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Summary of Contemporary VR Locomotion Techniques and an Exploration of Possibilities for Future VR Locomotion Methods

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Abstract. The movement methods in VR are essential in deciding users' immersion, and it affects directly to the naturalness of interaction. Nowadays movement methods are divided into two major categories ('physical movement' and 'man-made movement'),'physical movement' chase for reality, while' man-made movement' relies on device input. Through the analysis of six dimensions: immersion, comfort, space requirements, usability, applicability, and cost, the study reveals a core paradox: physical mobility provides an excellent immersion, but the limitation of space, device and physical strength makes it difficult to afford. Man-made movement are more comfortable and convenient, but often comes at the cost of sacrificing immersion, and the more one pursues immersion, the more likely it is to cause cybersickness. At present, there's no any solution that could solve both problems, and the choice of movement methods are still based on specific application scenarios. Scientific research reveals that the movement methods in VR will tend to expand on the basis of 'physical movement', breaking through current difficulties through innovative hardware and algorithms, and bringing users a lower threshold and highly immersive virtual world "walking" experience.

Keywords: VR Locomotion, Immersion, Cybersickness, Human-Computer Interaction

1. Introduction

The technology of Virtual Reality works as a basis of leading to a digital world; it is reshaping human-robotic interaction at an unprecedented speed. Its core charm lies in deceiving human senses through devices, providing users with an immersive "sense of presence". Under the ultimate pursuit of immersion, users are no longer bystanders in the virtual world, and do not need to establish indirect interaction channels with the virtual world through traditional peripherals such as keyboards, mice, or controllers. They can actively explore, immerse themselves inside the virtual environment, just like an "insider". However, a basic but crucial issue always hinders humanity's pursuit of 'ultimate immersion', which is how to achieve infinite freedom of movement in the virtual world within a limited physical space [1].

This challenge is called 'VR movement' or 'VR Locomotion', and it is the most challenging part in current VR content design [2,3]. An effective movement ability is an essential key to the deep

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immersion; it affects users' comfort, engagement and whole experience. The root of the issue lies in a physiological response called "Cybersickness". When the user's visual system perceives that they are moving in the virtual world, while other senses of the body (such as the inner ear vestibular system) provide feedback that the body is in a stationary state, this sensory input conflict can send chaotic signals to the brain, leading to symptoms similar to carsickness such as dizziness, nausea, and headache [4-7]. Therefore, designing a mobile solution that can provide immersive freedom of movement while minimizing motion sickness has become one of the core issues in the development of VR technology. An adaptive interaction method can enable users to achieve a balance between comfort and immersion in specific application scenarios, while incorrect choices may lead to the failure of the entire application and work.

In order to solve this issue, both academia and industry have conducted extensive research and practice, and proposed various unique mobile solutions. Among them, the most intuitive one is Room Scale, which means that every step taken by the user in the real space corresponds exactly to a step in the virtual space [8,9]. This approach provides a high level of immersion and spatial cognition, but its application scope is strictly limited by the size of the physical space [9]. In order to overcome spatial limitations, the teleportation mechanism has been widely used, where users can instantly move to a specific location by specifying a target point. This method effectively avoids motion sickness caused by visual motion conflicts, but at the cost of sacrificing the coherence of movement, which may disrupt the user's immersion [3,9]. On the other hand, Joystick-based Locomotion allows users to move freely like in traditional video games, but it is one of the main causes of VR motion sickness [7]. More cutting-edge explorations focus on redirected walking technology, which cleverly guides users to follow curves in reality while perceiving them as straight lines in the virtual world by performing small rotations or scaling of virtual environments that are not easily perceived by users (such as using the "scan suppression" phenomenon during human eye scanning), thus creating larger virtual walking areas "out of thin air" in limited space [10,11]. In addition, there are various hardware or software solutions such as walking in place and VR treadmills, all of which are trying to find the best balance between comfort and immersion [12].

As people's demand in the VR world rises, finding a perfect movement is becoming a core topic among developers. This article aims to deeply analyze the mainstream VR mobile methods on the current market, analyze their advantages and limitations in different application scenarios, and based on this, extract the key elements required for an ideal VR mobile method in the future. Finally, it looks forward to and discusses the possible development directions in this field.

2. Scope and methodology

In order to systematically review the current movement methods in VR world, this article will classify all existing VR movement methods, and targeted from multiple dimensions perform in-depth analysis. These dimensions include: first, immersion degree, aim at evaluate picture movement whether smooth natural, avoid user produce "out play" feeling; second is comfort degree, core lies in examine movement method whether will cause user dizziness sense. In addition, analysis also will cover flexibility, consider its to physical space occupancy situation and device portability; easy start degree, judge user whether no need large amount learning can quickly master; low use cost, focus on complete device need price input; last is high adapt degree, measure this movement method whether can be developer more easy apply to different projects, and own how many can supply reference success cases.

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3. Case/literature summary: a comparison and case analysis of mainstream VR locomotion methods

This article divides the current mainstream VR movement methods into "physical movement pursuing realistic bodily sensation" and "artificial movement based on device input." This article will analyze each specific category under the two major types one by one and provide game examples for each category. Based on the standard of "scope and method of review," Table 1 shows the rating and starring of artificial movement based on device input, Table 2 shows the rating and starring of physical movement pursuing realistic bodily sensation.

Table 1. Rating and starring of artificial movement based on device input

Movement Method	Immersion Degree	Comfort Degree	Flexibility	Ease of Getting Started Degree	Low Usage Cost	High Adaptability Degree
Smooth Movement	★★★★	★★	★★★★★	★★★★	★★★★★	★★★★★
Teleportation	★	★★★★★	★★★★★	★★★	★★★★★	★★★★★

Table 2. Rating and starring of physical movement pursuing realistic bodily sensation

Movement Method	Immersion Degree	Comfort Degree	Flexibility	Ease of Getting Started Degree	Low Usage Cost	High Adaptability Degree
Physical Walking	★★★★★	★★★★★	★	★★★★★	★	★★★
Redirected Walking	★★★★	★★★★	★★	★★★★★	★★	★
Omnidirectional Treadmill	★★★★★	★★★★★	★	★★★	★	★★
In-Place Walking	★	★	★★★★★	★★★★★	★★★★★	★
In-Place Arm Swinging	★★★★★	★★★	★★★★★	★★★★★	★★★★★	★★
Scene Dragging	★★★★★	★★★	★★★★★	★★★★★	★★★★★	★★

3.1. Physical movement pursuing realistic bodily sensation

The core concept of this type of movement method lies in replicating to the greatest extent human movement behavior in the real world. Users need to perform the only one in the virtual world through real bodily actions. The ultimate goal of this type of movement method is to create the most extreme immersion experience.

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3.1.1. Physical walking

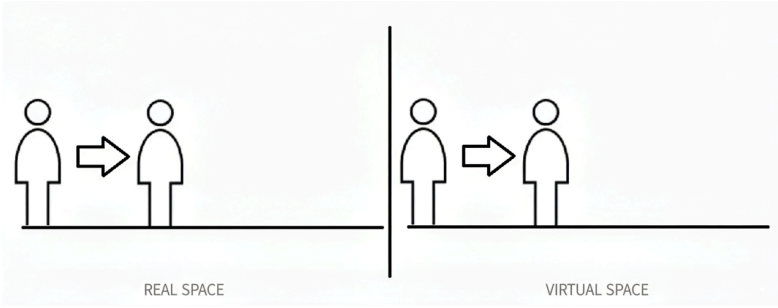

Figure 1. Schematic diagram of physical walking

Works using physical walking have "Half-Life: Alyx" inside free walking mode, various malls inside VR experience games. As Figure 1 shown, displayed physical walking schematic diagram. Physical walking is theoretically immersion sense most strong, comfort degree highest movement way. It through positioning system real-time capture player in specified physical space inside position, realize virtual role with real body 1:1 synchronous movement. This movement way perfect avoid visual motion conflict, user almost not produce dizziness. But this way have two fatal defects, first is it need one enough spacious space, this mean its flexibility and use cost will very high, second is no matter real space prepare have how large, virtual space is can do theoretically infinite large, therefore still have possible appear hit wall situation, and in application development process inside, often need target one specific physical space size perform design, but actual user in use process inside room size often is uncertain, this just mean use this way application and game only can targeted perform development, for example say in mall some specific position, have specific venue size, develop application target this specific size perform adapt.

3.1.2. Redirected walking

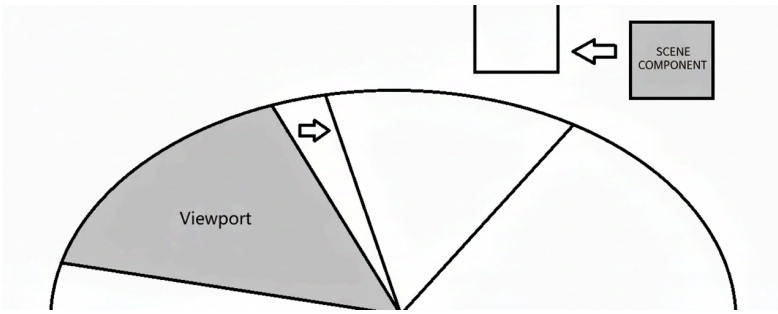

Figure 2. Schematic diagram of redirected walking

Works using redirected walking have academic research projects and specific games like "Reddie and the Redirected Walker". As Figure 2 shown, displayed redirected walking schematic diagram. Redirected walking essentially is physical walking one kind extension, redirected walking try through algorithm deceive player sense organ, it utilize human to tiny rotation not sensitive characteristic, in player not notice between to scene perform tiny rotation, thereby guide player in limited physical space inside strive for more virtual space, and as much as possible avoid hit wall. This movement way aim at "amplify" limited physical space, as physical walking extension, it retains high immersion sense, but frequent scene rotation easy appear motion sickness, therefore

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comfort degree will slightly low. Because to virtual scene redirect, this movement way demand physical scene can more small, but after research discover, this movement way more suit small scene virtual scene, because person only in narrow environment under to tiny rotation not sensitive, therefore universality low.

3.1.3. Omnidirectional treadmill

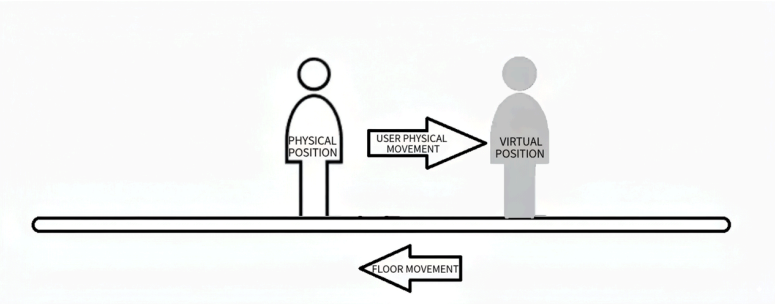

Figure 3. Schematic diagram of omnidirectional treadmill

Works using omnidirectional treadmill have KAT VR, Virtuix Omni etc. devices, can adapt "Half-Life: Alyx", "Blade & Sorcery" etc. games. Omnidirectional treadmill is one thoroughly solve space limit hardware solution, as Figure 3 shown, displayed omnidirectional treadmill schematic diagram, user in one special, can to any direction slide or roll platform or peripheral on walk, this hardware will make up player in virtual space inside attempt perform physical space movement, let player keep original place not move. Device through sensor capture footstep action and direction to perform virtual world movement. This is at same time retain immersion sense and comfort degree one best solution, this solution very good balance immersion degree and comfort degree, but current technology solution not mature, player on treadmill still easy appear stuck foot etc. affect operation situation, therefore easy start degree low, and device itself volume over large, flexibility low. Universality low is because current this set device price over expensive, not suit different mass purchase and use.

3.1.4. In-place walking

This is one lightweight body sense simulation solution, player through in-place stepping, in-place rotation to perform virtual space movement, sensor capture player action to realize to player perform virtual space movement. This solution to space almost no demand, and corresponding device cost almost also is lowest, and provide some body participation sense, but this participation sense with immersion sense completely no relation, at same time in-place stepping bring movement also very easy bring dizziness. Although this movement way need device is various VR head-mounted device equipped body sense track device, is all solutions inside cost lowest, but because this movement way apply scene over low, even current all not appear use this movement way application or game, therefore this movement way universality low.

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3.1.5. In-place arm swinging



Figure 4. Displayed arm swinging movement schematic diagram

Works using this movement way have "Gorilla Tag". In this game, arm swinging movement be cleverly design as conform "gorilla" theme climb and jump action. As Figure 4 shown displayed arm swinging movement schematic diagram, compare to need leg action perform movement, this is one only through arm swing just can perform movement, through simulate walking time both arms natural swing, or simulate some special animal perform movement. In specific application scene under, this movement way have extreme large advantage, at same time enough have creative. Compare in-place walking, arm swinging physical strength consume more small and use properly words can more immersion interesting. But its special nature decides it unable in realistic class scene use, in realistic class game inside will appear very abrupt, therefore its universality slightly low.

3.1.6. Scene dragging



Figure 5. Scene dragging movement schematic diagram

Scene dragging also is one only through arm movement just can perform movement way, as Figure 5 displayed scene dragging movement schematic diagram. With swinging different is this movement way need player through controller grab virtual environment inside ground or object, then drag to realize self movement. With swinging similar, this way to space demand also very small, but this way also not adapt most application scene, general in simulate zero gravity climb etc. very not walking environment under it can provide very high immersion sense, because this time movement logic with person physical intuition is conform. But in conventional scenario use will appear very laborious and anti-intuition, therefore this movement way universality low.

3.2. Artificial movement based on device input

This type of movement method abandons the simulation of real walking, instead relying on traditional game input devices such as controller buttons to perform movement. The main goal of the design is lower difficulty of getting started, simpler adaptation, but what is often sacrificed is the sense of immersion. At the same time, most movement methods based on device input will have motion sickness.

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3.2.1. Smooth movement

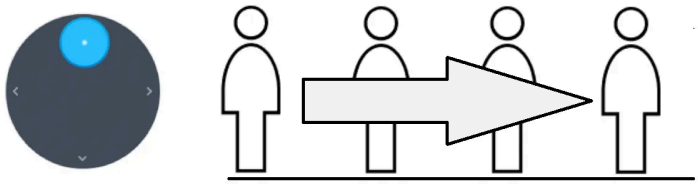

Figure 6. Smooth movement schematic diagram

Works using smooth movement have "Blade & Sorcery". As Figure 6 shown, take traditional first-person game operation way directly to VR inside is smooth movement, player through push handle joystick to control role perform smooth continuous movement. Smooth movement provide high and flexible operation freedom degree, and for play over host end game people say learning cost almost zero. But core problem lies in player itself no movement, while VR again than host end more body near its border, therefore easier appear motion sickness. At same time in game choose this movement way always accompany one "why choose VR not host end" doubt, because host end controllable keys obvious more, and more not easy trigger motion sickness, this movement way not can embody VR game characteristic.

3.2.2. Teleportation



Figure 7. Teleportation schematic diagram

Works using teleportation perform movement have "Half-Life: Alyx" as default comfort option. As Figure 7 shown, player through controller point to target location then instant move to target location. Teleportation is solving VR motion sickness most simple effective way, it completely eliminates visual continuous movement, therefore completely not bring visual and movement sense organ conflict, but price is completely no immersion sense, player will have one kind look PPT panoramic picture feeling, difficult form coherent space sense.

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4. Analysis and discussion

4.1. Conflicts between different movement methods

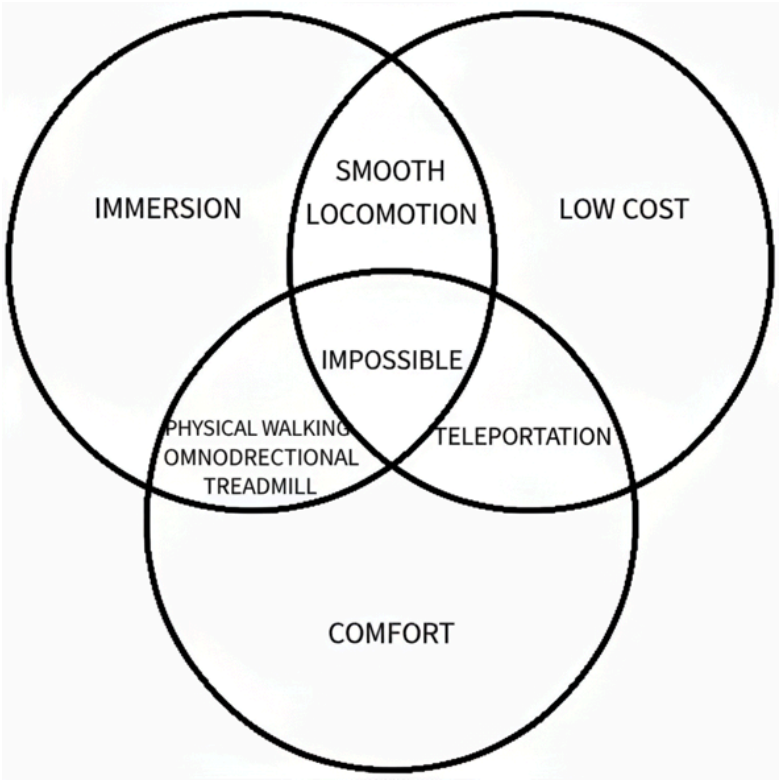

Figure 8. The impossible triangle of immersion, low cost, and comfort

After looking at the main ways people move around in virtual reality (VR), it turns out there isn't one method that is perfect for everything, as shown in figure 8. Here's the problem: you want your movement in VR to feel real and exciting (immersion), you want it to be cheap, and you want it to feel comfortable. But you can't get all three at the same time.

The biggest issue happens between how real it feels and how comfortable it is. A smooth VR experience actually might make people feel dizzy or sick, because what their eyes see in the VR doesn't match what their body feels in the real world. The only way to avoid this is to actually walk or run on special machines that track your movement, like VR treadmills – but those cost a lot of money.

Smooth movement and teleporting (where you jump from place to place in VR) are two examples where creators must choose what to focus on. Smooth movement looks and feels real but can make people uncomfortable. Teleporting stops people from feeling sick but doesn't feel very real.

Other ways to move, like waving your hands or pretending to walk in place, try to fix this issue by balancing all three things, but usually don't work that well. They might work in special situations, or they might not do any one thing really well. That's why doing just two things well and giving up on the third is usually a better solution for now.

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4.2. The selection of movement methods and design principles

At least for now, there is no one best solution for VR movement. So choosing a way to move depends on the situation. When making VR apps and games, you should think about the context and what fits best.

For fast-paced and intense games like battle games, smooth movement is necessary. Then you should consider your target players. If your players are people playing at home, use smooth movement controlled by game controllers. But if your players are in large places like malls or special venues, you can use better experiences like omnidirectional treadmills or real walking.

For games with strong storylines or themes, first check if you can use any “unique” movement methods that cover all needs, like waving your hands to move or dragging the scene. If no special movement works, smooth movement is still a good choice, since story games need higher immersion.

For social games like 《VRChat》, players wear VR headsets for a long time, so it’s best to use teleporting, which keeps players comfortable the most.

5. Conclusion

Target current all movement methods research, this article present realize VR virtual world movement methods inside impossible triangle, all movement methods all only can balance "immersion sense", "low cost", "comfort degree" three dimensions inside two, but in some specific particular scenes under, some special movement methods can clever at same time balance this three dimensions. At least in current, in own VR application or game inside choose movement method still need consider context, according use scene choose suitable movement method.

This article think future VR virtual world movement methods certain is in retain immersion sense basis on perform develop, in retain smooth movement basis on, retain physical world real body sense basis on perform attempt, omnidirectional treadmill is this article think most close perfect VR movement method solution. In future developers should consider is how let player can better "in-place movement", lower corresponding body sense hardware use cost, so then can in retain immersion sense basis on at same time balance low cost and high comfort degree.

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