Literature review of locomotion techniques in virtual reality

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Abstract

This study represents a systematic literature review in which we explored the locomotion techniques in virtual reality between 2012 and 2019. We analysed and compared 22 locomotion methods that we have identified in 26 papers included in our review. The objective is to better understand relevant locomotion techniques and their impact on the user experience. The review of the literature has shown a wide range of different locomotion techniques which each technique is characterized by different advantages and drawbacks, but classic locomotion techniques such as joystick outperformed all the proposed technique in the reviewed studies. We also proposed a taxonomy and two types of evaluation for locomotion techniques in virtual environment. These elements provide guidelines that may help researchers to choose the most adapted locomotion technique according to the aim of their study.

1. Introduction

Virtual reality allows the user to extract himself from real environment to immerse in a virtual environment where he can observe, interact, dialogue and even learn new skills. This flexibility has opened new horizons in several areas such as robotics, urban planning, industry, art and education, etc. For example, an aircraft pilot can train for difficult landings situations in inclement weather, without danger to himself or his passengers. A surgeon may be trained in a specific intervention, before actually performing it. In addition, there are situations that are difficult to reproduce in real world, such as a train derailment or a surgical complication. Users can then train and repeat complex situations at will in a controllable environment (Cherni, 2012). Over the last ten years, technological progress has significantly improved user experience in the virtual world. Despite the fact that locomotion is not the primary objective of virtual reality applications, it is considered to be one of the most important components of interaction in virtual reality experiences because it is indispensable and crucial to explore the virtual environment (Lee et al., 2018). The emergence of new virtual reality devices like the commercial releases of the HTC Vive and the Oculus Rift, marked the beginning of what some researchers call "a new era in the history of virtual reality". In this new era, common locomotion devices such as standard game controllers and joysticks have been shown, not adapted and causing disorientation in immersive virtual environments (Lathrop & Kaiser, 2002; Ruddle & Lessels, 2006). Thus, it is not clear how to effectively and inexpensively explore a virtual environment. In this way, finding an efficient method to move the player in the virtual environment became one of the most important challenges and induced a renewed interest in the locomotion techniques in virtual environment. Virtual reality locomotion enables the user to move in an infinite-scale virtual-world, it can be defined as self-propelled movements in the virtual environment while staying confined in a room-scale real-world environment (Hale & Stanney, 2014). Locomotion is an essential form of human computer interaction. In virtual reality, it has a direct effect on many aspects of user experience such as enjoyment, frustration, tiredness, motion sickness and presence. When the virtual environment is the same size as the physical environment of the user and the system allow him to move freely, the user can walk naturally to control the

virtual-world locomotion. However, when the virtual environment is larger than the physical environment, an alternative locomotion method must be used. Consequently, new locomotion techniques have emerged. The choice of the locomotion technique is still untapped in terms of understanding, development, use and experimentation. Thus, finding an efficient locomotion technique that does not alter the presence, does not cause motion sickness and avoid fatigue represents a real challenge that has become today the object of numerous research studies (Bowman et al., 2004; Kitson et al., 2017a).

In this paper, we present and discuss the main locomotion techniques that have been used and studied in virtual reality from January 2012 to April 2019. The main purpose is to provide guidelines that may help researchers for the choice of the locomotion technique that is adapted to the purpose of their experiment and associated use cases in the virtual environment.

2. Methodology

This study was undertaken according to the guidelines based on ten major steps required for a systematic literature review, which was proposed by Brereton and colleagues (2007) (see Figure 1).
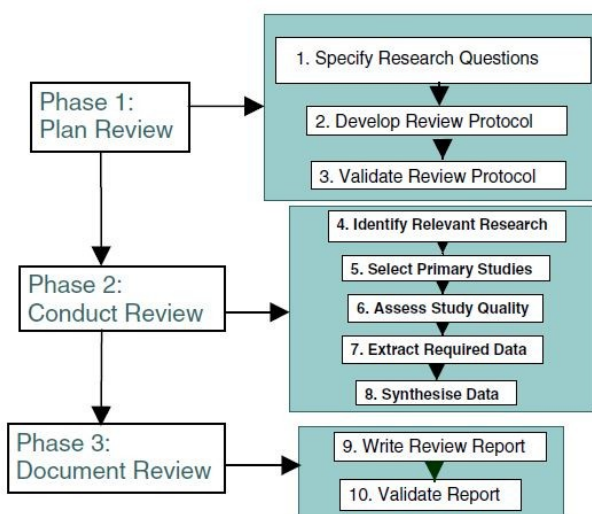

Figure 1. Systematic literature review process from Brereton et al. (2007)

2.1. Research question

To conduct the literature review, we have identified the following research question: What are the locomotion techniques in virtual environments used in research studies and how have they evolved over the past six years?

2.2. Identification of relevant studies

To identify relevant articles studying locomotion techniques in the virtual environment, a targeted search was conducted using keywords: [*virtual reality, moving, navigation techniques, locomotion*], in google scholar database[1]. Our search was focused on studies published between January 2012 and April 2019. A pre-selection based on the article's abstracts were used to identify the relevant studies.

Three inclusion criteria were considered:
- Only papers written in English or French;
- Only papers representing an empirical study on locomotion techniques in virtual environment;
- Only papers that study at least one locomotion technique.

After the first stage of research based on the article's abstracts, 61 papers were deemed relevant. After the second stage, 26 articles were selected and included in our study.

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1 https://scholar.google.fr/

3. Data Collection

Identification of locomotion techniques (LT) in virtual environments, their characteristics and the purpose of the studies carried out on these techniques are illustrated in Table 1. A total of twenty-two locomotion techniques has been identified.

Table 1. Main Locomotion techniques in virtual environments

Study and purpose	Locomotion technique
(*) Proposing a novel Walking-in-Place method using position and orientation tracking and comparing it to existing Walking-in-Place techniques using sensors to detect the walk (Lee et al., 2018)	- Walking-in-Place - New variant of Walking-in-Place
(*) Proposing two new techniques of Walking-in-Place in virtual environment with new gestural inputs and comparing with the existing one (Nilsson et al., 2013)	- Tapping-In-Place
Comparative study between teleporting and two classic virtual reality locomotion techniques in a navigation task in a virtual environment (Bozgeyikli et al., 2016b)	- Walking-in-Place - Point and teleport (User's tracked Hand) - Joystick
(*) Introducing a new method of implementing Walking-in-Place using an inexpensive accelerometer sensor. Then evaluating this method of Walking-in-Place by comparing it to normal walking and Arm Swinging (Wilson et al., 2016)	- Walking - Walking-in-Place - Arm Swinging
(*) Enhancing Walking-in-Place locomotion technique by adding walking-related cues like foot haptics system and auditory feedbacks (Kruijff et al., 2016)	- Walking-in-Place - Upgraded variant of Walking-in-Place
(*) Proposing a new approach to Walking-in-Place locomotion technique which allows people, when walking along linear paths, to control their virtual speed based on footstep amplitude and speed metrics. This method is then compared to classic Walking-in-Place techniques which are based on steps frequency (Bruno et al., 2013)	- Walking-in-Place - New variant of Walking-in-Place
Implementing a new locomotion technique based on hands gestures captured by a low-cost sensor called "Myo Armband" and comparing it to joystick and Walking-in-Place approaches (McCullough et al., 2015)	- Myo Arm (Arm Swinging) - Walking-in-Place - Joystick
Proposing a new approach for locomotion in virtual reality using smartphone's inertial sensors to detect the user steps (Tregillus & Folmer, 2016)	- Walking-in-Place
Testing four different hands free, easy to learn and low cost hands-free navigation methods and comparing them to a standard gamepad control, in a virtual environment with head mounted display (Zielasko et al., 2016)	- Walking-in-Place - Accelerator Pedal - Leaning (in seated position) - Shake your head - Joystick
Comparing a low-cost new leaning method based	- Body leaning - Walking-in-Place

on Wii-balance to the joystick and Walking-in-Place locomotion technique in a navigation task in a virtual environment (Harris et al., 2014)	- Joystick
Focusing on the effects of static and dynamic upper body leaning combined to the joystick on perceived distances travelled and self-motion perception (Kruijff et al., 2015)	- Leaning body + Joystick
Proposing and evaluating the usability of two locomotion techniques, both based on a combination of visual controls and hand gestures using low-cost sensors (Caggianese et al., 2015)	- Combined tracking of the user's head and hand
Comparison of joystick and four new locomotion techniques in a target finding task in an information rich virtual environment (Kitson et al., 2017a)	- Joystick - MuvMan (sit/stand active stool) - Head-Directed (based on HMD orientations) - NaviChair (revolving stool with springs) - Swivel Chair (a chair with leaning capabilities)
Study the impact of the NaviChair, a new motion cueing locomotion technique on spatial updating compared to a traditional non-embodied interface (the joystick) (Kitson et al., 2015)	- NaviChair - Joystick
Designing and implementing a new high fidelity locomotion technique: Human Joystick and comparing it to joystick (McMahan et al., 2012)	- Human Joystick - Classic joystick controller
Study of the effectiveness of a new locomotion technique based on the motion capture of different parts of the user's body (Guy et al., 2015)	- LazyNav
Proposing a new locomotion method based on pressure cushion to explore virtual environment in a seated position (Ohshima et al., 2016)	- Intuitive Striding Unit
Implementing and comparing eight locomotion techniques in an immersive virtual reality test environment (Bozgeyikli et al., 2016a)	- Redirected walking - Walking-in-Place - Hand Flapping - Flying - Point and teleport - Joystick controller - Stepper machine - Trackball controller
Analyzing the mutual influence between redirected walking and two different (verbal and spatial) working memory tasks using a dual-tasking method (Bruder et al., 2015)	- Redirected walking
Comparison of the impact of 3 navigation techniques (natural, semi-natural and artificial) on the performance in a navigation task (Nabiyouni et al., 2015)	- Virtusphere - Real walk - Joystick
Comparison of two locomotion techniques methods: a locomotion treadmill, which supports omni-directional movements, and Arm Swinging, which recognizes movement from the swinging back and forth of the users (Calandra et al., 2018).	- Omnidirectional virtual reality treadmill - Arm Swinging
Proposing and testing a new semi-natural virtual reality locomotion techniques: omnidirectional	- Omnidirectional treadmill - Joystick

treadmill (Warren & Bowman, 2017)	
Study of the use of a skateboard simulator to navigate in virtual environment (Sato et al., 2015)	- VibroSkate: skateboard simulator
Comparison of point and teleport locomotion technique, continues motion (joystick) and a new form of point and teleport method based on rapid and continuous movement to a selected node (Habgood et al., 2018)	- Point and teleport (with HTC VIVE controllers) - Joystick
Comparison of the enjoyment, frustration, effort, distance, occlusion, immersion, and motion sickness between the point and teleport locomotion technique and trackpad in a virtual reality experience (Linn, 2017)	- HTC Vive controllers: Point and teleport - Trackpad
Comparison of three locomotion techniques: contentious-motion, teleportation and World-In-Miniature (Berger & Wolf, 2018)	- World-In-Miniature - Continuous motion (OculusTouch Josystick) - Teleporting (using hand gestures)

Notes. (*) Locomotion technique (LT) that represents an extension or improvement of another already existing LT.

4. Locomotion techniques in virtual environment

Finding an intuitive, efficient and not expensive locomotion technique was the main object of the studies mentioned in Table 1 above. On the most general level, it is possible to distinguish between techniques using the user's body by tracking different parts of it to determine whether the user is walking or not and techniques using external peripheral to move in the virtual environment either for simulating walking or to move with a "non-natural" way.

4.1. Locomotion techniques taxonomy

As it will be highlighted in the next section, the literature review and the study of the locomotion techniques characteristics allowed us to distinguish three main categories of locomotion methods: user body centred methods, external peripheral centred methods and methods using both user's body and external peripheral. Each one of them can be broken down into many distinct subcategories.

Figure 2 represents our proposed taxonomy of locomotion techniques in virtual reality.
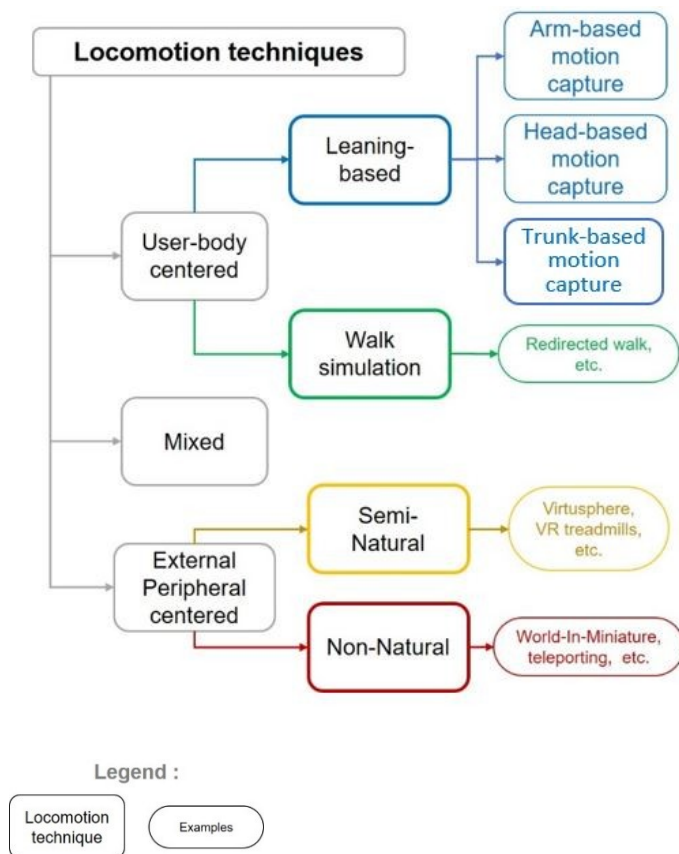
Figure 2. Virtual reality locomotion techniques taxonomy[2]

Referring to our proposed taxonomy of locomotion techniques in virtual reality, we can notice that nine out of the twenty-two identified locomotion techniques are belongs to the leaning based category which represents over 52% of the identified locomotion methods. The semi-natural approach comes in second position with the non-natural approaches. Each represents about 17% of the identified locomotion methods. Then, we find the combined approaches with about 9% followed by the walking simulation approaches which represents about 4% of the identified techniques (see Figure 3). This shows that most of the studies in the reviewed papers believed in the power of leaning based methods. Thus, for most of them, the most intuitive way to find the optimal locomotion technique in the virtual environment seems to be exploring the body motion cueing strategy. This trend is in accordance with many studies that showed that leaning based approaches increases the user's sensation of self-motion, enhance spatial perception and orientation and user experience (Bowman et al., 1998, 2004; Riecke et al., 2010).

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2 The color code is to visually distinguish the different categories of locomotion techniques and is identical between Figure 2, Figure 3, Table 2 and Table 3.
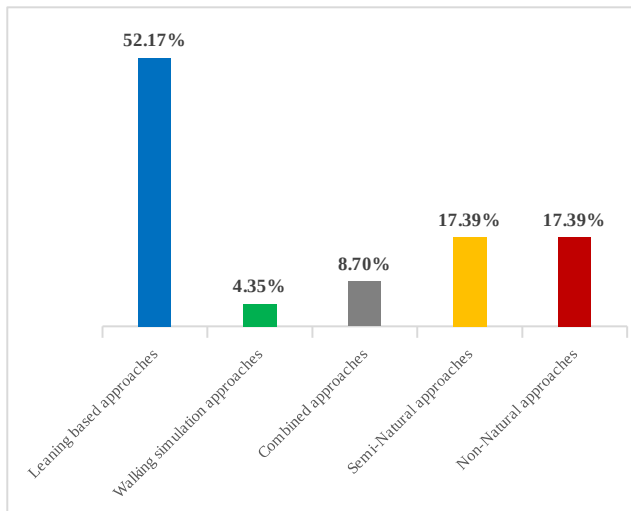
Figure 3. Percentage of distribution of the identified locomotion techniques according to our taxonomy

4.2. User-body centred techniques

4.2.1. Leaning-based locomotion techniques (LT)

In the interest of increasing the user's sensation of self-motion, enhance spatial perception and orientation and user experience, several studies tried to find the best locomotion technique by keeping the body motion cueing strategy to walk through the virtual environment (Bowman et al., 1998, 2004; Riecke et al., 2010). In leaning based locomotion techniques, walking is achieved by leaning the whole body or just parts of it into the desired direction. The leaning itself can be detected by standard tracking technology or with special devices like force plates, such as the Wii balance board (Zielasko et al., 2016). Different parts of the body are captured to detect whether the user is moving or not. In these studies, we can distinguish locomotion techniques that used the trunk motion cueing, those based on head tracking, those based on arm tracking and those that combines different part of the body motion cueing (see Figure 6).

Head-based motion capture LT

In the locomotion techniques based on head motion, called commonly "shake your head", the head rotation and tilt control the simulated transitions and rotations in the virtual environment (Kitson et al., 2017a; McMahan et al., 2012; Zielasko et al., 2016). In this method, the tracked position and/or rotation of the user's head is used to walk through the virtual environment. One of the most common leaning based locomotion techniques based on the head motion capture using the head mounted display position is the real walking method. In their studies, Wilson et al. (2016) and Nabiyouni et al. (2015) compared the natural walking method in virtual environment to other common locomotion techniques. Based on several parameters like the number of errors in the required task, the precision in the task and users' subjective rating of the naturalness, the ease of learn and the ease of walking, they found that real walking outperformed Walking-in-Place, Arm Swinging and other semi-natural locomotion techniques. However, real walking, although the most natural and immersive locomotion technique with a high subjective sense of presence (Slater et al., 1995), it requires too much space, which most physical environments do not provide and thus limits virtual environments to the size of the tracked space. Therefore, when the virtual environment is larger than the physical environment, real walking is not enough to explore the virtual environment and loses most of its interest.

Another common leaning based locomotion technique that can use the head motion capture is the Walking-in-Place. This method imitates walking. It encourages the users to engage their whole body in a realistic walking motion as much as possible but without actually moving forward. Many studies were carried out to compare this method to other locomotion methods (Bozgeyikli et al., 2016b, 2016a; McCullough et al., 2015) or even propose new variants of this method using different gestures inputs (Berger & Wolf, 2018; Nilsson et al., 2013). The results of the studies comparing this locomotion technique to other methods such

as Arm Swinging, point and teleport, leaning based methods in seated position, joystick, etc. showed that Walking-in-Place outperforms most of these techniques. Walking-in-Place can reduce the space needed for moving through virtual environment, with less simulator sickness. However, it presents some weak points and limits. The first limitation relates to the fact that, in many cases, there are many sensors to attach to the body of the user. Some studies tried to solve these problems by using other parameters to detect the walking like the position and orientation of the head mounted display (see Figure 4). Moreover the immersion level of the user is still low (Lee et al., 2018; Nilsson et al., 2013). In addition, standing position is not always appropriate to explore the virtual environment. The second limitation is that this technique may not be a suitable solution to exploring a significantly large virtual environment because it would take considerable time and physical energy. Thus, Walking-in-Place to explore a town or city might be exhausting. The weak point is that the immersion level of the users is reduced due to the fact that the users imitate walking without actually walking and the difficulty of the gestures required.
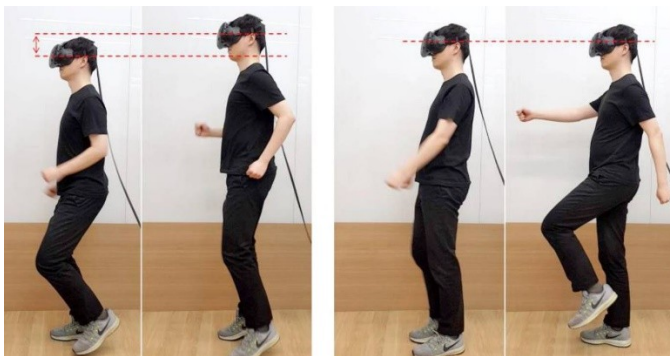

Figure 4. Walking-in-Place technique using the HMD position and orientation (from Lee et al., 2018)

Zielasko and colleagues (2016) used the inertial sensors built into the HMD to determine the position and the rotation of the seated user. The participant had to look up and look down to go forward and backward. Results showed that the joystick outperformed and had a better ranking than the head motion-based locomotion technique. It is worth noting that using the head movement to navigate and rotate in the virtual environment sacrifices the use of the head for other interactions like for example looking around in 360° without actually turning. McMahan and colleagues (2012) proposed different approaches of the same locomotion technique in a cave display configuration. They designed and implemented a new high-fidelity locomotion technique based on the head position tracking that they called Human Joystick and compared it to joystick navigation. By capturing the 2D horizontal vector from the center of the CAVE to the user's tracked head position and utilizing it as a joystick's 2D vector used for locomotion independently from the direction the user is facing (see Figure 5). They found that participants had a greater sense of presence with the Human Joystick method coupled to a high-fidelity display. However, with low fidelity display, the keyboard and mouse outperformed the Human Joystick technique.
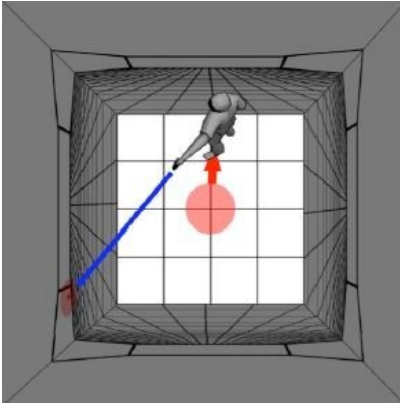
Figure 5. "Human Joystick" locomotion technique (from McMahan et al., 2012)

Trunk-based motion capture LT
The techniques based on trunk motion capture, consists in physically leaning or tilting the trunk as a means of translating according to two degrees of freedom (forward and backward) and rotating the user in the virtual space (Kitson et al., 2017b).
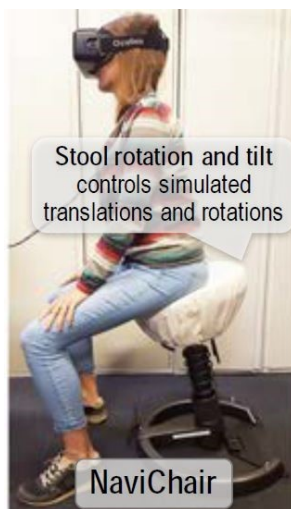

Figure 6. NaviChair: An example of locomotion technique based on the user trunk motion in seated position (from Kitson et al., 2017b)

Using trunk-based method, users can walk through the virtual environment in standing position. Harris and colleagues (2014) compared this method to joystick navigation and Walking-in-Place locomotion technique. In the first part of the study, they compared this locomotion technique to joystick navigation. They found that when participants explore the environment by physically leaning their spatial representation of the virtual environment is more accurate. In the second part of the study, they found that users were more oriented when they leaned to explore the environment, whereas they spent more time and physical energy to explore the virtual environment with the Walking-in-Place technique. Besides, participant expressed that the faster speed was more congruent with the leaning method than with Walking-in-Place. However, in the spatial knowledge test, turning errors and the latency of turning were lower in the Walking-in-Place technique configuration.
Furthermore, trunk-leaning based LT can also be in seated position (Kitson et al., 2017a, 2015; Zielasko et al., 2016). In their study, Kitson and colleagues (2017a) used a complex environment to compare four leaning based locomotion techniques to the joystick, in a target finding task. Comparisons were based on interviews and observations as well as data collected during the experiments. The results did not support the

predictions of the literature that the motion cueing interfaces will provide greater benefits over a non-motion cueing interface such as the joystick, for illusions of self-motion, spatial perception and orientation, enjoyment and engagement, as well as immersion and presence. The qualitative feedback showed that the joystick navigation offers easier and more precise control, is more comfortable and helps participants to feel more spatially oriented despite the fact that when using the joystick for moving, we sacrifice the use of the arm and the hand in the interaction with the virtual system. Yet, the four motion cueing techniques showed a trend towards providing a stronger sensation of self-motion. In their study, Zielasko and colleagues (2016) tested a leaning-based in seated position low cost hands-free navigation methods and compared it to a gamepad navigation, in a virtual environment with head mounted display. The results of the study showed that the leaning method performed very well in general and is able to compete against the gamepad navigation on different levels.

Arm-based motion capture LT

Users can also use their arm to walk through the virtual environment. One of the first methods using the human arm to control the user movements is the "Arm Swinging" methods (Habgood et al., 2018; McCullough et al., 2015). The basic idea of the method is that users swing their arms to move in the direction that they are looking (see Figure 7). Walking through the virtual environment using this technique requires tracking the position and the rotation of the user's hand using tracking devices. However, those tracking systems are expensive and very specific and suggest that it will never be a commodity level product (McCullough et al., 2015). Several studies tried to resolve the problem of sensors by using a wearable armband (accelerator sensors) that they attach on the thickest part of the user's forearm: the Myo armband. This locomotion technique was proposed for the first time by McCullough and colleagues (2015) who compared it to joystick and Walking-in-Place approaches. They found that this new arm swinging method outperforms the simple joystick in spatial orientation and that it is comparable to physically walking on foot. In their study, Wilson and colleagues (2016) compared Arm Swinging locomotion technique based on Myo armband to a new method of Walking-in-Place based on the Myo armband too and the real walking. The results showed that physical locomotion outperformed both Walking-in-Place and Arm Swinging in terms of spatial awareness. They also showed that Walking-in-Place method was better than Arm Swinging.
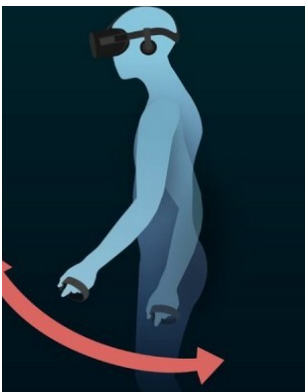
Figure 7. Arm Swinging locomotion technique: Swing your arm to control the movement in the virtual environment

Another way to travel in virtual reality based on the user's arm to control the movements in the virtual environment is a method called "point and teleport technique" (in opposite at the software automated teleportation). With this technique, users can travel from one place to another by pointing the place they want to go to and then they are in the new position (see Figure 8). The new place users wish to travel to is often called "the target location" (Bozgeyikli et al., 2019). In some applications, target locations are predefined, and the user have to point the target to indicate which one he wants to travel to. In other applications, instead of predefining targets, the users are free to teleport anywhere on the ground by pointing the target position. In

both cases, users have often a visual and sometimes an auditive feedback to confirm the selected target location and the movement of the user (Cherep et al., 2020). When pointing the target position, the teleportation can be actioned either by pushing a button or by pointing the target for longer than a certain amount of time. In this case, it is important to note that the use of the arm to interact with the VE is "sacrificed". Furthermore, point and teleport locomotion technique is known not to introduce motion sickness since it does not involve any visible translational motion (Bozgeyikli et al., 2019). In their study, Bozgeyikli and colleagues (2016b) compared this locomotion method with the Walking-in-Place and joystick-controlled techniques. To teleport in the virtual environment, users should point to the same place for two seconds. After that, the teleportation is triggered and the virtual avatar is instantaneously moved to the target position. In the experiments the users are required to go to ten destination points with each locomotion technique without colliding with static obstacles. They found that "point and teleport" method outperformed the Walking-in-Place and joystick-controlled techniques. Users were more rapid to reach the destinations and made a fewer number of collisions with the obstacles. However, the joystick method is easier to understand, requires less effort, induces less tiredness and users had a better control in the task. It is important to note that with this technique, the lowered arm posture of the user makes the teleportation inactive. Consequently, this design may not work well for applications in which the user is supposed to do some activities with their hands while waiting. In that case, another gesture or a controller must utilized to control the activeness of teleportation.
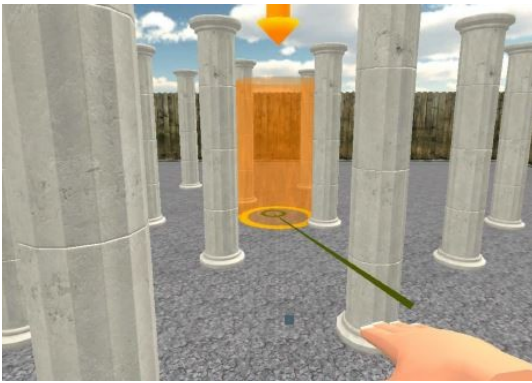

Figure 8. Point and teleport locomotion technique based on user's arm movements (from Bozgeyikli et al., 2016b)

Although the positive feedbacks of the users concerning the leaning-based locomotion technique, most of the comparative studies showed that common methods like joystick outperform leaning-based techniques. Besides, in the case of head tracking motion based, participants cannot move and look around at the same time. Also, in case of arm-based methods, the users cannot use freely their hands to interact with the virtual environment. Same thing with the trunk-based locomotion techniques, the movement of the trunk are restricted because they can be interpreted as commands to move forward or backward.

4.2.2. Walk simulation LT

For the purpose of capturing the benefits of real walking while extending the possible size of the virtual environment, several studies used the Redirected Walking locomotion technique. The Redirected walking is a technique that, like the Walking-in-Place methods, enables users to explore a virtual world that is considerably larger than the tracked workspace addressing the limitation of the size of the virtual environment (Zank & Kunz, 2015). This technique works by interactively rotating the virtual scene about the user, such that the user is made to continually walk towards the farthest "wall" of the tracker area (see Figure 9). Therefore, users are guided unnoticeably on a physical path that differs from the path the user perceives in the virtual world by manipulating the transformations from real to virtual movements (Bruder et al., 2015). For example, virtually rotating the view in the HMD to one side with every step causes the user to unknowingly compensate by walking a circular arc in the opposite direction, while having the illusion of

walking on a straight trajectory (Nabiyouni et al., 2015). This locomotion technique exploits the limitations of human perceptual mechanisms for sensing position, orientation and movement, suggesting that the user does not notice this rotation (Razzaque, 2005).
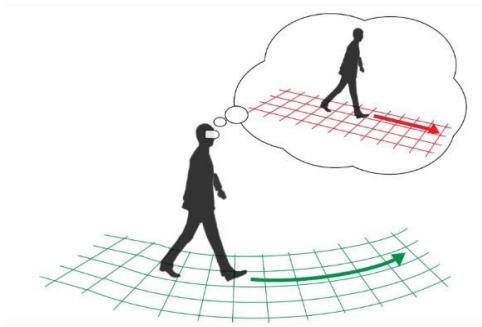

Figure 9. Redirected walking: walking in the real world on a curved path with a visually perceived straight path in the virtual world (from Matsumoto et al., 2016)

The problem associated with this approach is that the human perceptual system tolerates a certain amount of inconsistency between proprioceptive, vestibular and visual sensation in virtual environment. Several studies showed that users are not able to detect an inconsistency if their physical path is bent with a radius of at least 22 meters during virtual straightforward movements. If redirected walking is applied in a smaller workspace, manipulations become noticeable which reduces considerably the sense of presence of the user (Bruder et al., 2013; Steinicke et al., 2010). Then, below a certain radius, this technique is not suitable.

4.3. External Peripheral Centred

Different studies used the human body as a locomotion tool to explore the virtual environment whereas several studies did not believe in the body-centred self-motion cues but tried to focus on effective and intuitive locomotion techniques by using external peripherals. The locomotion techniques that belongs to this category can be compiled into two major sub-categories: "Semi-natural" and "Non-natural" methods.

4.3.1. Semi-natural LT

In the semi-natural approach, the aim is to be as near as possible from the real walk. In their study, Nabiyouni and colleagues (2015) performed an experiment to compare the real walking with a semi-natural locomotion technique and a traditional non-natural technique based on a game controller. The semi-natural locomotion technique was based on the Virtusphere device which is a large hollow sphere mounted on casters, in which a user wearing a head-mounted display can walk in any direction, to move through a virtual environment of any size (see Figure 10). Results showed that the Virtusphere was outperformed significantly by both the gamepad and real walking interfaces, indicating that it is slower, less precise, harder to use, more fatiguing and more difficult to control. The authors concluded that the relationship between interaction fidelity and effectiveness is more complicated.

Figure 10. The Virtusphere locomotion device[3]

A new semi-natural locomotion technique is the omnidirectional treadmill (Calandra et al., 2018; Warren & Bowman, 2017). The omnidirectional treadmill is a mechanical device that allows the user to perform locomotive motion in any direction, allowing for 360 degrees of movement (see Figure 11). Combined with a virtual head mounted display, this device is used to capture the user's feet movements and reproduce his/her behavior in a virtual world through an avatar (Calandra et al., 2018). Some locomotion techniques use special devices to control the locomotion and keep the users in a secure place. Omni-directional treadmills were designed and developed for this purpose. These treadmills sense walking in any direction and keep the user at the center.

In their study, Warren and Bowman (2017) compared the Virtuix omnidirectional treadmill to a classic game controller in a path following task in a virtual environment. They found that the game controller provides a better user experience than the Omni Virtuix. The omnidirectional treadmill is more natural and more playful, but it requires to wear an uncomfortable harness and presents a difficulty in turning while walking inducing fatigue after only a short usage session. The obtained result supports previous studies showing that realism in virtual reality systems is not always the most adapted solution.

In their study, Calandra and colleagues (2018) made a comparative study between two locomotion techniques methods: a locomotion treadmill, which supports omni-directional movements, and Arm Swinging, which recognizes movement from the swinging back and forth of the user. Results showed that the two methods were perceived as mostly equivalent in terms of usability factors like functionality, user interaction with objects, simulation fidelity, presence and motion sickness symptoms but with a slight advantage for Arm Swinging method.

3 From https://commons.wikimedia.org

Figure 11. Early bird system of omnidirectional treadmill: the Omni Virtuix[4]

While Omnidirectional treadmills are considered to be most similar compared to the way we move through physical space, they are expensive and difficult to use and to maintain. Besides, such a locomotion technique implies a proportional time and energy, and can be costly for the user in large environment, and have to be considered in experimental protocol (Calandra et al., 2018; Warren & Bowman, 2017). Nevertheless, several other omnidirectional treadmills were launched on the market those past two years, and no literature evaluating their performance are available for the moment and new specific studies on it could nuance those results for a more up to date review. For these reasons, several studies in virtual reality navigation interfaces still take the advantages of the power non-natural methods based on external peripheral as solution to travel in the virtual environment even if these methods provide a lower level of immersion.

4.3.2. Non-natural LT

One of the most used methods to walk through the virtual environment with a non-natural way is teleportation. It is becoming one of the most prominent means of VR interaction as it induces minimal motion sickness and offers the user an efficient way to move about virtual spaces that are larger than the tracked physical area (Riecke et al., 2018).

Habgood and colleagues (2018) compared the point and teleport locomotion technique to continuous walking approach using a classic gamepad method and to a new variations on the point and teleport method based on rapid and continuous movement of the user between predefined nodes positions in the virtual environment. Results showed that teleportation technique outperformed continuous walking approaches. They showed also that the rapid movement speeds reduce players' feelings of motion sickness as compared to continuous movement at normal walking speeds. However, the study was unable to demonstrate any benefits of this new variant of teleportation over classic teleportation in terms of user's feeling of presence. Nevertheless, this reduces significantly the number of collisions, as it limits the positions and transitions that the user can occupy.

Using "point and teleport" LT represents an efficient method to move through the virtual environment with a low level of motion sickness. Nevertheless, it may introduce a new problem caused by the disorientating effect of changing position without continuity of motion. Thus, it interferes with a user's sense of space and reduces the presence and immersion (Bowman et al., 1997).

In their study, Berger and Wolf (2018) presented a new locomotion technique that they called World-In-Miniature. This technique allows the user to change his viewpoint through picking and relocating his representing icon in a virtual miniature replica of the virtual environment he is located in (see Figure 12). An evaluation was undertaken to compare this locomotion technique with hand gestures-based teleportation and continuous walking approaches using the joystick of the Oculus Touch controller. They found that World-In-Miniature outperforms the other two techniques in navigation time for longer distances. Furthermore, it provides best spatial knowledge while causing least motion sickness among the compared methods. However, the large quantity of information that afford to the user can also induce a cognitive overload reducing the performance of the user in the main task (Berger & Wolf, 2018).
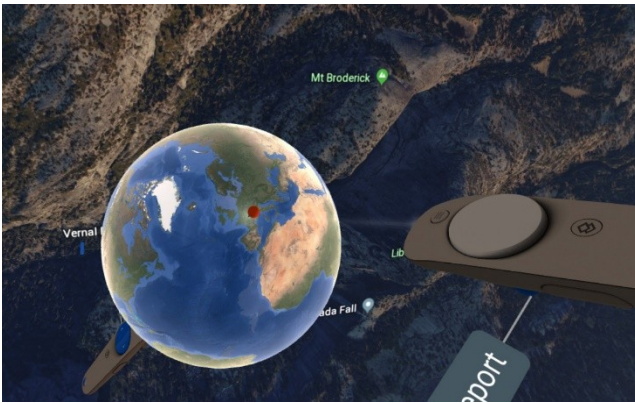
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4 From https://www.virtuix.com/https://www.virtuix.com/

Figure 12. World-In-Miniature locomotion technique in Google Earth VR

4.4. LT combining the use of the body and external peripheral

Some studies found better performance by combining leaning the user's body and the use of external peripheral. In their study, Kruijff and colleagues (2015) combined the trunk leaning and the joystick to control the movement in the virtual environment. They focused on the effects of static and dynamic upper body leaning combined to the joystick on perceived distances travelled and self-motion perception in the virtual environment. They found that leaning the trunk while using the joystick to travel in the virtual environment had a positive effect on the self-motion perception. The found results confirm previous work of Riecke and colleagues (2010), who found that controlling translations via joystick and rotations via physical rotations led to better performance than joystick navigation, and yielded almost comparable performance to actual walking in terms of search efficiency and time in a navigational search tasks. In their study, Ohshima and colleagues (2016) proposed a new variant of Walking-in-Place approach combined to head movement that they called: the virtual Intuitive Unit. In this approach, sited on a chair, the user can walk through the virtual environment by moving his legs up and down. The difference with the classic Walking-in-Place approach is that instead of placing sensors on the user's body, they used a pressure sensor module placed on the ground under his thigh. This method can be a solution for many problems of the Walking-in-Place approach. Nevertheless, it suffers from two main problems. The first problem is the high level of motion sickness that induce the Walking-in-Place approach in general. The second problem is the way the users control rotations in the virtual environment: the user must use the head rotation to control both of looking around and the rotation while walking. Bozgeyikli and colleagues (2016a) used a stepper machine to explore the virtual environment combined to head movement. The movement of the stepper machine was tracked by an optical motion tracking system with the use of a reflective marker. The stepping movement on the machine was transferred to the virtual world as locomotion using a marker that was attached on the pedal. A comparative study was undertaken between the stepper machine and other locomotion techniques. Results showed that, although outperformed by joystick and point and teleport techniques, the stepper machine received high scores in comfortability, enjoyment and control precision. The main problem with this approach is that, same as the Intuitive Striding Unit proposed by Ohshima and colleagues (2016), both of looking around and the locomotion direction was defined by the user's head direction which makes it more difficult to use, decreases the control precision and limits the interactions with the virtual environment that can be made simultaneously.

5. Evaluation of locomotion techniques

The extraction and analysis of the locomotion techniques in the reviewed papers led us to propose an assessment and a comparison between the twenty-two identified locomotion techniques.

Table 2 represents the proposed comparison we made based on the most common virtual reality ration criterion that we identified in the reviewed papers. The relevant selected criterions are: the presence in the virtual environment (i.e., immersion sensation), the ease of use, the control precision, the spatial orientation, the self-motion sensation (i.e., sensation of controlling the movement), the tiredness, the motion sickness, the

adaptation for large virtual environment and the adaptation for virtual reality interaction. The provided ratings were from "--" to "++". The worst score "--" means that the given comparison criterion is not fulfilled at all, whereas the best score "++" means that the comparison criterion is completely fulfilled. For example, in the "ease of use" criterion, the score "++" was assigned to the real walk locomotion technique. However, this technique requires too much space, which most physical environments do not provide. For this reason, in the criterion "adaption for large VE" the score "--" was assigned to it.

Table 2. Comparative table between the different locomotion techniques identified in the reviewed papers

	Presence in the VE	Ease of use	Control precision	Spatial orientation	Self-motion	Tiredness	Motion Sickness	Adaptation for large VE	Adaptation to VR
Real walk	++	++	++	+	++	++	++	--	++
LazyNav	+	-	--	+	+	+	--	+	-
Arm Swinging	++	+	-	+	+	-	--	-	--
Walking in place	+	++	+	+	+	-	-	-	+
Teleporting (Hand Gestures)	++	+	++	-	-	++	++	++	-
Human Joystick	+	-	+	+	-	+	--	+	+
Body leaning (Stand position)	+	+	-	+	+	+	--	+	-
MuvMan	+	-	-	+	+	+	-	+	-
Shake your head	-	-	-	+	+	+	-	+	-
NaviChair	+	-	-	+	+	+	-	+	-
Swivel	+	-	-	+	+	+	-	+	-
Redirected Walking	-	+	-	+	+	-	++	+	+
Intuitive striding unit	+	+	-	+	+	+	--	+	--
Body leaning + Joystick	+	-	+	+	+	+	-	+	-
Virtusphere	+	--	--	+	+	--	+	+	+
VibroSkate	+	-	-	+	-	+	--	+	+
Stepper machine	+	-	+	+	+	--	-	+	-
Omnidirec-tional treadmill	++	-	+	+	++	-	+	+	++
Joystick	+	++	++	++	--	++	--	++	-
Teleporting (HMD Controllers)	++	++	++	-	-	++	++	++	+
Accelerator pedal	+	-	-	+	-	-	-	+	+
World-In-Miniature	+	-	-	+	-	+	+	+	+

The table above represents an initial synthesis and rating of the locomotion techniques in the reviewed studies. This proposition would, however, have its limits because not all the techniques were compared to one another. But it would offer a global vision and a current assessment based on our first comparative study. Another limit of this assessment is that some of the identified locomotion techniques, like for example the omnidirectional treadmills, are newly developed and are in constant evolution. Therefore, evidence suggests that the advantages and disadvantages cannot be fixed once and for all.

Another point of view that would help in the choice locomotion technique for an experiment, is the ability to track a body part for its natural moves. For several systems presented in this paper, body parts are used in a non-natural way, and thus cannot be used to interact in the scene or being recorded as the participant natural behavior. In Table 3, the systems specifications are referred to body parts in four categories: neutral, natural, constrained and sacrificed. The neutral category (the grey box in the Table 3) is for the systems which does not involve the body part, then those parts are not monitored. The natural category (the green box in the Table 3) is for the systems which track the body parts in a natural way and give a feedback as it is. The constrained category (the yellow box in the Table 3) is for the systems which track body parts, but limit their interactions (e.g., VibroSkate). The sacrificed category is for those which use body parts in a non-natural way and prevent to use them for interactions in the scene. If the system does not depend on the body part, it has been labeled as optional (blue in the table). For example, the Arm Swinging technique is incompatible with an experiment which intend to measure the moves of forearms on a drumkit, they will then be labeled as sacrificed, because this body part is dedicated to locomotion in a non-natural way. In opposite, for the redirected walking technique, the head is monitored in a natural way, and its signal can be used to record this body part in as natural. If a body part is either not used or not monitored by the locomotion system, it would be labelled as neutral, meaning that it can be used if needed, but no signal will refer to it.

Table 3. Body parts dedicated to locomotion techniques

	Head	Trunk	Forearms	Hands	Legs	Feet
Real walk	Natural	Neutral	Neutral	Neutral	Neutral	Neutral
LazyNav	Sacrificed	Sacrificed	Neutral	Neutral	Neutral	Sacrificed
Arm Swinging	Optional	Neutral	Sacrificed	Sacrificed	Neutral	Neutral
Walking-In-Place	Optional	Neutral	Neutral	Neutral	Sacrificed	Sacrificed
Teleporting (Hand Gestures)	Natural	Neutral	Sacrificed	Sacrificed	Neutral	Neutral
Human Joystick	Neutral	Neutral	Sacrificed	Sacrificed	Neutral	Neutral
Body leaning (Stand position)	Neutral	Sacrificed	Neutral	Neutral	Sacrificed	Sacrificed
MuvMan	Neutral	Sacrificed	Neutral	Neutral	Sacrificed	Sacrificed
Shake your head	Sacrificed	Neutral	Neutral	Neutral	Neutral	Neutral
NaviChair	Neutral	Sacrificed	Neutral	Neutral	Sacrificed	Sacrificed
Swivel Chair	Neutral	Constrained	Neutral	Sacrificed	Sacrificed	Sacrificed
Redirected Walking	Natural	Neutral	Neutral	Neutral	Neutral	Neutral
Intuitive striding unit	Constrained	Sacrificed	Neutral	Neutral	Sacrificed	Sacrificed
Body leaning + Joystick	Neutral	Constrained	Sacrificed	Sacrificed	Neutral	Neutral
Virtusphere	Natural	Neutral	Neutral	Neutral	Neutral	Neutral
VibroSkate	Neutral	Constrained	Neutral	Neutral	Constrained	Constrained
Stepper machine	Natural	Neutral	Neutral	Neutral	Sacrificed	Sacrificed
Omnidirectional treadmill	Natural	Natural	Neutral	Neutral	Natural	Natural
Joystick	Neutral	Neutral	Sacrificed	Sacrificed	Neutral	Neutral
Teleporting (HMD Controllers)	Constrained	Neutral	Neutral	Neutral	Neutral	Neutral
Accelerator pedal	Neutral	Constrained	Neutral	Neutral	Sacrificed	Sacrificed
World-In-Miniature	Natural	Neutral	Neutral	Optional	Neutral	Neutral

6. Conclusion

In this paper, we presented a systematic literature review on locomotion techniques in virtual environments. Results showed that different approaches were used to find the most appropriate way to travel in the virtual environment. Over than fifty percent of the reviewed papers used the body-centred self-motion cues since there are strong arguments supporting its role to improve orientation and spatial judgments and reduce motion sickness (Bowman et al., 1998, 2004; Riecke et al., 2010). We proposed a taxonomy of locomotion techniques in virtual environments which provides to researchers a clearer vision of the way user can travel in virtual environments since it distinguishes and classify the locomotion technique according to their main features. Our taxonomy provides also guidelines that may help researchers for the choice of the locomotion technique that is adapted to the purpose of their experiment and associated use cases in the virtual environment. The review of the literature allowed us to find that, although the wide range of different locomotion techniques that has been proposed, classic non-natural methods such as joystick outperformed these techniques in most of the reviewed studies. Besides, each technique is characterized by different advantages and drawbacks. Thus, finding effective and intuitive locomotion technique which is easy to use, with a good control precision, maintaining the spatial orientation, ensuring a satisfying sense of presence with a minimum level of tiredness and not inducing motion sickness, still representing a significant challenge in the virtual reality field. An important detail that may help in the choice of the locomotion technique in accordance with the aim of the experiment is to distinguish which body parts will be engaged for locomotion. Indeed, for some cases, the used system can enter in conflict with researcher's centers of interest, especially for behavior observation through posture. Also, some population are not able to use every system, such as wheelchair users. Our proposed taxonomy helps to choose a tool adapted to the protocol.

In addition, while humans navigate with ease by walking in the real world, realistic simulation of natural locomotion is difficult to achieve in virtual environments (Nabiyouni et al., 2015). Omni-directional treadmills were designed and developed for this purpose and can be a potential solution. Besides the fact that this motion platform is stills expensive and difficult to maintain, it is also not well understood, because now, to the best of our knowledge, there are only two studies that focused on the omnidirectional treadmills. Moreover, this technique is closer to the real walk in terms of natural use of body parts. In our future work, we plan to explore this new locomotion interface by confirming its usability for exploring virtual environments and comparing it to common locomotion techniques in different virtual tasks. The objective is to break this technological limitation and find an effective and intuitive locomotion technique which is in line with the technological progress particularly with the display devices.

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