP, in concept, requires very limited physical space, the issue of unintentional positional drift, especially associated with marching WIP gestures [119], still requires a sufficient space that is void of obstacles. Otherwise, alternative WIP gestures such as tapping or wiping [86] should be used instead. Platform-based implementations of WIP were proposed to satisfy a special target experience such as uneven terrain simulation [90]. Aside from the cost and instrumentation that such solutions require [84], platform-based implementations pose the risk of falling off the platform during locomotion [94]. Recent WIP implementations often capitalize on the sensors already available at the HMD, but they are criticized because they couple steering to head direction [110]. Aside from solving this issue with the addition of extra sensors [1], [86], partial decoupling solutions were proposed without any extra sensors [111]. Other solutions also proposed to complement WIP with LDS interfaces [173] to achieve decoupling. While such coupling did hinder participants' navigation performance in some studies [160], other studies found that WIP with head steering resulted in better spatial orientation compared to that with the torso [95]. Control precision of current WIP implementations is one of the most contemporary challenges to the applicability of WIP. This issue likely stems from limitations of the step detection algorithms such as false positives and negatives [9], [84], which usually manifest as latency in starting and stopping of locomotion [99]. Due to this, the use of WIP in narrow spaces (e.g., mazes) has been challenging [114]. The control limitations of WIP has also made it difficult to navigate curved paths [110], [115].

Gait negation techniques keep users within the confines of the physical space by canceling their displacement [147] while experiencing the full gait cycle. Such techniques depend on dedicated platforms that often offer rich locomotion experiences that go beyond walking such as the simulation of inertial forces [131], [133], uneven terrains [139] and surface textures [140]. Some of these platforms also support decoupling of head direction from steering [122], allowing for more realistic locomotion. Their dependency on a platform, however, has introduced a number of challenges that can limit their adoption and applicability. Users can lose balance and fall off these platforms, especially when adjusting their orientation [125]. A harness can be used to mitigate this risk [212], but it can restrict users' movement and affect the naturalism of locomotion [131], [213]. The range of speeds and accelerations supported by most of these platforms is limited [124], [130], especially for step-based devices [140], [146], making it impossible to support virtual scenarios that require running. Some of these platforms are very unfamiliar, which has affected their performance [15], and required more time for training [142] and balance adaptation [16]. Finally, acquiring such platforms is costly, affecting their chances of adoption by the masses.

Spatial steering techniques offer continuous steering body input provided by the head, hands, torso or leaning. Their implementation often depends on either the already available sensors of the HMD or cheap sensing platforms, making them affordable for the masses. Because users are stationary while using these techniques, unlimited virtual distances can be covered with limited physical space and low exertion [158]. Spatial steering techniques yielded the shortest completion time in naive and primed search tasks compared to selection and manipulation-based techniques, making them good candidates when this measure is the most important [175]. Aside from a few implementations [165], [167], many spatial steering techniques require upper-body input, making them candidates for seated virtual experiences and people with motor impairments. Unlike walking-based techniques, spatial steering techniques, especially HDS, make it possible to offer vertical locomotion, usually designed using the flying metaphor. Although such techniques are usually labeled as virtual [162], they have shown their potential to mimic ecological forms of locomotion other than natural walking such as skiing [154] and surfing [167]. The suitability of these techniques, however, is affected by their design characteristics. GDS couples the viewpoint with steering direction, making users unable to look around while moving in a certain direction. Such coupling can make GDS easier to learn and effective to some degree in basic navigation tasks such as path integration [14], but it can also impede effective information gathering during exploration [160], [174]. GDS uses the head to provide steering input. This may have the benefits of better steering control, which could be why GDS had better accuracy than HDS [160]. It may also provide synchronized vestibular input with yaw optical flow, which may reduce the incidence of VR sickness [209]. This overloading of the head, however, may result in excess head rotations, leading to discomfort [175]. On the contrary, HDS decouples steering from viewing by delegating steering to the hands. While decoupling was useful in search tasks [175], the use of the hands for steering has introduced a number of challenges such as fatigue resulting from prolonged use [157] and hand overloading with both locomotion and object manipulation, which requires learning how to switch between the two modes [151]. TDS offers a hands-free spatial steering interface that also decouples viewing from steering at the expense of adding an extra sensor [161]. LDS also has similar benefits to TDS with the caveats that leaning interfaces were not found optimal for precise locomotion scenarios [214] and that chair interfaces had usability issues that were linked to their unfamiliar design [171], [172].

Physical steering techniques help users steer with a physical prop that often aims to mimic the steering experience of a real-world vehicle. The haptic feedback as well as the natural mapping of the physical prop to its real-world counterpart makes such techniques suitable in cases when realistic vehicular locomotion is desired. A challenge to these techniques is the potential mismatch between physical realism of the steering prop and the realism of feedback forces that it provides, which may negatively affect the user experience [3]. Such a mismatch can make the performance of a technique worse than both virtual and natural locomotion techniques, placing it at the uncanny valley of interaction performance [215].

Selection-based techniques offer minimal involvement of the user in the process of locomotion. Discrete target selection techniques, such as teleportation, allow users to cover great virtual distances quickly with minimal physical effort [184]. The selection nature of these techniques poses a challenge in virtual scenarios when precise locomotion is required [175]. Due to their discrete nature, these techniques are most suitable for primed search tasks at which users have a particular target in mind [175] and have prior knowledge about the destination [184]. Their discreteness also makes them inefficient in naive search and exploration tasks [175]. This is in part due to the potential loss of information along the path between the source and the destination [164]. The lack of any optical flow is one of the key reasons that made teleportation popular in the VR industry as it helps reducing the incidence of VR sickness [164]. This instant jumping, however, is the cause of disorientation, which has been the most critical issue of teleportation [160], [183], [184]. The effects of disorientation can be reduced by introducing an accelerated transition between the source and destination [181], [182], [183], but speed of the transition has to be slow enough to enable spatial awareness and fast enough so that the duration of visual-vestibular conflict is reduced [3]. Disorientation can also be reduced by spatial familiarization of the destination beforehand [184]. As a low-exertion locomotion technique, teleportation may discourage users from using real walking, if available, which may lead to low presence [216]. Techniques that enable teleportation with body input [183] are, therefore, encouraged if more body engagement is desired. Most of the current target selection techniques require an input device, which may affect the overall performance of users in scenarios with demanding object manipulation. To mitigate this limitation, hands-free target selection techniques can be used instead [34], [183]. In tasks that require intensive cognitive load, target selection techniques that depend on maps should be avoided as they tend to have a negative effect on cognitive load [175], [185].

Manipulation-based techniques offer virtual locomotion either by manipulating the virtual viewpoint or by manipulating the virtual world. This has been realized either with hand gestures that are often borrowed from existing object manipulation techniques [175], [176] or with virtual avatar manipulation techniques on a WIM [188]. Hand gesture techniques are suitable in scenarios that demand heavy object manipulation, at which users can reuse the same technique for both object manipulation and locomotion. This, however, is at the expense of having to switch regularly between the two modes [3]. Due to the great physical effort that they often demand, such techniques are not suitable to travel long virtual distances [175]. Unlike grounded locomotion that mimics how we navigate the real world, locomotion using WIMs offers a larger spatial context of VE that can be viewed from multiple perspectives and at various scales [188]. Similar to the issue with teleportation, moving the virtual viewpoint instantly when the user's avatar is placed at a new location in the WIM can be disorienting. This can be mitigated by smoothly moving the viewpoint as it is transitioned from the source to the destination [188]. When the VE has structured paths (e.g., a virtual city), the viewpoint can be transitioned over a path that is constrained by the structure of the VE to provide better spatial awareness [189]. Varying the scale of the WIM is another issue that needs to be dealt with to improve the effectiveness of such technique. This can be addressed either by introducing WIM scrolling interfaces [190] or by using a dedicated scaling gesture [34].

Multiscale VLTs are suitable for VEs with details that cannot be shown all at once either due to their complexity or due to their hierarchical nature [195]. Techniques that move the virtual viewpoint through discrete levels of scale carry the concern associated with target selection techniques in that they should keep the user spatially oriented throughout the locomotion experience, which has been addressed by adding wayfinding aids [196]. Discrete techniques should also make objects with nested scales discoverable using appropriate metaphors (e.g., a magnifying glass [195]). Along with the automatic adjustment of scale, auto scaling techniques should also modulate the navigation speed and the stereo visual parameters to avoid inducing VR sickness [200] or eye discomfort resulting from vergence-accommodation conflict [197]. To improve the navigation performance, auto scaling techniques should also consider collision avoidance as a factor when the aforementioned parameters are automatically modulated [198].

5 Conclusion

In this paper, we survey the recent developments in VR locomotion research by presenting the implementations, evaluations, and classifications of virtual locomotion techniques. We also discuss the strengths, weaknesses, and applicability of the surveyed techniques in order to provide guidance on when each technique may or may not be suitable. We hope that the outcome of this work will provide the VR locomotion research community with a high-level overview of the field's state of the art that is helpful to better understand and advance the design and evaluation of VR locomotion techniques.

References

[1] J. N. Templeman, P. S. Denbrook, and L. E. Sibert, "Virtual locomotion: Walking in place through virtual environments," *Presence: Teleoperators Virtual Environ.*, vol. 8, no. 6, pp. 598–617, 1999.

[2] M. Slater and M. V. Sanchez-Vives, "Enhancing our lives with immersive virtual reality," *Frontiers Robot. AI*, vol. 3, 2016, Art. no. 47.

[3] J. J. LaViola Jr, E. Kruijff, R. P. McMahan, D. A. Bowman, and I. P. Poupyrev, *3D User Interfaces: Theory and Practice*. Reading, MA, USA: Addison-Wesley, 2017.

[4] J. Jerald, *The VR Book: Human-Centered Design for Virtual Reality*. Williston, VT, USA: Morgan & Claypool, 2015.

[5] R. P. McMahan, R. Kopper, and D. A. Bowman, "Principles for designing effective 3D interaction techniques," in *Handbook of Virtual Environments: Design, Implementation, and Applications*. Boca Raton, FL, USA: CRC Press, 2014, pp. 285–311.

[6] J. M. Hollerbach, "Locomotion interfaces," in *Handbook of Virtual Environments: Design, Implementation, and Applications*. Boca Raton, FL, USA: CRC Press, 2002, pp. 239–254.

[7] R. P. McMahan, "Exploring the effects of higher-fidelity display and interaction for virtual reality games," Dept: Computer Science, Ph.D. dissertation, Virginia Tech, Blacksburg, VA, USA, 2011.

[8] S. S. Chance, F. Gaunet, A. C. Beall, and J. M. Loomis, "Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration," *Presence: Teleoperators Virtual Environ.*, vol. 7, no. 2, pp. 168–178, 1998.

[9] M. Usoh, K. Arthur, M. C. Whitton, R. Bastos, A. Steed, M. Slater, and F. P. Brooks Jr, "Walking $>$ walking-in-place $>$ flying, in virtual environments," in *Proc. Conf. Comput. Graph. Interactive Tech.*, 1999, pp. 359–364.

[10] C. Zanbaka, S. Babu, D. Xiao, A. Ulinski, L. Hodges, and B. Lok, "Effects of travel technique on cognition in virtual environments," in *Proc. IEEE Virtual Reality*, 2004, pp. 149–286.

[11] E. A. Suma, S. Babu, and L. F. Hodges, "Comparison of travel techniques in a complex, multi-level 3D environment," in *Proc. IEEE Symp. User Interfaces*, 2007, pp. 147–153.

[12] E. A. Suma, S. L. Finkelstein, M. Reid, A. Ulinski, and L. F. Hodges, "Real walking increases simulator sickness in navigationally complex virtual environments," in *Proc. IEEE Virtual Reality*, 2009, pp. 245–246.

[13] R. A. Ruddle, E. Volkova, and H. H. Bülthoff, "Learning to walk in virtual reality," *ACM Trans. Appl. Perception*, vol. 10, no. 2, pp. 11:1–11:17, 2013.

[14] R. A. Ruddle and S. Lessels, "The benefits of using a walking interface to navigate virtual environments," *ACM Trans. Comput.-Human Interaction*, vol. 16, no. 1, pp. 5:1–5:18, 2009.

[15] M. Nabiyouni, A. Saktheeswaran, D. A. Bowman, and A. Karanth, "Comparing the performance of natural, semi-natural, and non-natural locomotion techniques in virtual reality," in *Proc. IEEE Symp. User Interfaces*, 2015, pp. 3–10.

[16] E. Medina, R. Fruland, and S. Weghorst, "Virtusphere: Walking in a human size VR hamster ball" in *Proc. Human Factors Ergonomics Soc. Annu. Meeting*, 2008, pp. 2102–2106.

[17] I. E. Sutherland, "A head-mounted three dimensional display," in *Proc. Fall Joint Comput. Conf.*, 1968, pp. 757–764.

[18] UNC tracker project. [Online]. Available: http://www.cs.unc.edu/tracker/

[19] G. Welch, G. Bishop, L. Vicci, S. Brumback, K. Keller, and D. Colucci, "High-performance wide-area optical tracking: The hiball tracking system," *Presence: Teleoperators Virtual Environ.*, vol. 10, no. 1, pp. 1–21, 2001.

[20] K. Meyer, H. L. Applewhite, and F. A. Biocca, "A survey of position trackers," *Presence: Teleoperators Virtual Environ.*, vol. 1, no. 2, pp. 173–200, 1992.

[21] D. K. Bhatnagar, "Position trackers for head mounted display systems: A survey," UNC Chapel Hill, Chapel Hill, NC, USA, Tech. Rep. TR93, 1993.

[22] G. Welch and E. Foxlin, "Motion tracking: No silver bullet, but a respectable arsenal," *IEEE Comput. Graph. Appl.*, vol. 22, no. 6, pp. 24–38, Nov./Dec. 2002.

[23] J. Rolland, L. Davis, and Y. Baillot, "A survey of tracking technology for virtual environments," in *Fundamentals of Wearable Computers and Augumented Reality*. Boca Raton, FL, USA: CRC Press, 2001, pp. 67–112.

[24] Y.-W. Chow, "A cost-effective 3D interaction approach for immersive virtual reality," *Int. J. Recent Trends Eng. Technol.*, vol. 1, no. 1, pp. 527–529, 2009.

[25] T. Pintaric and H. Kaufmann, "Affordable infrared-optical pose-tracking for virtual and augmented reality," in *Proc. IEEE Virtual Reality Workshop Trends Issues Tracking Virtual Environ.*, 2007, pp. 44–51.

[26] E. Foxlin, L. Naimark, et al., "Vis-tracker: A wearable vision-inertial self-tracker," in *Proc. IEEE Virtual Reality*, 2003, pp. 199–206.

[27] S. Maesen, P. Goorts, and P. Bekaert, "Scalable optical tracking for navigating large virtual environments using spatially encoded markers," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2013, pp. 101–110.

[28] D. Pustka, J.-P. Hülß, J. Willneff, F. Pankratz, M. Huber, and G. Klinker, "Optical outside-in tracking using unmodified mobile phones," in *Proc. IEEE Int. Symp. Mixed Augmented Reality*, 2012, pp. 81–89.

[29] S. Razzaque, Z. Kohn, and M. C. Whitton, "Redirected walking," in *Proc. Eurographics*, 2001, pp. 105–106.

[30] E. A. Suma, G. Bruder, F. Steinicke, D. M. Krum, and M. Bolas, "A taxonomy for deploying redirection techniques in immersive virtual environments," in *Proc. IEEE Virtual Reality Workshops*, 2012, pp. 43–46.

[31] F. Steinicke, G. Bruder, L. Kohli, J. Jerald, and K. Hinrichs, "Taxonomy and implementation of redirection techniques for ubiquitous passive haptic feedback," in *Proc. Int. Conf. Cyberworlds*, 2008, pp. 217–223.

[32] V. Interrante, B. Ries, and L. Anderson, "Distance perception in immersive virtual environments, revisited," in *Proc. IEEE Virtual Reality*, 2006, pp. 3–10.

[33] E. Langbehn, P. Lubos, G. Bruder, and F. Steinicke, "Bending the curve: Sensitivity to bending of curved paths and application in room-scale VR," *IEEE Trans. Vis. Comput. Graph.*, vol. 23, no. 4, pp. 1389–1398, Apr. 2017.

[34] J. J. LaViola Jr, D. A. Feliz, D. F. Keefe, and R. C. Zeleznik, "Hands-free multi-scale navigation in virtual environments," in *Proc. ACM Symp. Interactive 3D Graph.*, 2001, pp. 9–15.

[35] S. Razzaque, D. Swapp, M. Slater, M. C. Whitton, and A. Steed, "Redirected walking in place," in *Proc. Eurographics Workshop Virtual Environ.*, 2002, pp. 123–130.

[36] N. Nitzsche, U. D. Hanebeck, and G. Schmidt, "Motion compression for telepresent walking in large target environments," *Presence: Teleoperators Virtual Environ.*, vol. 13, no. 1, pp. 44–60, 2004.

[37] B. Williams, G. Narasimham, T. P. McNamara, T. H. Carr, J. J. Rieser, and B. Bodenheimer, "Updating orientation in large virtual environments using scaled translational gain," in *Proc. ACM Symp. Appl. Perception Graph. Vis.*, 2006, pp. 21–28.

[38] B. Williams, G. Narasimham, B. Rump, T. P. McNamara, T. H. Carr, J. Rieser, and B. Bodenheimer, "Exploring large virtual environments with an HMD when physical space is limited," in *Proc. ACM Symp. Appl. Perception Graph. Vis.*, 2007, pp. 41–48.

[39] V. Interrante, B. Ries, and L. Anderson, "Seven league boots: A new metaphor for augmented locomotion through moderately large scale immersive virtual environments," in *Proc. IEEE Symp. User Interfaces*, 2007, pp. 167–170.

[40] D. Engel, C. Curio, L. Tcheang, B. Mohler, and H. H. Bülthoff, "A psychophysically calibrated controller for navigating through large environments in a limited free-walking space," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2008, pp. 157–164.

[41] G. Bruder, F. Steinicke, and K. H. Hinrichs, "Arch-explore: A natural user interface for immersive architectural walkthroughs," in *Proc. IEEE Symp. 3D User Interfaces*, 2009, pp. 75–82.

[42] F. Steinicke, G. Bruder, K. Hinrichs, and A. Steed, "Presence-enhancing real walking User Interface for first-person video games," in *Proc. ACM Symp. Video Games*, 2009, pp. 111–118.

[43] E. A. Suma, S. Clark, D. Krum, S. Finkelstein, M. Bolas, and Z. Warte, "Leveraging change blindness for redirection in virtual environments," in *Proc. IEEE Virtual Reality*, 2011, pp. 159–166.

[44] T. C. Peck, H. Fuchs, and M. C. Whitton, "The design and evaluation of a large-scale real-walking locomotion interface," *IEEE Trans. Vis. Comput. Graph.*, vol. 18, no. 7, pp. 1053–1067, Jul. 2012.

[45] J. Goldfeather and V. Interrante, "Adaptive redirected walking in a virtual world," in *Proc. IEEE Virtual Reality Workshop Perceptual Illusions Virtual Environ.*, 2012, pp. 17–20.

[46] G. Cirio, P. Vangorp, E. Chapoulie, M. Marchal, A. Lécuyer, and G. Drettakis, "Walking in a cube: Novel metaphors for safely navigating large virtual environments in restricted real workspaces," *IEEE Trans. Vis. Comput. Graph.*, vol. 18, no. 4, pp. 546–554, Apr. 2012.

[47] E. A. Suma, Z. Lipps, S. Finkelstein, D. M. Krum, and M. Bolas, "Impossible spaces: Maximizing natural walking in virtual environments with self-overlapping architecture," *IEEE Trans. Vis. Comput. Graph.*, vol. 18, no. 4, pp. 555–564, Apr. 2012.

[48] K. Vasylevska, H. Kaufmann, M. Bolas, and E. A. Suma, "Flexible spaces: Dynamic layout generation for infinite walking in virtual environments," in *Proc. IEEE Symp. 3D User Interfaces*, 2013, pp. 39–42.

[49] R. Zhang and S. A. Kuhl, "Flexible and general redirected walking for head-mounted displays," in *Proc. IEEE Virtual Reality*, 2013, pp. 127–128.

[50] M. A. Zmuda, J. L. Wonser, E. R. Bachmann, and E. Hodgson, "Optimizing constrained-environment redirected walking instructions using search techniques," *IEEE Trans. Vis. Comput. Graph.*, vol. 19, no. 11, pp. 1872–1884, Nov. 2013.

[51] P. Lubos, G. Bruder, and F. Steinicke, "Safe-&-round: Bringing redirected walking to small virtual reality laboratories," in *Proc. ACM Symp. Spatial User Interaction*, 2014, p. 154.

[52] S. Freitag, D. Rausch, and T. Kuhlen, "Reorientation in virtual environments using interactive portals," in *Proc. IEEE Symp. User Interfaces*, 2014, pp. 119–122.

[53] K. Matsumoto, Y. Ban, T. Narumi, Y. Yanase, T. Tanikawa, and M. Hirose, "Unlimited corridor: Redirected walking techniques using visuo haptic interaction," in *Proc. ACM SIGGRAPH Emerging Technol.*, 2016, pp. 20:1–20:2.

[54] H. Chen and H. Fuchs, "Supporting free walking in a large virtual environment: Imperceptible redirected walking with an immersive distractor," in *Proc. Comput. Graph. Int. Conf.*, 2017, pp. 22:1–22:6.

[55] R. Yu, W. S. Lages, M. Nabiyouni, B. Ray, N. Kondur, V. Chandrashekar, and D. A. Bowman, "Bookshelf and bird: Enabling real walking in large VR spaces," in *Proc. IEEE Symp. User Interfaces*, 2017, pp. 116–119.

[56] S. P. Sargunam, K. R. Moghadam, M. Suhail, and E. D. Ragan, "Guided head rotation and amplified head rotation: Evaluating semi-natural travel and viewing techniques in virtual reality," in *Proc. IEEE Virtual Reality*, 2017, pp. 19–28.

[57] S. Razzaque, "Redirected walking," Dept: Computer Science, Ph.D. dissertation, UNC Chapel Hill, Chapel Hill, NC, USA, 2005.

[58] E. Hodgson, E. Bachmann, and D. Waller, "Redirected walking to explore virtual environments: Assessing the potential for spatial interference," *ACM Trans. Appl. Perception*, vol. 8, no. 4, 2011, Art. no. 22.

[59] T. Nescher, Y.-Y. Huang, and A. Kunz, "Planning redirection techniques for optimal free walking experience using model predictive control," in *Proc. IEEE Symp. User Interfaces*, 2014, pp. 111–118.

[60] M. Azmandian, T. Grechkin, M. Bolas, and E. Suma, "Automated path prediction for redirected walking using navigation meshes," in *Proc. IEEE Symp. 3D User Interfaces*, 2016, pp. 63–66.

[61] T. C. Peck, H. Fuchs, and M. C. Whitton, "Improved redirection with distractors: A large-scale-real-walking locomotion interface and its effect on navigation in virtual environments," in *Proc. IEEE Virtual Reality*, 2010, pp. 35–38.

[62] G. Cirio, M. Marchal, T. Regia-Corte, and A. Lécuyer, "The magic barrier tape: a novel metaphor for infinite navigation in virtual worlds with a restricted walking workspace," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2009, pp. 155–162.

[63] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe, “Analyses of human sensitivity to redirected walking,” in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2008, pp. 149–156.

[64] F. Steinicke, G. Bruder, J. Jerald, H. Frenz, and M. Lappe, “Estimation of detection thresholds for redirected walking techniques,” *IEEE Trans. Vis. Comput. Graph.*, vol. 16, no. 1, pp. 17–27, Feb. 2010.

[65] G. Bruder, F. Steinicke, K. H. Hinrichs, and M. Lappe, “Reorientation during body turns,” in *Proc. Joint Virtual Reality Conf.*, 2009, pp. 145–152.

[66] C. T. Neth, J. L. Souman, D. Engel, U. Kloos, H. H. Bulthoff, and B. J. Mohler, “Velocity-dependent dynamic curvature gain for redirected walking,” *IEEE Trans. Vis. Comput. Graph.*, vol. 18, no. 7, pp. 1041–1052, Jul. 2012.

[67] R. Zhang and S. A. Kuhl, “Human sensitivity to dynamic rotation gains in head-mounted displays,” in *Proc. ACM Symp. Appl. Perception*, 2013, pp. 71–74.

[68] T. Grechkin, J. Thomas, M. Azmandian, M. Bolas, and E. Suma, “Revisiting detection thresholds for redirected walking: combining translation and curvature gains,” in *Proc. ACM Symp. Appl. Perception*, 2016, pp. 113–120.

[69] A. Paludan, J. Elbaek, M. Mortensen, M. Zobbe, N. C. Nilsson, R. Nordahl, L. Reng, and S. Serafin, “Disguising rotational gain for redirected walking in virtual reality: Effect of visual density,” in *Proc. IEEE Virtual Reality*, 2016, pp. 259–260.

[70] S. Serafin, N. C. Nilsson, E. Sikstrom, A. De Goetzen, and R. Nordahl, “Estimation of detection thresholds for acoustic based redirected walking techniques,” in *Proc. IEEE Virtual Reality*, 2013, pp. 161–162.

[71] N. C. Nilsson, E. Suma, R. Nordahl, M. Bolas, and S. Serafin, “Estimation of detection thresholds for audiovisual rotation gains,” in *Proc. IEEE Virtual Reality*, 2016, pp. 241–242.

[72] P. Schmitz, J. Hildebrandt, A. C. Valdez, L. Kobbelt, and M. Ziefle, “You spin my head right round: Threshold of limited immersion for rotation gains in redirected walking,” *IEEE Trans. Vis. Comput. Graph.*, vol. 24, no. 4, pp. 1623–1632, Apr. 2018.

[73] X. Xie, Q. Lin, H. Wu, G. Narasimham, T. P. McNamara, J. Rieser, and B. Bodenheimer, “A system for exploring large virtual environments that combines scaled translational gain and interventions,” in *Proc. Symp. Appl. Perception Graph. Vis.*, 2010, pp. 65–72.

[74] G. Bruder, P. Lubas, and F. Steinicke, “Cognitive resource demands of redirected walking,” *IEEE Trans. Vis. Comput. Graph.*, vol. 21, no. 4, pp. 539–544, Apr. 2015.

[75] R. Kopper, C. Stinson, and D. Bowman, “Towards an understanding of the effects of amplified head rotations,” in *Proc. IEEE Virtual Reality Workshop Perceptual Illusions Virtual Environ.*, 2011, pp. 10–15.

[76] E. D. Ragan, S. Scerbo, F. Bacim, and D. A. Bowman, “Amplified head rotation in virtual reality and the effects on 3D search, training transfer, and spatial orientation,” *IEEE Trans. Vis. Comput. Graph.*, vol. 23, no. 8, pp. 1880–1895, Aug. 2017.

[77] S. Freitag, B. Weyers, and T. W. Kuhlen, “Examining rotation gain in CAVE-like virtual environments,” *IEEE Trans. Vis. Comput. Graph.*, vol. 22, no. 4, pp. 1462–1471, Apr. 2016.

[78] T. C. Peck, H. Fuchs, and M. C. Whitton, “Evaluation of reorientation techniques and distractors for walking in large virtual environments,” *IEEE Trans. Vis. Comput. Graph.*, vol. 15, no. 3, pp. 383–394, May 2009.

[79] E. A. Suma, D. M. Krum, S. Finkelstein, and M. Bolas, “Effects of redirection on spatial orientation in real and virtual environments,” in *Proc. IEEE Symp. User Interfaces*, 2011, pp. 35–38.

[80] E. A. Suma, S. Clark, S. L. Finkelstein, and Z. Wartell, “Exploiting change blindness to expand walkable space in a virtual environment,” in *Proc. IEEE Virtual Reality*, 2010, pp. 305–306.

[81] E. Langbehn, P. Lubos, and F. Steinicke, “Evaluation of locomotion techniques for room-scale VR. joystick, teleportation, and redirected walking,” in *Proc. Virtual Reality Int. Conf.*, 2018, pp. 4:1–4:9.

[82] E. Hodgson and E. Bachmann, “Comparing four approaches to generalized redirected walking: Simulation and live user data,” *IEEE Trans. Vis. Comput. Graph.*, vol. 19, no. 4, pp. 634–643, Apr. 2013.

[83] E. Hodgson, E. Bachmann, and T. Thrash, “Performance of redirected walking algorithms in a constrained virtual world,” *IEEE Trans. Vis. Comput. Graph.*, vol. 20, no. 4, pp. 579–587, Apr. 2014.

[84] M. Slater, A. Steed, and M. Usoh, “The virtual treadmill: A naturalistic metaphor for navigation in immersive virtual environments,” in *Proc. Eurographics Workshop Virtual Environ.*, 1995, pp. 135–148.

[85] M. Slater, M. Usoh, and A. Steed, “Steps and ladders in virtual reality,” in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 1994, pp. 45–54.

[86] N. C. Nilsson, S. Serafin, M. H. Laursen, K. S. Pedersen, E. Sikström, and R. Nordahl, “Tapping-in-place: Increasing the naturalness of immersive walking-in-place locomotion through novel gestural input,” in *Proc. IEEE Symp. 3D User Interfaces*, 2013, pp. 31–38.

[87] E. Guy, P. Punpongsanon, D. Iwai, K. Sato, and T. Boubekeur, “LazyNav: 3D ground navigation with non-critical body parts,” in *Proc. IEEE Symp. 3D User Interfaces*, 2015, pp. 43–50.

[88] D. Zielasko, S. Horn, S. Freitag, B. Weyers, and T. W. Kuhlen, “Evaluation of hands-free HMD-based navigation techniques for immersive data analysis,” in *Proc. IEEE Symp. 3D User Interfaces*, 2016, pp. 113–119.

[89] L. Bouguila and M. Sato, “Virtual locomotion system for large-scale virtual environment,” in *Proc. IEEE Virtual Reality*, 2002, pp. 291–292.

[90] L. Bouguila, B. Hirsbrunner, M. Sato, and M. Iwashita, “Virtual locomotion interface with ground surface simulation,” in *Proc. Int. Conf. Artif. Reality Telexistence*, 2003.

[91] L. Bouguila, F. Evequoz, M. Courant, and B. Hirsbrunner, “Walking-pad: a step-in-place locomotion interface for virtual environments,” in *Proc. ACM Int. Conf. Multimodal Interfaces*, 2004, pp. 77–81.

[92] D. Lala and T. Nishida, “Visie: A spatially immersive interaction environment using real-time human measurement,” in *Proc. IEEE Int. Conf. Granular Comput.*, 2011, pp. 363–368.

[93] D. J. Zielinski, R. P. McMahan, and R. B. Brady, “Shadow walking: An unencumbered locomotion technique for systems with under-floor projection,” in *Proc. IEEE Virtual Reality*, 2011, pp. 167–170.

[94] B. Williams, S. Bailey, G. Narasimham, M. Li, and B. Bodenheimer, “Evaluation of walking in place on a Wii balance board to explore a virtual environment,” *ACM Trans. Appl. Perception*, vol. 8, no. 3, pp. 19:1–19:14, 2011.

[95] B. Williams, M. McCaleb, C. Strachan, and Y. Zheng, “Torso versus gaze direction to navigate a ve by walking in place,” in *Proc. ACM Symp. Appl. Perception*, 2013, pp. 67–70.

[96] K. Fujita, “Wearable locomotion interface using walk-in-place in real space (WARP) for distributed multi-user walk-through application,” in *Proc. IEEE Virtual Reality Workshop*, 2004, pp. 29–30.

[97] L. Yan, R. Allison, and S. Rushton, “New simple virtual walking method-walking on the spot,” in *Proc. Immersive Projection Technol.*, 2004.

[98] J.-S. Kim, D. Gračanin, and F. Quek, “Sensor-fusion walking-in-place interaction technique using mobile devices,” in *Proc. IEEE Virtual Reality Workshops*, 2012, pp. 39–42.

[99] J. Feasel, M. C. Whitton, and J. D. Wendt, “LLCM-WIP: Low-latency, continuous-motion walking-in-place,” in *Proc. IEEE Symp. 3D User Interfaces*, 2008, pp. 97–104.

[100] J. D. Wendt, M. C. Whitton, and F. P. Brooks, “GUD WIP: Gait-understanding-driven walking-in-place,” in *Proc. IEEE Virtual Reality*, 2010, pp. 51–58.

[101] L. Bruno, J. Pereira, and J. Jorge, “A new approach to walking in place,” in *Proc. Human-Comput. Interaction – INTERACT*, 2013, pp. 370–387.

[102] L. Bruno, M. Sousa, A. Ferreira, J. M. Pereira, and J. Jorge, “Hip-directed walking-in-place using a single depth camera,” *Int. J. Human-Comput. Stud.*, vol. 105, no. 9, pp. 1–11, 2017.

[103] N. C. Nilsson, S. Serafin, and R. Nordahl, “Establishing the range of perceptually natural visual walking speeds for virtual walking-in-place locomotion,” *IEEE Trans. Vis. Comput. Graph.*, vol. 20, no. 4, pp. 569–578, Apr. 2014.

[104] N. C. Nilsson, S. Serafin, and R. Nordahl, “The influence of step frequency on the range of perceptually natural visual walking speeds during walking-in-place and treadmill locomotion,” in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2014, pp. 187–190.

[105] J.-S. Kim, D. Gračanin, K. Matković, and F. Quek, “Finger walking in place (FWIP): A traveling technique in virtual environments,” in *Proc. Int. Symp. Smart Graph.*, 2008, pp. 58–69.

[106] J.-S. Kim, D. Gracanin, K. Matkovic, and F. Quek, “iphone/ipod touch as input devices for navigation in immersive virtual environments,” in *Proc. IEEE Virtual Reality*, 2009, pp. 261–262.

[107] M. McCullough, H. Xu, J. Michelson, M. Jackoski, W. Pease, W. Cobb, W. Kalescky, J. Ladd, and B. Williams, “Myo arm: swinging to explore a VE,” in *Proc. ACM Symp. Appl. Perception*, 2015, pp. 107–113.

[108] B. Sarupuri, M. L. Chipana, and R. W. Lindeman, “Trigger walking: A low-fatigue travel technique for immersive virtual reality,” in *Proc. IEEE Symp. 3D User Interfaces*, 2017, pp. 227–228.

[109] L. Terziman, M. Marchal, M. Emily, F. Multon, B. Arnaldi, and A. Lécuyer, “Shake-your-head: Revisiting walking-in-place for desktop virtual reality,” in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2010, pp. 27–34.

[110] S. Tregillus and E. Folmer, “Vr-step: Walking-in-place using inertial sensing for hands free navigation in mobile VR environments,” in *Proc. ACM CHI Conf. Human Factors Comput. Syst.*, 2016, pp. 1250–1255.

[111] T. Pfeiffer, A. Schmidt, and P. Renner, “Detecting movement patterns from inertial data of a mobile head-mounted-display for navigation via walking-in-place,” in *Proc. IEEE Virtual Reality*, 2016, pp. 263–264.

[112] M. Slater, M. Usoh, and A. Steed, “Taking steps: the influence of a walking technique on presence in virtual reality,” *ACM Trans. Comput.-Human Interaction*, vol. 2, no. 3, pp. 201–219, 1995.

[113] A. Syed Muhammad, S. C. Ahn, and J.-I. Hwang, “Effect of using walk-in-place interface for panoramic video play in VR,” in *Proc. Symp. Spatial User Interaction*, 2016, p. 203.

[114] T. C. Peck, H. Fuchs, and M. C. Whitton, “An evaluation of navigational ability comparing redirected free exploration with distractors to walking-in-place and joystick locomotio interfaces,” in *Proc. IEEE Virtual Reality*, 2011, pp. 55–62.

[115] L. Terziman, M. Marchal, F. Multon, B. Arnaldi, and A. Lécuyer, “Comparing virtual trajectories made in slalom using walking-in-place and joystick techniques,” in *Proc. Joint Virtual Reality Conf.*, 2011, pp. 55–58.

[116] M. Xu, M. Murcia-López, and A. Steed, “Object location memory error in virtual and real environments,” in *Proc. IEEE Virtual Reality*, 2017, pp. 315–316.

[117] J.-S. Kim, D. Gracanin, K. Matkovic, and F. K. Quek, “The effects of finger-walking in place (FWIP) for spatial knowledge acquisition in virtual environments,” in *Proc. Int. Symp. Smart Graph.*, 2010, pp. 56–67.

[118] P. T. Wilson, W. Kalescky, A. MacLaughlin, and B. Williams, “VR locomotion: walking > walking in place > arm swinging,” in *Proc. ACM Int. Conf. Virtual Reality Continuum Appl. Ind.*, 2016, pp. 243–249.

[119] N. C. Nilsson, S. Serafin, and R. Nordahl, “The perceived naturalness of virtual locomotion methods devoid of explicit leg movements,” in *Proc. Motion Games*, 2013, pp. 155–164.

[120] F. P. Brooks Jr, “Walkthrougha dynamic graphics system for simulating virtual buildings,” in *Proc. ACM Workshop Interactive 3D Graph.*, 1987, pp. 9–21.

[121] F. Brooks, J. Airey, J. Alspaugh, and A. Bell, “Final technical report: Walkthrough project,” *Report Nat Sci. Found.*, NC Chapel Hill, Tech Rep. TR92-026, 1992.

[122] R. P. Darken, W. R. Cockayne, and D. Carmein, “The omni-directional treadmill: A locomotion device for virtual worlds,” in *Proc. ACM Symp. User Interface Softw. Technol.*, 1997, pp. 213–221.

[123] H. P. Crowell III, J. A. Faughn, P. K. Tran, and P. W. Wiley, “Improvements in the omni-directional treadmill: Summary report and recommendations for future development,” Army Res. Lab Aberdeen Proving Ground, Army Research Laboratory, Tech. Rep. ARL-TR-3958, 2006.

[124] H. Iwata, “The torus treadmill: Realizing locomotion in VEs,” *IEEE Comput. Graph. Appl.*, vol. 19, no. 6, pp. 30–35, Nov./Dec. 1999.

[125] H. N. T. Miyasato, “A new approach for canceling turning motion in the locomotion interface, ATLAS,” in *Proc. ASME Dyn. Syst. Control*, 1999, pp. 405–406.

[126] J. M. Hollerbach, Y. Xu, R. Christensen, S. C. Jacobsen, et al., “Design specifications for the second generation sarcos treadport locomotion interface,” in *Proc. ASME Dyn. Syst. Control*, 2000, pp. 1293–1298.

[127] J. Hollerbach, D. Grow, and C. Parker, “Developments in locomotion interfaces,” in *Proc. Int. Conf. Rehabil. Robot.*, 2005, pp. 522–525.

[128] J.-Y. Huang, “An omnidirectional stroll-based virtual reality interface and its application on overhead crane training,” *IEEE Trans. Multimedia*, vol. 5, no. 1, pp. 39–51, Mar. 2003.

[129] A. Nagamori, K. Wakabayashi, and M. Ito, “The ball array treadmill: A locomotion interface for virtual worlds,” in *Proc. IEEE Virtual Reality Workshop New Directions User Interfaces*, 2005, pp. 3–6.

[130] M. C. Schwaiger, T. Thummel, and H. Ulbrich, “A 2D-motion platform: The cybercarpet,” in *Proc. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2007, pp. 415–420.

[131] J. L. Souman, P. R. Giordano, M. Schwaiger, I. Frissen, T. Thümmel, H. Ulbrich, A. D. Luca, H. H. Bülthoff, and M. O. Ernst, “Cyberwalk: Enabling unconstrained omnidirectional walking through virtual environments,” *ACM Trans. Appl. Perception*, vol. 8, no. 4, pp. 25:1–25:22, 2011.

[132] D. Tristano, J. Hollerbach, and R. Christensen, “Slope display on a locomotion interface,” *Exp. Robot. VI*, vol. 250, pp. 193–201, 2000.

[133] J. M. Hollerbach, D. Checcacci, H. Noma, Y. Yanagida, and N. Tetsutani, “Simulating side slopes on locomotion interfaces using torso forces,” in *Proc. Symp. Haptic Interfaces Virtual Environ. Teleoperator Syst.*, 2003, pp. 91–98.

[134] T. Sugihara and T. Miyasato, “The terrain surface simulator ALF (alive! floor),” in *Proc. Int. Conf. Artif. Reality Telexistence*, 1998, pp. 170–174.

[135] H. Noma, T. Sugihara, and T. Miyasato, “Development of ground surface simulator for tel-e-merge system,” in *Proc. IEEE Virtual Reality*, 2000, pp. 217–224.

[136] R. C. Hayward and J. M. Hollerbach, “Implementing virtual stairs on treadmills using torso force feedback,” in *Proc. IEEE Int. Conf. Robot. Autom.*, vol. 1, 2002, pp. 586–591.

[137] G. P. Roston and T. Peurach, “A whole body kinesthetic display device for virtual reality applications,” in *Proc. IEEE Int. Conf. Robot. Autom.*, 1997, pp. 3006–3011.

[138] J. Wang, Y. Zhao, P. Jia, N. Tu, and D. Zhu, “Locomotion interface on a virtual plane,” in *Proc. Laval Virtual*, 1999, pp. 61–68.

[139] H. Iwata, H. Yano, and F. Nakaizumi, “Gait master: A versatile locomotion interface for uneven virtual terrain,” in *Proc. IEEE Virtual Reality*, 2001, pp. 131–137.

[140] R. Boian, M. Bouzit, G. Burdea, and J. Deutsch, “Dual stewart platform mobility simulator,” in *Proc. IEEE Eng. Med. Biol. Soc.*, 2004, pp. 4848–4851.

[141] J. Yoon and J. Ryu, “A novel locomotion interface with two 6-DOF parallel manipulators that allows human walking on various virtual terrains,” *Int. J. Robot. Res.*, vol. 25, no. 7, pp. 689–708, 2006.

[142] D. Swapp, J. Williams, and A. Steed, “The implementation of a novel walking interface within an immersive display,” in *Proc. IEEE Symp. 3D User Interfaces*, 2010, pp. 71–74.

[143] S. C. Grant and L. E. Magee, “Navigation in a virtual environment using a walking interface,” in *Proc. RTO Human Factors Med Workshop*, 1997, pp. 81–92.

[144] H. Iwata and T. Fujii, “Virtual perambulator: a novel interface device for locomotion in virtual environment,” in *Proc. IEEE Virtual Reality Annu. Int. Symp.*, 1996, pp. 60–65.

[145] K. J. Fernandes, V. Raja, and J. Eyre, “Cybersphere: The fully immersive spherical projection system,” *Commun. ACM*, vol. 46, no. 9, pp. 141–146, 2003.

[146] H. Iwata, H. Yano, H. Fukushima, and H. Noma, “Circulafloor,” *IEEE Comput. Graph. Appl.*, vol. 25, no. 1, pp. 64–67, Jan. 2005.

[147] H. Iwata, H. Yano, and M. Tomiyoshi, “String walker,” in *Proc. ACM SIGGRAPH Emerging Technol.*, 2007, Art. no. 20.

[148] M. R. Mine, “Virtual environment interaction techniques,” Dept: Computer Science, Ph.D. dissertation, UNC Chapel Hill, Chapel Hill, NC, USA, 1995.

[149] S. Stellmach and R. Dachselt, “Designing gaze-based User Interfaces for steering in virtual environments,” in *Proc. Symp. Eye Tracking Res. Appl.*, 2012, pp. 131–138.

[150] W. Robinett and R. Holloway, “Implementation of flying, scaling and grabbing in virtual worlds,” in *Proc. ACM Symp. Interactive 3D Graph.*, 1992, pp. 189–192.

[151] K. M. Fairchild, B. H. Lee, J. Loo, H. Ng, and L. Serra, “The heaven and earth virtual reality: Designing applications for novice users,” in *Proc. IEEE Virtual Reality Int. Symp.*, 1993, pp. 47–53.

[152] P. Boudoin, S. Otmane, and M. Mallem, “Fly over, a 3D interaction technique for navigation in virtual environments independent from tracking devices,” in *Proc. Int. Conf. Virtual Reality*, 2008, pp. 7–13.

[153] D. Bowman, C. Wingrave, J. Campbell, and V. Ly, “Using pinch gloves (TM) for both natural and abstract interaction techniques in virtual environments,” Virginia Tech, Blacksburg, VA, USA, Tech. Rep. TR-01-23, 2001.

[154] M. Haydar, M. Maidi, D. Roussel, and M. Mallem, “A new navigation method for 3D virtual environment exploration,” in *Proc. Amer. Inst. Phys. Conf.*, 2009, pp. 190–195.

[155] M. C. Cabral, C. H. Morimoto, and M. K. Zuffo, “On the usability of gesture interfaces in virtual reality environments,” in *Proc. Latin Amer. Conf. Human-Comput. Interaction*, 2005, pp. 100–108.

[156] C. Papadopoulos, D. Sugarman, and A. Kaufmant, “Nunav3D: A touch-less, body-driven interface for 3D navigation,” in *Proc. IEEE Virtual Reality Workshops*, 2012, pp. 67–68.

[157] J. Cardoso, “Comparison of gesture, gamepad, and gaze-based locomotion for VR worlds,” in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2016, pp. 319–320.

[158] F. Zhang, S. Chu, R. Pan, N. Ji, and L. Xi, "Double hand-gesture interaction for walk-through in VR environment," in *Proc. IEEE/ACIS Int. Conf. Comput. Inf. Sci.*, 2017, pp. 539–544.

[159] A. Ferracani, D. Pezzatini, J. Bianchini, G. Biscini, and A. Del Bimbo, "Locomotion by natural gestures for immersive virtual environments," in *Proc. Int. Workshop Multimedia Alternate Realities*, 2016, pp. 21–24.

[160] D. A. Bowman, D. Koller, and L. F. Hodges, "Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques," in *Proc. IEEE Int. Symp. Virtual Reality*, 1997, pp. 45–52.

[161] E. A. Suma, S. L. Finkelstein, S. Clark, P. Goolkasian, and L. F. Hodges, "Effects of travel technique and gender on a divided attention task in a virtual environment," in *Proc. IEEE Symp. 3D User Interfaces*, 2010, pp. 27–34.

[162] E. Suma, S. Finkelstein, M. Reid, S. Babu, A. Ulinski, and L. F. Hodges, "Evaluation of the cognitive effects of travel technique in complex real and virtual environments," *IEEE Trans. Vis. Comput. Graph.*, vol. 16, no. 4, pp. 690–702, Jul./Aug. 2010.

[163] C. Christou, A. Tzanavari, K. Herakleous, and C. Poullis, "Navigation in virtual reality: comparison of gaze-directed and pointing motion control," in *Proc. Mediterranean Electrotechnical Conf.*, 2016, pp. 1–6.

[164] C. G. Christou and P. Aristidou, "Steering versus teleport locomotion for head mounted displays," in *Proc. Int. Conf. Augmented Reality Virtual Reality Comput. Graph.*, 2017, pp. 431–446.

[165] G. de Haan, E. J. Griffith, and F. H. Post, "Using the Wii balance board as a low-cost VR interaction device," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2008, pp. 289–290.

[166] D. Valkov, F. Steinicke, G. Bruder, and K. H. Hinrichs, "Traveling in 3D virtual environments with foot gestures and a multi-touch enabled WIM," in *Proc. Virtual Reality Int. Conf.*, 2010, pp. 171–180.

[167] J. Wang and R. W. Lindeman, "Isometric versus elastic surfboard interfaces for locomotion in virtual reality," in *Proc. IASTED Int. Conf. Human-Comput. Interaction*, 2011.

[168] J. Wang and R. Lindeman, "Leaning-based travel interfaces revisited: frontal versus sidewise stances for flying in 3D virtual spaces," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2012, pp. 121–128.

[169] M. Carrozzino, G. Avveduto, F. Tecchia, P. Gurevich, and B. Cohen, "Navigating immersive virtual environments through a foot controller," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2014, pp. 23–26.

[170] S. Beckhaus, K. J. Blom, and M. Haringer, "Chairio–the chair-based interface," in *Concepts and Technologies for Pervasive Games: A Reader for Pervasive Gaming Research*. Herzogenrath, Germany: Shaker Verlag, 2007, pp. 231–264.

[171] A. Kitson, B. E. Riecke, A. M. Hashemian, and C. Neustaedter, "Navichair: Evaluating an embodied interface using a pointing task to navigate virtual reality," in *Proc. ACM Symp. Spatial User Interaction*, 2015, pp. 123–126.

[172] A. Kitson, A. M. Hashemian, E. R. Stepanova, E. Kruijff, and B. E. Riecke, "Comparing leaning-based motion cueing interfaces for virtual reality locomotion," in *Proc. IEEE Symp. 3D User Interfaces*, 2017, pp. 73–82.

[173] S. Tregillus, M. Al Zayer, and E. Folmer, "Handsfree omnidirectional VR navigation using head tilt," in *Proc. ACM CHI Conf. Human Factors Comput. Syst.*, 2017, pp. 4063–4068.

[174] D. A. Bowman, D. Koller, and L. F. Hodges, "A methodology for the evaluation of travel techniques for immersive virtual environments," *Virtual Reality*, vol. 3, no. 2, pp. 120–131, 1998.

[175] D. A. Bowman, D. B. Johnson, and L. F. Hodges, "Testbed evaluation of virtual environment interaction techniques," *Presence: Teleoperators Virtual Environ.*, vol. 10, no. 1, pp. 75–95, 2001.

[176] I. Poupyrev, M. Billinghurst, S. Weghorst, and T. Ichikawa, "The Go-Go interaction technique: non-linear mapping for direct manipulation in VR," in *Proc. ACM Symp. User Interface Softw. Technol.*, 1996, pp. 79–80.

[177] D. C. Brogan, R. A. Metoyer, and J. K. Hodgins, "Dynamically simulated characters in virtual environments," *IEEE Comput. Graph. Appl.*, vol. 18, no. 5, pp. 58–69, Sep./Oct. 1998.

[178] F. P. Brooks, "What's real about virtual reality?" *IEEE Comput. Graph. Appl.*, vol. 19, no. 6, pp. 16–27, Nov. 1999.

[179] R. Schroeder, A. Huxor, and A. Smith, "Activeworlds: Geography and social interaction in virtual reality," *Futures*, vol. 33, no. 7, pp. 569–587, 2001.

[180] E. Bozgeyikli, A. Raij, S. Katkoori, and R. Dubey, "Point & teleport locomotion technique for virtual reality," in *Proc. Symp. Comput.-Human Interaction Play*, 2016, pp. 205–216.

[181] J. D. Mackinlay, S. K. Card, and G. G. Robertson, "Rapid controlled movement through a virtual 3D workspace," in *Proc. Conf. Comput. Graph. Interactive Tech.*, 1990, pp. 171–176.

[182] J. Bhandari, P. MacNeilage, and E. Folmer, "Teleportation without spatial disorientation using optical flow cues," in *Proc. Graph. Interface*, 2018, pp. 162–167.

[183] B. Bolte, F. Steinicke, and G. Bruder, "The jumper metaphor: an effective navigation technique for immersive display setups," in *Proc. Virtual Reality Int. Conf.*, 2011, pp. 1–7.

[184] N. H. Bakker, P. O. Passenier, and P. J. Werkhoven, "Effects of head-slaved navigation and the use of teleports on spatial orientation in virtual environments," *Human Factors*, vol. 45, no. 1, pp. 160–169, 2003.

[185] D. A. Bowman, E. T. Davis, L. F. Hodges, and A. N. Badre, "Maintaining spatial orientation during travel in an immersive virtual environment," *Presence: Teleoperators Virtual Environ.*, vol. 8, no. 6, pp. 618–631, 1999.

[186] C. Ware and S. Osborne, "Exploration and virtual camera control in virtual three dimensional environments," in *Proc. ACM Symp. Interactive 3D Graph.*, 1990, pp. 175–183.

[187] D. A. Bowman and L. F. Hodges, "An evaluation of techniques for grabbing and manipulating remote objects in immersive virtual environments," in *Proc. ACM Symp. Interactive 3D Graph.*, 1997, pp. 35–38.

[188] R. Stoakley, M. J. Conway, and R. Pausch, "Virtual reality on a WIM: interactive worlds in miniature," in *Proc. ACM CHI Conf. Human Factors Comput. Syst.*, 1995, pp. 265–272.

[189] T. Ropinski, F. Steinicke, and K. Hinrichs, "A constrained road-based VR navigation technique for travelling in 3D city models," in *Proc. Int. Conf. Augmented Tele-Existence*, 2005, pp. 228–235.

[190] C. A. Wingrave, Y. Haciahmetoglu, and D. A. Bowman, "Overcoming world in miniature limitations by a scaled and scrolling WIM," in *Proc. IEEE Symp. 3D User Interfaces*, 2006, pp. 11–16.

[191] J. Butterworth, A. Davidson, S. Hench, and M. T. Olano, "3DM: A three dimensional modeler using a head-mounted display," in *Proc. ACM Symp. Interactive 3D Graph.*, 1992, pp. 135–138.

[192] D. P. Mapes and J. M. Moshell, "A two-handed interface for object manipulation in virtual environments," *Presence: Teleoperators Virtual Environ.*, vol. 4, no. 4, pp. 403–416, 1995.

[193] M. R. Mine, F. P. Brooks Jr, and C. H. Sequin, "Moving objects in space: exploiting proprioception in virtual-environment interaction," in *Proc. Conf. Comput. Graph. Interactive Tech.*, 1997, pp. 19–26.

[194] F. Argelaguet and M. Maignant, "Giant: stereoscopic-compliant multi-scale navigation in VEs," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2016, pp. 269–277.

[195] R. Kopper, T. Ni, D. A. Bowman, and M. Pinho, "Design and evaluation of navigation techniques for multiscale virtual environments," in *Proc. IEEE Virtual Reality*, 2006, pp. 175–182.

[196] F. Bacim, D. Bowman, and M. Pinho, "Wayfinding techniques for multiscale virtual environments," in *Proc. IEEE Symp. 3D User Interfaces*, 2009, pp. 67–74.

[197] C. Ware and D. Fleet, "Context sensitive flying interface," in *Proc. ACM Symp. Interactive 3D Graph.*, 1997, pp. 127–130.

[198] J. McCrae, I. Mordatch, M. Glueck, and A. Khan, "Multiscale 3D navigation," in *Proc. ACM Symp. Interactive 3D Graph. Games*, 2009, pp. 7–14.

[199] D. R. Trindade and A. B. Raposo, "Improving 3D navigation in multiscale environments using cubemap-based techniques," in *Proc. ACM Symp. Appl. Comput.*, 2011, pp. 1215–1221.

[200] F. Argelaguet, "Adaptive navigation for virtual environments," in *Proc. IEEE Symp. 3D User Interfaces*, 2014, pp. 123–126.

[201] S. Freitag, B. Weyers, and T. W. Kuhlen, "Automatic speed adjustment for travel through immersive virtual environments based on viewpoint quality," in *Proc. IEEE Symp. 3D User Interfaces*, 2016, pp. 67–70.

[202] S. Mirhosseini, I. Gutenko, S. Ojal, J. Marino, and A. E. Kaufman, "Automatic speed and direction control along constrained navigation paths," in *Proc. IEEE Virtual Reality*, 2017, pp. 29–36.

[203] F. Carvalho, D. R. Trindade, P. F. Dam, A. Raposo, and I. H. dos Santos, "Dynamic adjustment of stereo parameters for virtual reality tools," in *Proc. Symp. Virtual Reality*, 2011, pp. 66–72.

[204] I. Cho, J. Li, and Z. Wartell, "Multi-scale 7DOF view adjustment," *IEEE Trans. Vis. Comput. Graph.*, vol. 24, no. 3, pp. 1331–1344, Mar. 2018.

[205] L. L. Arns, "A new taxonomy for locomotion in virtual environments," Dept: Computer Science, Ph.D. dissertation, Iowa State Univ., Ames, IA, USA, 2002.

[206] N. C. Nilsson, S. Serafin, and R. Nordahl, "Walking in place through virtual worlds," in *Proc. Int. Conf. Human-Comput. Interaction*, 2016, pp. 37–48.
[207] M. Slater and M. Usoh, "Body centred interaction in immersive virtual environments," *Artif. Life Virtual Reality*, vol. 1, no. 1994, pp. 125–148, 1994.
[208] J. D. Wendt, "Real-walking models improve walking-in-place systems," Dept: Computer Science, Ph.D. dissertation, UNC Chapel Hill, Chapel Hill, NC, USA, 2010.
[209] S. M. LaValle, *Virtual Reality*. Cambridge, U.K.: Cambridge Univ. Press, 2016.
[210] M. Nabiyouni and D. A. Bowman, "A taxonomy for designing walking-based locomotion techniques for virtual reality," in *Proc. ACM Companion Interactive Surfaces Spaces*, 2016, pp. 115–121.
[211] A. S. Muhammad, S. C. Ahn, and J.-I. Hwang, "Active panoramic VR video play using low latency step detection on smartphone," in *Proc. IEEE Int. Conf. Consum. Electron.*, 2017, pp. 196–199.
[212] J.-Y. Huang, W.-H. Chiu, Y.-T. Lin, M.-T. Tsai, H.-H. Bai, C.-F. Tai, C.-Y. Gau, and H.-T. Lee, "The gait sensing disc-a compact locomotion device for the virtual environment," in *Proc. Int. Conf. Central Eur. Comput. Graph. Vis Interactive Digit Media*, 2000, pp. 290–297.
[213] H. Iwata, "Walking about virtual environments on an infinite floor," in *Proc. IEEE Virtual Reality*, 1999, pp. 286–293.
[214] J. Wang and R. W. Lindeman, "Comparing isometric and elastic surfboard interfaces for leaning-based travel in 3D virtual environments," in *Proc. IEEE Symp. 3D User Interfaces*, 2012, pp. 31–38.
[215] R. P. McMahan, C. Lai, and S. K. Pal, "Interaction fidelity: the uncanny valley of virtual reality interactions," in *Proc. Int. Conf. Virtual Augmented Mixed Reality*, 2016, pp. 59–70.
[216] J. Bhandari, S. Tregillus, and E. Folmer, "Legomotion: scalable walking-based virtual locomotion," in *Proc. ACM Symp. Virtual Reality Softw. Technol.*, 2017, pp. 18:1–18:8.

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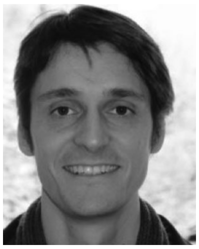

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