Research Trends in Virtual Reality Locomotion Techniques

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Abstract

Virtual reality (VR) researchers have had a long-standing interest in studying locomotion for developing new techniques, improving upon prior ones, and analyzing their effects on users. To help organize prior work, several researchers have presented taxonomies for categorizing locomotion techniques in general. More recently, researchers have begun to conduct systematic reviews to better understand what locomotion techniques have been investigated. In this paper, we present our own systematic review of locomotion techniques based on a well-established taxonomy, and we use k-means clustering to identify to what extent locomotion techniques have been explored. Our results indicate that selection-based, walking-based, and steering-based locomotion techniques have been moderately to highly explored while manipulation-based and automated locomotion techniques have been less explored. We also present results on what types of metrics have been used to evaluate locomotion techniques. While usability, discomfort, and travel performance metrics have been moderately to highly explored, other metrics, such as biometrics, user experience, and emotions, have been less explored.

Index Terms: Human-centered computing—Human computer interaction (HCI)—Interaction paradigms—Virtual reality

1 Introduction

Locomotion has been and continues to be a challenge to virtual reality (VR) researchers and developers. Limited tracking spaces and capabilities often limit users' physical movements. Yet, many VR applications are based in large, sometimes massive, virtual environments. This physical-virtual spatial conflict inherently limits the benefits of head tracking and real walking while also necessitating some form of virtual locomotion [52].

VR researchers and developers have created hundreds of distinct locomotion techniques in attempts to create natural locomotion for users [24]. In turn, researchers have developed numerous taxonomies to help categorize locomotion techniques [61]. Some researchers have also conducted systematic reviews of VR locomotion in order to better understand locomotion techniques [7, 22]. However, there has been little research on which locomotion techniques have been well investigated and which have been investigated to a lesser extent.

In order to better understand which locomotion techniques have been investigated, we have conducted our own systematic review and used a well-established locomotion taxonomy [11] to categorize and present our results. We have also used the k-means clustering algorithm [33] on our results to determine to what extent different locomotion techniques have been explored. Our results indicate that the Point-and-Teleport technique [48] and Joystick-directed Steering [80] have been highly explored. Walking-in-Place [26], Redirected Walking [85], and Head-directed Steering [74] have all been moderately explored. All other locomotion techniques have been less explored, including several that have appeared in consumer VR games, such as Point-and-Motion [48], Arm Swinging [19], Scene-in-Hand [23], Automated Steering [76], and Automated Teleport [76].

In addition to presenting research trends regarding locomotion techniques themselves, we also present results about what metrics have been used to evaluate locomotion techniques. Employing k-means clustering [33] on our metrics results, we found that travel performance metrics, such as time and accuracy, have been highly explored while perceived usability metrics (e.g., the System Usability Scale [15]) and discomfort metrics (e.g., the Simulator Sickness Questionnaire [44]) have been moderately explored. However, other types locomotion metrics have been less explored, such as biometrics, user experience, and emotions.

Overall, our results indicate that more research should be conducted on several locomotion techniques, particularly some that have been employed in consumer VR games. Additionally, our results suggest that more research should be conducted to better understand how locomotion techniques affect biometrics, user experiences, and emotions. Our results also indicate that non-standard questionnaires are used too frequently and that researchers should take care to use validated and reliable questionnaires, particularly for perceived usability. The primary contributions of this paper include:

- One of the largest systematic reviews of locomotion techniques and the first to identify to what extent techniques have been explored by using the k-means clustering algorithm.
- The first systematic review of locomotion techniques to identify what types of locomotion metrics have been explored and to what extent by using k-means clustering.

2 Related Work

In this section, we discuss general locomotion taxonomies and prior systematic reviews of locomotion.

2.1 General Locomotion Taxonomies

There have been several prior initiatives to organize locomotion techniques at a high level in the form of taxonomies. Mine [64] presented one of the earliest locomotion taxonomies, which categorized locomotion techniques based on their direction and speed of motion. Bowman et al. [9] presented a similar taxonomy that also included input conditions, such as continuous input. Later on, Bowman et al. [10] presented another locomotion taxonomy based on starting to move, indicating a position and orientation, and stopping movement. Arns [4] took another approach to categorizing locomotion techniques based on whether translations and rotations were physical or virtual and if any special interaction devices, such as a treadmill, were involved.

Wendt [90] presented another general locomotion taxonomy based on whether the user is physically mobile or stationary, each of which further breaks down into subcategories. Nabiyouni and Bowman [67] presented another taxonomy based on several locomotion features, including movement range, walking surface, transfer function, user support, walking movement style, and input properties. Nilsson et al. [69] presented a non-component approach to developing a locomotion taxonomy by categorizing techniques along three axes: the user's physical movements (mobile or stationary),

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the source of virtual movement (body-centric or vehicular), and the plausibility of the metaphor (mundane or magical).

Most relevant to our research is the general locomotion taxonomy initially presented by Bowman et al. [11], updated by LaViola et al. [52], and later reiterated by Al Zayer et al. [3]. This taxonomy categorizes locomotion techniques into walking-based, steering-based, selection-based, manipulation-based, and automated, which are further subcategorized. In this work, we use this taxonomy to categorize and present the results of our systematic review. We chose this taxonomy because recent research found that this taxonomy has had the greatest impact among the various taxonomies [61].

2.2 Systematic Reviews of Locomotion

Unlike locomotion taxonomies, there are few systematic reviews of locomotion techniques and research. Boletsis [7] conducted one of the first systematic reviews of locomotion techniques using the Scopus database, which involved 92 initial search results, 36 included publications, and 73 instances of 11 distinct locomotion techniques. In addition to the locomotion technique results, Boletsis also discussed how many publications investigated usability, user experience, perception, or travel performance, but not specific metrics, as we do in the current work.

Cherni et al. [22] have presented another systematic review of VR locomotion techniques using Google Scholar, which involved 61 initial publications, 26 included publications, and 62 instances of 22 distinct locomotion techniques. Based on their results, they have presented another locomotion taxonomy including leaning-based, walking-based, semi-natural (e.g., treadmills), non-natural (e.g., teleportation), and mixed approaches.

Di Luca et al. [24] have recently presented the *Locomotion Vault*, which is a comprehensive database of locomotion techniques found by searching publications, gaming venues, websites, social media, and blog posts on VR locomotion. While not technically a systematic review, Di Luca et al. identified 109 unique locomotion techniques, from which they identified eight categories of locomotion techniques based on commonalities among the techniques (e.g., gesture, grab).

Also recently, Prinz et al. [61] conducted a systematic review on locomotion taxonomies, as opposed to the techniques themselves. Based on their review, they found that there is a rising number of taxonomies introduced per year. They also found that taxonomies are shifting to focus on specific groups of techniques, like our chosen taxonomy [11], as opposed to components or aspects of locomotion.

In this paper, we present a systematic review based on 141 search results, 91 initial publications, and 63 included publications (see Sect. 3). We have used a well-established taxonomy [3, 11, 52], which has been shown to have the greatest impact among the various locomotion taxonomies [61], to categorize and present our results pertaining to 180 instances of 29 distinct techniques (see Sect. 4), which makes it the largest systematic review to the best of our knowledge. Unlike prior reviews, we have used the k-means clustering algorithm [33] to identify to what extent locomotion techniques have been explored (see Sect. 3.5). Furthermore, we present results pertaining to what types of metrics have been used to evaluate locomotion techniques and to what extent (see Sect. 5).

3 Systematic Review

We conducted a systematic review to identify well-explored locomotion techniques and metrics, and in turn, to identify lesser-explored techniques and metrics. Systematic reviews use explicit procedural methods to minimize bias and provide more-reliable findings [36]. Systematic reviews help to confirm current practices, identify new practices, and inform future research [66]. We followed the systematic review methodology presented by Khan et al. [46].

3.1 Framing the Question

The first step of a systematic review is to identify unambiguous and structured research questions [46]. Our research questions were:

RQ1: *Which locomotion techniques have been highly explored, moderately explored, and less explored?*

RQ2: *Which locomotion metrics have been highly explored, moderately explored, and less explored?*

3.2 Identifying Relevant Publications

The second step of a systematic review is to extensively search for relevant studies based on predefined inclusion and exclusion criteria [46]. For our systematic review, we used the Web of Science (WoS) database, which was the first international literature database and contains journals with higher impact factors than other databases, such as Scopus [2]. To ensure our results were relevant to VR locomotion techniques, we limited our search to publications containing ”virtual reality” or ”VR”, ”locomotion” or ”travel”, and ”technique” in their abstracts. These inclusion criteria yielded a Web of Science (WoS) search with 141 results (as of June 1, 2021).

As suggested by Levac et al. [54], we reviewed the abstracts yielded by our WoS search and applied our exclusion criterion to avoid downloading and reading irrelevant publications. Our exclusion criterion was to omit any research not focused on locomotion. For example, there were several publications that mentioned locomotion techniques but were actually focused on selection or manipulation techniques. This process excluded 50 results, leaving 91 publications to review.

3.3 Assessing Study Quality

The third step of a systematic review is to provide a more-refined quality assessment of the selected studies based on guidelines and checklists [46]. For this process, we applied additional inclusion and exclusion criteria to our selected studies. First, any included publication must present at least one user study with reported measures dependent upon the locomotion technique. Second, any included publication must either explicitly compare one or more locomotion techniques or be focused on the effects of a new locomotion technique. Finally, we excluded any publications that presented duplicate results, in order to avoid skewing our statistics. After applying these criteria, we narrowed our review to 63 publications.

3.4 Summarizing the Evidence

The fourth step of a systematic review is to synthesize the data by tabulating study characteristics [46]. We used a shared spreadsheet to record information about each study, including its locomotion techniques and metrics. We classified locomotion techniques based on the locomotion technique originally presented by Bowman et al. [11], which is the most cited locomotion taxonomy [61].

3.5 Interpreting the Findings

The fifth step of a systematic review is to make inferences based on the observed results [46]. In order to make inferences with regard to which locomotion techniques have been highly explored, moderately explored, and less explored, we applied the k-means clustering algorithm [33] with three clusters for the three categories, implemented in scikit-learn [73] with default parameters, to our locomotion category and individual technique results. Similarly, to make inferences with regard to the locomotion metrics, we again applied the k-means clustering algorithm with three clusters and default parameters to our metric categories and individual metric results. We discuss these results and their implications in Sect. 4.6 for locomotion techniques and Sect. 5.11 for locomotion metrics.

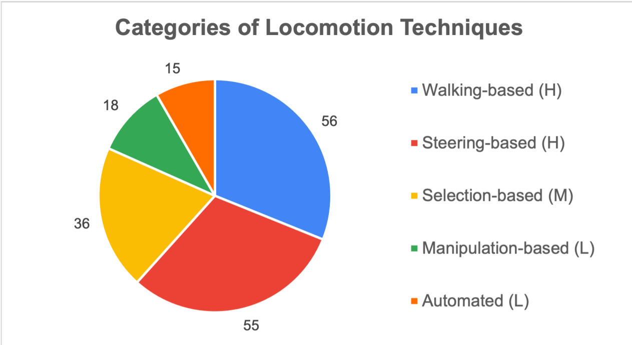

Figure 1: Instances of each category of locomotion techniques, based on the well-established taxonomy [11,52], and if they have been highly (H), moderately (M), or less (L) explored.

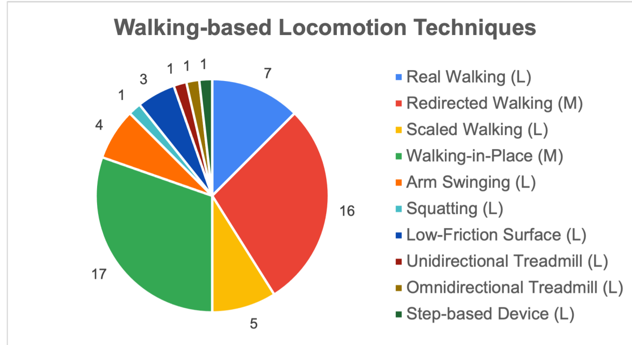

Figure 2: Instances of walking-based locomotion techniques and if they have been highly (H), moderately (M), or less (L) explored.

4 Locomotion Techniques

We categorized the locomotion techniques into the following categories based on the most-cited locomotion taxonomy [3, 11, 52]: walking-based, steering-based, selection-based, manipulation-based, and automated.

4.1 Walking-based Locomotion

Walking-based locomotion techniques are travel techniques that rely on the user's physical body movements [11, 52]. As seen in Fig. 1, walking-based techniques are the most-researched category of locomotion. Walking-based techniques can be separated into three subcategories: full-gait, partial-gait, and gait-negation locomotion [3, 52].

4.1.1 Full-Gait Locomotion

Full-gait locomotion techniques involve both main phases of the human gait cycle: the stance phase and the swing phase [52]. ***Real Walking*** employs one-to-one head tracking to afford the most natural locomotion method, but this limits virtual travel to the physical boundaries of the real-world tracking space [12]. ***Redirected Walking*** attempts to circumvent this constraint by redirecting users away from the boundaries of the tracking space [85]. This can be accomplished through either a "stop-and-go" method, in which the virtual world is rotated about a stationary user, or a "continuous" method, in which small rotations are applied to the virtual world to redirect the user along a curved physical path [17]. Finally, ***Scaled Walking*** scales virtual movements based on physical head tracking, such that one physical step results in several virtual steps [49].

Interestingly, full-gait techniques account for exactly half (28 of 56) of the walking-based techniques (see Fig. 2). Redirected Walking is clearly the most researched full-gait locomotion technique and the second-most researched walking-based technique overall. Redirected Walking techniques have been compared to other locomotion techniques [50], applied during blinking [51], and investigated for reactive environment alignment [87].

In contrast to Redirected Walking, Real Walking and Scaled Walking have been studied less (see Fig. 2). It is not surprising that Real Walking is less explored than Redirected Walking, as any user study involving Real Walking must employ short-distance travel tasks to be fairly compared to other locomotion techniques that are not constrained by the physical boundaries of head tracking [67]. Similarly, while Scaled Walking affords virtual travel farther than Real Walking, it also requires limited-distance travels tasks, as it is also constrained by the physical tracking boundaries [1].

4.1.2 Partial-Gait Locomotion

Partial-gait locomotion techniques focus on particular aspects of human gait without involving all of the biomechanics of a full gait cycle [52]. ***Walking-in-Place*** involves users moving only their feet while standing in place, in order to virtually move forward [26]. Similarly, ***Arm Swinging*** involves users moving only their arms while standing in place, in order to virtually move [19]. On the other hand, ***Squatting*** involves users lowering their hips and then standing back up [47].

Walking-in-Place was the most investigated walking-based locomotion technique (see Fig. 2) in the research. We found numerous variations of Walking-in-Place, including detecting head bobbing [31] and actual foot tracking [8]. On the other hand, we found that Arm Swinging is less explored, which is surprising considering that it has been implemented in consumer VR games such as *Thief Simulator VR*. Likewise, Squatting is also less explored, though prior results indicate that Arm Swinging is preferred to Squatting [47].

4.1.3 Gait-Negation Locomotion

Gait-negation locomotion techniques involve special locomotion devices that negate the physical movements of the user [52]. ***Low-Friction Surface*** techniques employ low-friction, curved surfaces and low-friction shoes to negate the user's steps [3]. ***Unidirectional Treadmill*** techniques employ a common treadmill device to negate the user's steps in a single physical direction [96]. ***Omnidirectional Treadmill*** techniques employ specially constructed devices to negate the user's steps in any physical direction [52]. Finally, ***Step-based Device*** techniques detect the user stepping in place, like Walking-in-Place techniques, but employ devices that the user steps on [13].

Overall, gait-negation techniques accounted for approximately one-tenth (6 of 56) of all walking-based techniques (see Fig. 2). Low-Friction Surface devices, such as the Virtuix Omni [5], the Cyberith Virtualizer [20], and the KATVR KATWalk [19], have been investigated. However, little research has been conducted to investigate Unidirectional Treadmills [96], Omnidirectional Treadmills [67], and Step-based Devices [13].

4.2 Steering-based Locomotion

Steering-based locomotion techniques are travel techniques that allow the user to continuously specify either an absolute or relative direction of travel [52]. As seen in Fig. 1, steering-based techniques are the second-most researched category of locomotion. Steering-based locomotion techniques can be separated into two subcategories: spatial and non-spatial [3, 52].

4.2.1 Spatial Steering

Spatial steering techniques allow the user to control the direction of travel by manipulating a 3D tracked device while usually pressing

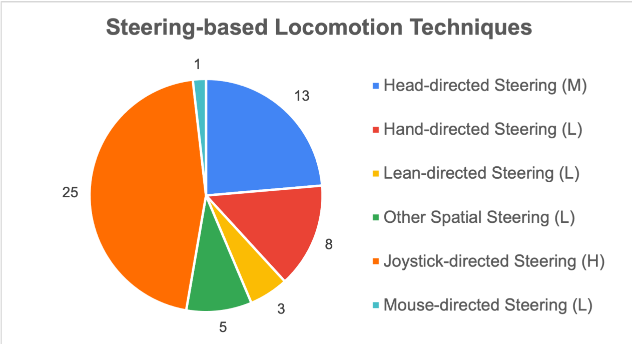

Figure 3: Instances of steering-based locomotion techniques and if they have been highly (H), moderately (M), or less (L) explored.

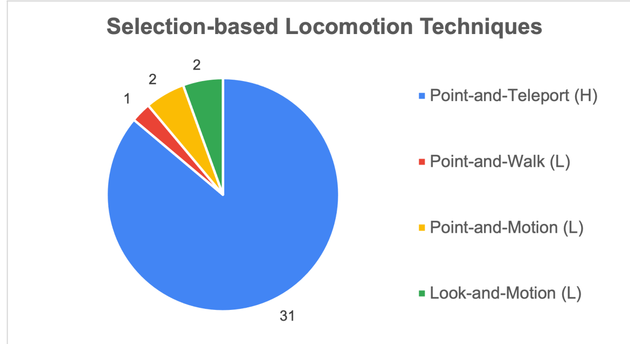

Figure 4: Instances of selection-based locomotion techniques and if they have been highly (H), moderately (M), or less (L) explored.

a button or joystick [52]. ***Head-directed Steering***, also referred to as *Gaze-directed Steering* [74], moves the user in the forward direction of the head-mounted display (HMD), which allows the user to control the direction of travel by turning their head [18]. ***Hand-directed Steering*** moves the user in a direction specified by their hand or a handheld device, which allows them to look around while traveling [58]. ***Lean-directed Steering*** allows the user to lean from a central tracking position to define a travel direction [18]. Other spatial steering techniques include Eye-directed Steering [74], Head-directed Steering combined with non-spatial steering [74], and a Redirected Wheelchair [16].

Spatial steering techniques account for more than half (29 of 55) of the steering-based techniques (see Fig. 3). Head-directed Steering is the most investigated spatial steering technique. Hand-directed Steering has also been evaluated in several studies. However, Lean-directed Steering and the other spatial steering techniques have been less explored.

4.2.2 Non-spatial Steering

Non-spatial steering techniques allow the user to control the direction of travel through 2D input [52]. ***Joystick-directed Steering*** allows the user to control the direction of travel by simply using a joystick to control forward and backward movements and their heading within the virtual environment [80]. ***Mouse-directed Steering*** functions similarly by using 2D mouse input instead of a joystick [74].

Joystick-directed Steering has by far been the most investigated steering-based locomotion technique (see Fig. 3), despite being a non-spatial steering technique. This is most likely due to the fact that Joystick-directed Steering is commonly employed in both VR and non-VR games [80]. On the other hand, Mouse-directed Steering has been less explored, likely due to requiring a surface [74].

4.3 Selection-based Locomotion

Selection-based locomotion techniques are travel techniques that allow the user to select a destination to travel to or a path to travel along [52]. In our systematic review, we found four types of selection-based locomotion techniques: Point-and-Teleport, Point-and-Walk, Point-and-Motion, and Look-and-Motion. ***Point-and-Teleport*** locomotion allows the user to point to a destination and press a button to select it, and then the user is instantaneously positioned at that destination [13]. Similarly, the ***Point-and-Walk*** technique allows the user to point to a destination to select it, but requires the user to walk through a portal to teleport to the selected destination [57]. In contrast to these teleportation techniques, ***Point-and-Motion*** techniques smoothly translate the user from the original location to the selected destination [63]. The ***Look-and-Motion*** technique functions similar to Point-and-Motion, except the user looks at the destination instead of pointing toward it [39].

Given consumer VR games and default selection-based locomotion techniques provided by development toolkits, such as the SteamVR Unity plugin, it was not surprising to find that the Point-and-Teleport technique was the most-explored selection-based technique and the most-explored locomotion technique overall (see Fig. 4). However, it was surprising to find how few studies have investigated the other selection-based techniques.

In addition to the distinct types of selection-based techniques, we also found variations of the techniques within our systematic review. Most of the pointing techniques relied on handheld controllers for 3D input [18]. However, we found a few examples that employed barehand tracking [13, 82]. Similarly, we found that most of the pointing techniques employed some type of curved arc for indirectly pointing at destinations [31], but a few implementations employed a straight ray instead [28].

4.4 Manipulation-based Locomotion

Manipulation-based locomotion techniques are travel techniques that allow the user to manually control their position within the virtual environment, usually through a virtual hand technique [52]. In our review, we found five types of manipulation-based locomotion techniques: Manipulate-to-Steer, Camera-in-Hand, Scene-in-Hand, World-in-Miniature, and Dragging.

Manipulate-to-Steer techniques involve performing some type of 3D manipulation in order to define a steering direction. Examples of Manipulate-to-Steer techniques include manipulating a trackball [13], an elastically suspended grip [95], and a virtual hamster ball [37]. ***Camera-in-Hand*** locomotion allows the user to directly move the virtual camera around by physically moving their hand or handheld device around in the same manner [75]. Camera-in-Hand can also be implemented as a bimanual technique (i.e., *Camera-in-Hands*) [23]. ***Scene-in-Hand*** locomotion functions similarly except virtual movements are inverse of the physical movements (i.e., moving one's hand forward moves the virtual camera backward relative to the scene) [23]. ***World-in-Miniature*** locomotion allows the users to adjust their position within the virtual environment by manipulating a representation of themselves within a miniature version of the environment [6]. Finally, ***Dragging*** is our term for any manipulation-based locomotion technique that employs dragging gestures on a touchscreen interface to manipulate one's position within the virtual environment [86]. *Drag'n Go* is a specific example of Dragging [65].

Manipulation-based techniques are the second least investigated category of locomotion techniques (see Fig. 1). Outside of Manipulate-to-Steer, which had nine instances within our systematic review results, the other manipulation-based techniques have clearly been less explored than other locomotion techniques (see Table 1).

4.5 Automated Locomotion

Automated locomotion techniques are travel techniques in which the system controls the user's movements through the virtual environment [52]. Semi-automated locomotion techniques are automated techniques that allow the user to decide certain facets of travel, such as when to move to the next destination [52]. In our systematic review, we found four types of automated locomotion techniques: Automated Steering, Semi-automated Steering, Automated Teleport, and Semi-automated Teleport.

Automated Steering functions like conventional steering techniques (i.e., continuous movement along a specified direction) except the system decides both the direction and when movement occurs [76]. ***Semi-automated Steering*** functions similarly except the user can control either when to move [95] or how fast to move [72]. With ***Automated Teleport***, the system decides when and what destinations to automatically and instantly move the user to [76]. Finally, ***Semi-automated Teleport*** works similarly except the user controls when to teleport [70].

Automated locomotion techniques are less explored than walking-based, steering-based, and selection-based techniques (see Fig. 1). Automated Steering is by far the most explored of the automated techniques (see Table 1). However, all of the automated techniques have been less explored than other locomotion techniques.

4.6 Inferences about Locomotion Techniques

As described in Sect. 3.5, we applied the k-means clustering algorithm [33] with three clusters (i.e., highly explored, moderately explored, and less explored) to our locomotion technique results. Based on the resulting category clusters, we found that walking-based and steering-based techniques have been highly explored while selection-based techniques have been moderately explored, and manipulation-based and automated techniques have been less explored. Based on the individual technique clusters, we found that the Point-and-Teleport and Joystick-directed Steering techniques have been highly explored while the Walking-in-Place, Redirected Walking, and Head-directed Steering techniques have been moderately explored. On the other hand, all other instances of locomotion techniques have been statistically less explored. See Table 1 for a summary of these results.

Table 1: Summary of locomotion categories, techniques, and the extent they have been explored.

Category	Technique	#	Explored
Walking-based	Real Walking	7	Less
	Redirected Walking	16	Moderately
	Scaled Walking	5	Less
	Walking-in-Place	17	Moderately
	Arm Swinging	4	Less
	Squatting	1	Less
	Low-Friction Surface	3	Less
	Unidirectional Treadmill	1	Less
	Omnidirectional Treadmill	1	Less
	Step-based Device	1	Less
Steering-based	Head-directed Steering	13	Moderately
	Hand-directed Steering	8	Less
	Lean-directed Steering	3	Less
	Other Spatial Steering	5	Less
	Joystick-directed Steering	25	Highly
	Mouse-directed Steering	1	Less
Selection-based	Point-and-Teleport	31	Highly
	Point-and-Walk	1	Less
	Point-and-Motion	2	Less
	Look-and-Motion	2	Less
Manipulation-based	Manipulate-to-Steer	9	Less
	Camera-in-Hand	3	Less
	Scene-in-Hand	2	Less
	World-in-Miniature	1	Less
	Dragging	3	Less
Automated	Automated Steering	7	Less
	Semi-automated Steering	4	Less
	Automated Teleport	1	Less
	Semi-automated Teleport	3	Less

5 Locomotion Metrics

In addition to classifying locomotion techniques, we also noted and classified the metrics (i.e., dependent measures) that researchers investigated with regard to the locomotion techniques. We have grouped these metrics into the following categories: travel performance, cognitive performance, biometrics, usability, user experience, discomfort, presence, effort, emotion, and preference. We discuss all of these categories in the subsections below.

5.1 Travel Performance Metrics

We classified any dependent measures that pertain to how well the user could travel using a given locomotion technique as *travel performance* metrics. These travel performance metrics addressed several aspects of travel, including time, success, accuracy, error, distance, velocity, and activations.

Time metrics focus on how much time users need to complete a travel task with a given locomotion technique [18, 63]. ***Success*** metrics define some concept of successfully completing a travel task, such as traveling along a predefined route [58, 75] or finding specific objects within the environment [31, 72]. ***Accuracy*** metrics define some concept of *how closely* the user completes an intended travel task, such as how closely a user follows a target path [67, 94], terminates travel near a target destination [1, 28], or terminates travel toward a target direction [28]. ***Error*** metrics define some concept of unsuccessfully completing a travel task, such as colliding with obstacles [13, 37], taking damage [31], or voluntarily aborting the task [39]. ***Distance*** metrics focus on how much virtual distance the user travels during a given task [1, 31]. ***Velocity*** metrics usually focus on movement speeds, such as the user's mean travel speed [37, 88] or the mean speed of the user's steps [1]. ***Activation*** metrics focus on how many times a travel technique is activated during a given task, such as how many times the user teleports with a Point-and-Teleport technique [82], how many steps the user takes with a Scaled Walking technique [1], and how many times a Redirected Walking technique requires a reset [87].

Travel performance metrics account for approximately 40% of all instances of locomotion metrics within our systematic review (see Fig. 5). Of those, time is the most common travel performance metric (see Fig. 6) and the most common metric overall. Successes, accuracy, errors, distance, and travel activations have been moderately explored locomotion metrics. However, velocity is clearly an underexplored metric.

5.2 Cognitive Performance Metrics

During our review, we identified three categories of dependent measures that rely upon the user's cognitive capabilities, which we refer to as *cognitive performance* metrics. These categories include spatial understanding, spatial memory, and knowledge acquisition.

Spatial understanding metrics rely on how well the user understands spatial distances within the virtual environment and the spatial relationships among objects and locations within the environment [52]. Examples of spatial understanding metrics include walking toward unseen objects [71], pointing toward positions of previously visited locations [50], pointing toward the prior position of a missing object [76], and verbally estimating the dimensions of a virtual room [50]. ***Spatial memory*** metrics rely on how well

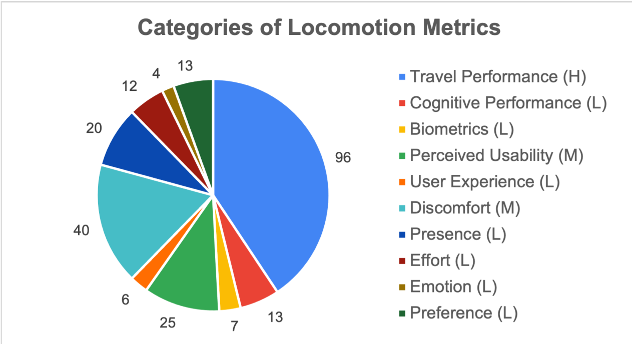

Figure 5: Instances of each category of locomotion metrics and if they have been highly (H), moderately (M), or less (L) explored.

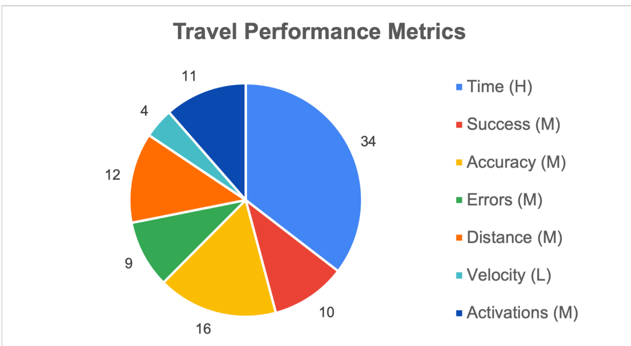

Figure 6: Instances of travel performance locomotion metrics and if they have been highly (H), moderately (M), or less (L) explored.

the user recalls the spatial layout of the virtual environment and the positions of the objects within it. Examples of spatial memory metrics include recalling the locations of buildings on a map [21] and placing objects in a real-world counterpart of the virtual environment [93]. ***Knowledge acquisition*** metrics rely on how well the user learns information and facts while moving in the virtual environment and are often measured with knowledge tests administered after the experience [21, 86].

Of the cognitive performance metrics, we found eight instances of spatial understanding metrics (moderately explored), three instances of spatial memory metrics (less explored), and two instances of knowledge acquisition metrics (less explored).

5.3 Biometrics

Biometrics are signals generated by the human body that can be detected to recognize and identify physiological and psychological states of a user, and even users themselves [40]. During our systematic review, we came across three types of biometrics that researchers have investigated with regard to locomotion techniques: heart rate, postural instability, and skin conductance.

Heart rate is a common biometric that can be used to estimate physical effort [20, 47] and predict emotional states [5]. ***Postural instability*** is another biometric that is often measured through changes in one's center of pressure (COP) while standing. It has been used as an indicator for motion sickness [91]. ***Skin conductance*** is another common biometric that depends on how a subject sweats during an experiment. It has been used as an indicator for presence (i.e., the sense of "being there" [35]) [84].

In our systematic review, we found four instances of heart rate metrics (less explored), two instances of postural instability metrics (less explored), and one instance of skin conductance (less explored).

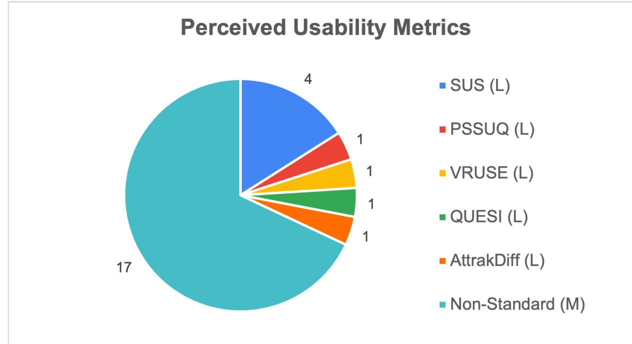

Figure 7: Instances of perceived usability locomotion metrics and if they have been highly (H), moderately (M), or less (L) explored.

Hence, there is much unknown about how locomotion techniques affect biometrics.

5.4 Percieved Usability Metrics

Usability metrics attempt to measure the subjective quality of a user interface, including aspects like ease of use, ease of learning, and affordances, and are usually captured via questionnaires [52]. In our systematic review, we found that researchers have used a wide range of questionnaires to measure usability.

The *System Usability Scale* (***SUS***) addresses the overall usability of a system, including aspects such as how often the subject would like to use the system, through 10 Likert-scale questions [15]. Similarly, the *Post-Study System Usability Questionnaire* ((***PSSUQ***) uses 19 questions to address the overall usefulness of a system and the subject's perception of the interface [55]. The ***VRUSE*** is a lengthy usability questionnaire that evaluates the overall system usability of virtual environment systems through 100 Likert-scale questions [42]. The *Questionnaire for the Subjective Consequences of Intuitive Use* (***QUESI***) focuses on the concept of intuitive use and low mental workload through 14 Likert-scale questions [68]. The ***AttrakDiff*** measures the appeal of an interface with 21 pairs of opposite adjectives [34]. Finally, several researchers have employed ***non-standard*** methods, which are custom questionnaires that have not been validated or demonstrated to be reliable [59]. In addition to potentially producing unreliable results, the results of non-standard questionnaires can not be generalized across studies, limiting their overall benefits to the community [60].

With regard to the standard questionnaires. SUS is clearly the most frequently employed usability questionnaire with the others appearing only once in our systematic review (see Fig. 7). On the other hand, non-standard questionnaires have been the most frequently used method for measuring usability, which is problematic, as such results are not validated, possibly unreliable, and not generalizable [59, 60].

5.5 User Experience Metrics

User experience metrics attempt to measure the overall subjective quality of experiencing a user interface, beyond basic usability aspects, and including how the user emotionally feels about the experience [52]. Like percieved usability metrics, user experience metrics are usually captured via questionnaires. In our systematic review, we found that researchers have used several different questionnaires to gauge user experiences.

The *Intrinsic Motivation Inventory* (***IMI***) measures the user's intrinsic motivation about an activity along four dimensions: interest-enjoyment, effort-importance, tension-pressure, and perceived competence [62]. The *Physical Activity Enjoyment Scale* (***PACES***) evaluates the subject's enjoyment for performing a physical activity through 16 Likert-scale questions [43]. The *Game Experience Questionnaire* (***GEQ***) assesses the user experience of a game from several aspects, including immersion, flow, competence, positive and negative affect, tension, and challenge [38]. Similarly, the *Player Experience of Need Satisfaction* (***PENS***) addresses several aspects of game experiences, including in-game autonomy, in-game competence, intuitive controls, preference for future play, game enjoyment, and presence [79]. Again, we found that some researchers used non-standard questionnaires as user experience metrics within our systematic review.

Of the user experience metrics, we found one instance of each of the standardized questionnaires (i.e., IMI, PACES, GEQ, and PENS) and two instances of non-standard questionnaires (all less explored).

5.6 Discomfort Metrics

Discomfort metrics attempt to subjectively measure how comfortable or uncomfortable the locomotion techniques were to use and whether they induced any type of sickness. In our systematic review, we found several examples of different questionnaires and methods employed as discomfort metrics.

The *Simulator Sickness Questionnaire* (***SSQ***), developed by Kennedy et al. [44], includes 16 questions that contribute to three subfactor scores pertaining to disorientation, nausea, and oculomotor discomforts. Similarly, the *Motion Sickness Assessment Questionnaire* (***MSAQ***) also employs 16 questions that contribute to four subfactors pertaining to gastrointestinal, central, peripheral, and sopite syndrome-related symptoms [29]. Likewise, the *Pensacola Diagnostic Index* (***PDI***) is based on various scales pertaining to dizziness, headache, warmth, sweating, drowsiness, and nausea [30]. The *Device Assessment Questionnaire* (***DAQ***) consists of 13 questions that address issues of physical operation, fatigue, and comfort [25].

In contrast to the previous post-experience questionnaires, the *Fast Motion Sickness Scale* (***FMS***) employs a verbal rating scale, ranging from zero (“no sickness at all”) to 20 (“frank sickness”), every minute during an experience [45]. Similarly, the *Discomfort Score* (***DS***) asks participants “On a scale of 0-10, 0 being how you felt coming in, 10 is that you want to stop, where are you now?” during an experience [27]. It was originally administered verbally every three minutes of an experience [77], but has been used more often as an in-VR questionnaire administered after a certain tasks [27]. Again, we also found that some researchers employed non-standardized metrics to gauge discomfort within their studies.

Discomfort metrics have been well explored and are the second most-researched category of locomotion metrics (see Fig. 5). Of the discomfort metrics found within our systematic review, the SSQ is by far the most common discomfort metric (see Fig. 8). The remaining standardized discomfort metrics appeared once or twice in our review, and we found five instances of non-standardized discomfort metrics.

5.7 Presence Metrics

Presence metrics aim to measure how present or ”there” participants feel within the virtual environment [35]. While some of the previous usability and user experience metrics include one or two presence questions, we found several questionnaires devoted to just the concept of presence.

The presence questionnaire developed by Slater, Usoh, and Steed [83] (***SUS-PQ***) includes six Likert-scale questions comparing the participant’s VR experience to real-world experiences. The *Igroup Presence Questionnaire* (***IPQ***) has 15 questions with three subscales regarding spatial presence, involvement, and experienced realism [78]. The presence questionnaire developed by Witmer and Singer [92] (***WS-PQ***) is a lengthier 32-question instrument that addresses factors such as control, sensory, distraction, and realism. Similarly, the *Engagement, Enjoyment, and Immersion* (E^2I) includes nine items constructed based on sensory, distraction, realism,

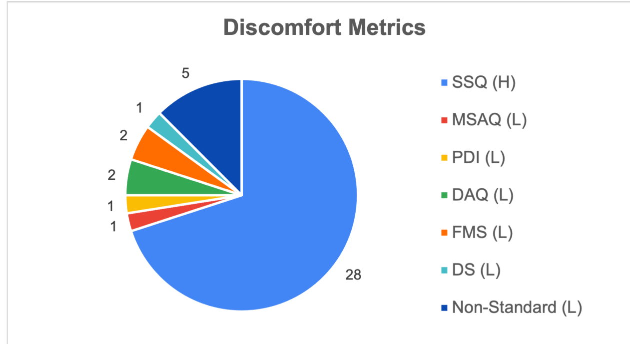

Figure 8: Instances of discomfort locomotion metrics and if they have been highly (H), moderately (M), or less (L) explored.

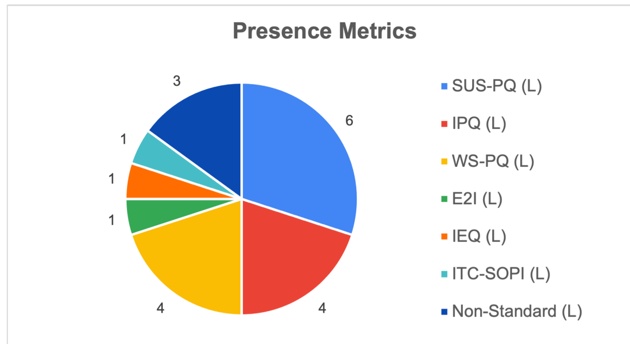

Figure 9: Instances of presence locomotion metrics and if they have been highly (H), moderately (M), or less (L) explored.

and control factors [56]. The *Immersive Experience Questionnaire* (***IEQ***) is another lengthy presence questionnaire with 31 questions that primarily focus on presence, but also address usability, user experience, and emotions [41]. The *ITC-Sense of Presence Inventory* (***ITC-SOPI***) is a presence questionnaire that focuses on the participant’s experience with interactive media and includes four subfactors: sense of physical space, engagement, ecological validity, and negative effects [53]. Again, we also found some instances of non-standard questionnaires used to measure presence.

The SUS-PQ appeared in our systematic review the most, closely followed by the IPQ and WS-PQ (see Fig. 9). However, we found that all individual presence metrics have been less explored than other locomotion metrics.

5.8 Effort Metrics

Effort metrics help assess how much demand a system or locomotion technique requires to use. In our systematic review, we found only two standardized effort metrics. The *NASA Task Load Index* (***NASA-TLX***) is a common tool used to subjectively measure mental demand, physical demand, temporal demand, effort, performance, and frustration [32]. The *Subjective Mental Effort Questionnaire* (***SMEQ***) is a single scale for measuring effort, ranging from “Not at all hard to do” to beyond “Tremendously hard to do” [81].

We found nine instances of the NASA-TLX (moderately explored) and one instance of the SMEQ (less explored) within our review. We also found a couple instances of non-standard effort metrics.

5.9 Emotion Metrics

While other types of metrics touch on the emotions of participants, such as the user experience metrics, *emotion* metrics are only concerned with the emotions of participants. We found only two standardized emotion metrics in our review. The *Positive and Negative Affect Schedule* (***PANAS***) is comprised of two 10-item mood scales that address both positive and negative emotions, such as excited and irritable, respectively [89]. The *Self-Assessment Manakin* (***SAM***) is a pictorial assessment that directly measures pleasure, arousal, and dominance with regard to an experience [14].

Emotion metrics are the least-explored category of locomotion metrics (see Fig. 5). In our review, we found only two instances of PANAS and two instances of SAM.

5.10 Preference Metrics

Preference metrics simply assess whether participants prefer one locomotion technique over another. They can either be direct one-to-one comparisons, or they can ask participants to rank multiple techniques in order. Of the 63 selected publications, 13 employed preference metrics, which have been moderately explored (see Fig. 5).

5.11 Inferences about Locomotion Metrics

As described in Sect. 3.5, we also applied the k-means clustering algorithm [33] with three clusters (i.e., highly explored, moderately explored, and less explored) to our results pertaining to categories of locomotion metrics and individual metrics. Based on the resulting category clusters, we found that travel performance metrics have been highly explored and that perceived usability and discomfort metrics have been moderately explored. However, all other categories of locomotion metrics have been statistically less explored. In terms of individual metrics, time and the SSQ have been highly explored. Moderately explored individual metrics include success, accuracy, errors, distance, activations, spatial understanding, non-standard usability questionnaires, the NASA-TLX, and preference. All other metrics have been less explored.

6 Discussion

In this section, we discuss our results pertaining to research trends in locomotion techniques and locomotion metrics.

6.1 Research Trends for Locomotion Techniques

Based on our systematic review and results, Point-and-Teleport and Joystick-directed Steering have been extensively explored. Walking-in-Place, Redirected Walking, and Head-directed Steering have been well explored too, though not to the same degree as the two previous locomotion techniques.

On the other hand, we found that all other types of locomotion techniques have been statistically less explored. While this is not surprising for some techniques, such as the gait-negation techniques, it does highlight areas of research that can be further and more deeply investigated. For example, several of the less-explored locomotion techniques appear in consumer VR games. Point-and-Motion appears in VR games such as *Half-Life: Alyx* and *DOOM VFR*. Arm Swinging appears in *Thief Simulator VR* and *Hot Dogs, Horseshoes & Hand Grenades*. Scene-in-Hand techniques appear in *GORN* and *Baby Hands*. Automated Steering appears in *Pistol Whip* and *Ragnarock*, and Automated Teleport appears in *SUPERHOT VR*. Hence, all of these locomotion techniques likely deserve more research.

Similarly, we found that all of the automated and semi-automated techniques have been less explored. However, recent research by Lai et al. [48] has found that automated locomotion affords significantly better cognitive load than other types of locomotion techniques. Hence, more research on automated and semi-automated locomotion techniques is likely warranted.

6.2 Research Trends for Locomotion Metrics

Based on our clustering results, we found that travel performance metrics are highly explored in locomotion research, which is logical given the importance of being able to effectively use a provided locomotion technique. Similarly, we found that perceived usability and discomfort metrics have been moderately explored, which is also not surprising, considering how important these aspects are.

However, we found that all other types of locomotion metrics have been statistically less explored. This includes metrics such as cognitive performance, biometrics, user experience, presence, effort, emotion, and even preference. Some of these are surprising, such as presence, which is a commonly investigated metric for VR research. However, it is important to note that the large number of travel performance instances skewed the k-means clustering results. Upon removing the travel performance metrics from our k-means clustering calculations, we found that presence would be considered a moderately explored metric along with perceived usability and discomfort would have been considered highly explored.

On the other hand, some of the less-explored locomotion metrics are not surprising. In particular, we believe that our results highlight that more research should be conducted with regard to the effects of locomotion techniques on biometrics, user experience, and emotions.

Finally, another important observation that we have made from our systematic review is that non-standard questionnaires are too frequently used. As discussed, non-standard questionnaires produce results that are not validated, possibly unreliable, and not generalizable [59, 60]. Yet, we found that non-standard questionnaires accounted for the majority of instances for perceived usability metrics and user experience metrics. Additionally, we found instances of non-standard questionnaires being used for discomfort and presence metrics, despite well-known standards being available. Hence, we highly encourage researchers to stop using non-standard questionnaires to investigate locomotion techniques.

6.3 Limitations of Our Research

As with any research, there are limitations of our methodologies and results. One notable limitation are the required search terms that we used for identifying relevant publications. While most locomotion research papers likely include the required abstract terms, there are obviously some highly relevant publications that were omitted from our initial WoS search due to the requirements. However, while these publications would have changed the specific number of techniques and metrics found in our results, we do not believe these changes would have significantly affected our outcomes, particularly the k-means clusters. Hence, our results are still highly relevant.

Another limitation of our research is the taxonomy [11] that we chose to organize and present our results. Using a different taxonomy, particularly one focused on components or aspects of locomotion instead of groups [61], would likely have changed our results. However, we chose to use the taxonomy because it has been shown to have the greatest impact in terms of citations [61].

7 Conclusion

In this paper, we have presented a systematic review of VR locomotion techniques, including 63 selected publications. We have used a well-established locomotion taxonomy to categorize and present the results of our review. We have used the k-means clustering algorithm to identify locomotion techniques that have been highly explored, moderately explored, and less explored. Our results indicate that researchers should further investigate several locomotion techniques, including Point-and-Motion, Arm Swinging, Scene-in-Hand, Automated Steering, and Automated Teleport. Furthermore, we have also identified several locomotion metrics that have been investigated and identified to what extent each have been employed in VR locomotion research. Our results specifically indicate that more research should be conducted with regard to biometrics, user experience metrics, and emotions. Additionally, our results indicate that non-standard questionnaires are used too frequently. We hope these results will help VR researchers and developers to consider locomotion techniques and metrics that warrant more investigation.

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