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From Teleportation to Climbing: A Review of Locomotion Techniques in the Most Used Commercial Virtual Reality Applications

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ABSTRACT

Exploration of virtual reality locomotion has a rich history, including in the creation of taxonomies categorising individual techniques. However, most existing research collects data from academic sources only, with both historic industry practitioner exploration and a state-of-the-art understanding of locomotion in commercial applications comparatively underexplored. This systematic software-level review of the complete locomotion options in 330 of the most used virtual reality applications released between 2016 and 2023 on the Steam, Meta, Oculus, Viveport, and SideQuest platforms highlights the trends and gaps that exist between industry and academic exploration. Results suggest a decline in the usage of teleportation, with the prevalence of titles containing at least one teleportation technique decreasing from 48% of those released in 2016 to 18% in 2023. Arm-tracked grabbing locomotion techniques such as climbing meanwhile are being increasingly adopted by practitioners, from almost unused in 3% of applications released in 2016 to over 30% in each year between 2020 and 2023. Additionally, although the tracking capabilities afforded by consumer-level head-mounted display hardware has resulted in a high exploration of room-scale tracking, the large academic focus on walking-based locomotion appears to not be shared by practitioners, where room-scale tracking instead is most often paired with conventional controller joystick sliding locomotion. Finally, temporal analysis results showing the growing number of locomotion techniques offered in an average application signifies the need for further accessibility-related locomotion research, particularly in areas beyond visual sickness mitigation. Our findings highlight the continuing evolution of locomotion in commercial virtual reality applications, with industry practitioner locomotion technique adoption rates displaying the divergent interests between industry and academia, in turn adding rigour to future locomotion selections across both domains.

KEYWORDS

VR; extended reality; immersive technologies; metaverse; input modalities; travel; navigation; haptic; games; accessibility; virtual environment; survey; systematic software review

1. Introduction

The ability to travel to spatially distant locations, also known as locomotion, is an essential navigation task in the majority of computer-generated virtual environments (VEs), with various locomotion techniques allowing for different methods of controlling the viewpoint travel motion (Bowman et al., 1998). Locomotion is of particular importance in the three-dimensional VEs rendered in virtual reality (VR), with an extensive history of researching unique locomotion techniques, including magical locomotion beyond what is physically possible to achieve in real-world travel (Slater & Usoh, 1994). Differences in size between physical spaces, whether due to confined real room sizes or VR tracking range limitations, and the theoretically arbitrarily large VEs (Danyluk & Willett, 2019; Williams et al., 2007), necessitates the exploration of locomotion techniques beyond real walking tracking (Bruder et al., 2012).

Locomotion within VR is continuously evolving alongside technical advancements in VR hardware, with modern VR head mounted display (HMD) hardware equipped with 6 degrees of freedom (6DoF) tracking sensors leading to a surge in development of novel locomotion techniques since 2015 (Di Luca et al., 2021). The untethered connection and inside-out tracking sensors commonly found in consumer-level HMDs such as the Meta Quest series of devices have extended tracking ranges, whilst the increased fidelity in hand tracking capabilities, including capacitive touch sensors to sense finger positioning (Kudry & Cohen, 2022), has led to a growth in academic interest in novel hand tracked locomotion techniques (Huang et al., 2019). The lack of standardisation practices and industry-wide VR guidelines however has resulted in a fragmented landscape lacking clear conclusions on best practices (Heilemann et al., 2021; Zhao et al., 2019), with the continual introduction of novel locomotion implementations necessitating interaction adaptation from users.

Despite the growth in academic exploration of VR locomotion, it remains unclear as to how explored both established and novel locomotion techniques are by industry practitioners. Understanding industry adoption is crucial in

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order to align academic research with industry practice, in turn enhancing the practical relevance of future academic locomotion research. The current research-practice gap (Norman, 2010) in the empirical understanding of locomotion exploration amongst industry practitioners has resulted in locomotion research projects making assumptions about the adoption rates of techniques in commercial applications with little or no empirical evidence, such as the inclusion of teleportation based upon the assumed widespread usage of the technique in commercial VR applications (Funk et al., 2019; Langbehn et al., 2018; Sayyad et al., 2020), including the unsupported claims that teleportation is the de-facto standard in industry (Matviienko et al., 2022; Müller et al., 2023). This review therefore aims to address this gap by empirically assessing the software-level exploration levels of all locomotion techniques amongst industry practitioners, with systematic review inclusion criteria based upon application usage metrics to ensure that commercially available and largely used VR applications are included in the data set. These findings provide researchers with a stronger understanding of real-world technique implementation, contributing to a representative overview of VR practices, in turn strengthening justifications for locomotion technique selection based upon empirical evidence, an action so far often ignored in comparative academic research studies (Boletsis & Cedergren, 2019). Additionally, the transfer of academic knowledge to industry practices has proven historically significant in driving the adoption of VR, in particular in the implementation of sickness research findings to address a significant cause of the decline of the VR industry in the early 1990s (Wohlgenannt et al., 2020). This review will therefore provide a vital source of continued academic engagement with the growing VR industry, with the results revealing both potential market gaps and future research directions, in turn uncovering novel locomotion usability and accessibility insights.

1.1. Accessibility

As seen with the mainstream failure of VR consumer-level hardware in the 1990s due in part to the negative simulator sickness impact (Wohlgenannt et al., 2020), a key component in VR acceptance is in the creation of accessible experiences. Techniques to mitigate simulator sickness, including discrete locomotion techniques such as teleportation (Habgood et al., 2018), snap turn rotation (Sargunam & Ragan, 2018), and reducing the field of view (FoV) during continuous travel (Teixeira & Palmisano, 2021), have to date received the largest amount of academic accessibility research focus due primarily to being the first order barrier to VR adoption (Hamilton, 2018). The transfer of this academic knowledge to industry practices has proven historically significant in driving the adoption of consumer-level HMDs, with this review categorising the extent to which best practice design guidelines for sickness mitigation (Porcino et al., 2017; 2022) have been implemented by industry practitioners.

Beyond simulator sickness, the primary reliance on HMD stereoscopic visual and binaural sound feedback could potentially make VR locomotion inaccessible to sensory impaired individuals (Hamilton, 2018). This review further addresses locomotion accessibility by additionally exploring how locomotion is conveyed beyond visual viewpoint travel motion, with results categorising how locomotion haptic cues have been implemented in commercial VR applications. The majority of applications designed for consumer-level HMDs require input from bimanual handheld controllers, which in turn provide tactile haptic responses in the form of vibrotactile feedback. This may prove vital in the effort to make VR more accessible, particularly for blind and visually impaired (BVI) audiences, as haptic information is a key resource for supporting the spatial performance of BVI individuals (Lahav & Mioduser, 2008). This review therefore both categorises how locomotion haptic feedback is currently implemented, as well as acting as a call to action for further accessibility focused VR locomotion research.

1.2. Contributions

The main contributions of this review are:

1. The first systematic review of locomotion techniques in commercial VR applications, with technique adoption rates identifying industry practitioner exploration.
2. Identification of the most common haptic cues associated with locomotion in commercial applications, highlighting the gap in the exploration of potentially accessible locomotion haptic cues.
3. An empirical comparison of locomotion exploration between academia and industry, identifying academic researcher and industry practitioner interest overlaps and potential gaps.

2. Related work

This section begins with a discussion on existing locomotion technique reviews, followed by an introduction to locomotion taxonomies grouping these techniques. The importance of VR accessibility will then be addressed, before an exploration of how haptic cues have made VR locomotion more accessible.

2.1. Locomotion techniques

As found by Martinez et al. (2022), systematic reviews of locomotion techniques have historically remained underexplored in comparison to the creation of locomotion taxonomies, with their systematic review being the only one that has empirically categorised academic locomotion technique exploration. The majority of locomotion research, beyond taxonomy creation, either compares novel implementations of techniques against existing techniques within the same category, such as alternative teleportation aiming methods (Bozgeyikli et al., 2016; Funk et al., 2019; Matviienko et al., 2022), or the performance and/or preferences amongst a handful of techniques across categories when used for specific tasks (Buttussi & Chittaro, 2021; Franz et al., 2023; Suma et al., 2010).

Existing locomotion technique systematic reviews primarily focus on academic sources (Di Luca et al., 2021), with commercial techniques rarely subject to rigorous empirical review (Habgood et al., 2017). The techniques categorised in the Locomotion Vault database aim to address this academic and practitioner gap by extending the search criteria to both academia and industry (Di Luca et al., 2021), with the focus on classifying novel techniques made possible by the tracking capabilities of sensor-based consumer-level HMD hardware additionally ensuring timely technique categorisation. Analysis of temporal trends categorised solely upon technique novelty however has the potential to obscure established, but less innovative, locomotion categories. This could be particularly problematic in accessibility-related research focused on non-novel locomotion techniques, such as the user experience assessment of six established techniques for upper-body motor impaired users from Franz et al. (2023), with inclusion criteria based upon novel categorisation schemes potentially resulting in the accessibility of less innovative, but commercially highly offered techniques, remaining under-evaluated.

There has been a lack of locomotion technique reviews collecting data from commercial applications to date, although Habgood et al. (2017) reviewed the locomotion of games released in the first three months of the PlayStation VR lifecycle following the October 2016 release. Results include a surprisingly high interest in flying and almost no teleportation locomotion examples, however the short timeframe, small number of titles, and focus on a singular console hardware device limits the applicability of the results to the wider VR market. Reviews analysing locomotion techniques in commercial PC or standalone VR applications are rare, with an exploration of an Oculus Rift application from Tan et al. (2015) being one of the only examples that partially investigates locomotion, highlighting the adverse effect on gaming experiences of excessive head movements. The use of the "Half-Life 2" game (Valve, 2023b) however may have impacted findings, with the application not built for or officially supported by VR hardware, and therefore containing techniques not designed with VR locomotion in mind. Building an understanding of VR-specific locomotion is vital to assess the effectiveness of the existing techniques adopted in industry, along with informing future research directions to address potential user experience, usability, and accessibility issues of techniques for a diverse audience.

2.2. Locomotion taxonomies

To understand the broad range of locomotion technique possibilities, there has been an extensive history in the creation of taxonomies to categorise the underlying design components shared between techniques (Al Zayer et al., 2020). Locomotion taxonomies have evolved over time to fill research gaps and cover novel locomotion trends, with distinct clusters of locomotion taxonomy styles evident throughout the history of VR locomotion research (Prinz et al., 2022). Early VR locomotion taxonomies include influential work presented by Hand (1997), categorising techniques in to egocentric and exocentric frames of reference, Mine (1995), categorising techniques based upon direction of motion and speed within the control element cluster, and the mundane or magical metaphor cluster taxonomy from Slater and Usoh (1994), all of which made up the core focus of research until 1998 (Prinz et al., 2022). Categorisation of locomotion techniques within the control element cluster, such as the work from Mine (1995) and Bowman et al. (1997), was the standard approach to VE locomotion research between 1998 and 2016 (Prinz et al., 2022), whilst the seminal taxonomy from Jerald (2015) categorising techniques within the metaphor cluster represents the standard metaphor-based categorisation approach since 2017 (Prinz et al., 2022).

Along with an increase in locomotion techniques since 2015 (Di Luca et al., 2021), the launch of sensor-based consumer-level HMD devices has also greatly increased the average number of taxonomies created per year (Prinz et al., 2021), with many of the more recent taxonomies specifically addressing the novel locomotion techniques made possible by sensor-based HMD tracking capabilities. Relative position locomotion made possible by the availability of highly accurate body and hand tracking in particular has seen an increase in the creation of novel body tracked techniques (Di Luca et al., 2021), with this paradigm reflected in the focus of newly created taxonomies, such as the taxonomy from Cherni et al. (2020) focusing extensively on body tracked leaning locomotion.

Although the number of locomotion taxonomies is large, the vast majority of existing locomotion taxonomies are based entirely upon systematic reviews of academic literature (Di Luca et al., 2021), with the understanding of how commercial VR applications present locomotion almost entirely ignored in the creation of taxonomies. This uncertain understanding of industry practitioner exploration could potentially result in unrepresentative and unsuitable taxonomies when applied to commercial application analysis, with taxonomies created from academic sources potentially overemphasising techniques within highly academically explored categories and under-representing the most used practitioner techniques.

2.3. Locomotion accessibility

Although VR-specific legal requirements for accessibility do not exist, broader information and communications technologies accessibility-related regulatory requirements, as defined by the protections of equal access to all human rights in Article 9 of the United Nations Convention for the Rights of Persons with Disabilities (United Nations, 2016), indirectly apply to all VR experiences. Evolving international legal frameworks for compliance, as presented by national laws such as the Americans with Disabilities Act (U.S. Department of Justice Civil Rights Division, 2024) and UK Equality Act 2010 (Government Equalities Office, 2015), must be adhered to when designing for VR. The recent VR accessibility lawsuit settlement legally binding the provision of captioning in the Viveport Infinity VR subscription platform (Eisenberg & Baum, LLP, 2023) underpins the legal importance of adherence, with practitioner guidelines updated to require captioning in all future software releases on the platform (Feingold, 2023) additionally emphasising the importance for industry practitioners in maintaining awareness of emerging legal and VR platform-specific accessibility requirements.

Challenges around locomotion in VR are a significant barrier to use, in particular for physical, cognitive, visual, and/or auditory impaired users (Creed et al., 2023a). Locomotion techniques relying solely on visual feedback, such as visual-only teleportation targeting, have proven particularly inaccessible for BVI individuals for example, with feedback suggesting the addition of accessible audio or haptic cues during locomotion may prove beneficial (Collins et al., 2023). Accessibility focused research has highlighted the importance of customisation to allow applications to be tailored to match individual needs (Creed et al., 2023b; Dudley et al., 2023; Franz et al., 2021; Yamagami et al., 2022), including for example the importance of remapping controls for more complex actions that might require simultaneous button inputs (Mott et al., 2020), or allowing for the alteration of inaccessible gestures for wheelchair users (Gerling et al., 2020). These findings are particularly relevant for the gesture-based VR locomotion techniques afforded by consumer-level HMD tracking capabilities (Boletsis, 2017), with different techniques requiring varying levels of motor ability to perform (Di Luca et al., 2021).

2.4. Haptics

Haptics have been shown in academic research to be important in VR to create a sense of presence, the subjective perception of being in the VE, with research showing that a lack of tactile representation of actions negatively impacts immersion (Kudry & Cohen, 2022). The vibrotactile feedback provided by HMD handheld controllers provide accessible, compact, and adaptable haptic interfaces without the need for extensive training to understand the vibrotactile cues (Wee et al., 2021), with the continued marketing position of HMD manufacturers such as Sony (Nishino, 2021), Valve (2019a), and Meta (2023a) on higher definition handheld controller haptic feedback highlighting the growing industry focus on haptics.

In addition to increasing immersion, haptic feedback can be vital in improving accessibility in VR, for example enhancing accuracy for wheelchair users (Pei et al., 2023) and increasing access to the technology for BVI individuals (Siu et al., 2020; Wee et al., 2021; Zhao et al., 2018). Handheld controller vibrotactile feedback cues designed for BVI gamers has demonstrated the promising results for hand-based haptic feedback in VR guidance tasks (Wedoff et al., 2019), with survey results from Andrade et al. (2019) further highlighting the strong desire amongst blind gamers for accessible mainstream VR experiences. Analysis suggests however that the current general lack of accessibility features in commercial VR, such as audio and/or haptic feedback to convey information about the environment, has resulted in a strong feeling of exclusion for BVI audiences (Guerreiro et al., 2023).

Prior haptic research has additionally shown that vibrotactile feedback can assist specifically with navigation tasks, for example improving spatial guidance (Weber et al., 2011) and successfully conveying spatial information in VR (Kreimeier et al., 2019), with vibrotactile haptic cues from off-the-shelf VR handheld controllers assisting with locomotion for BVI participants (Kreimeier & Götzelmann, 2019). The taxonomy of sounds in VR from Jain et al. (2021) however suggests that navigation associated haptic feedback may be underexplored in mainstream VR applications, with 0% of the 33 analysed applications containing movement haptic feedback. A wider understanding of the implementation of handheld controller vibrotactile haptic cues associated with locomotion however remains unclear.

3. Review method

A systematic software review broadly following Kitchenham's (2004) software engineering procedure was conducted to assess locomotion technique adoption amongst industry practitioners. Inclusion criteria were based upon commercial application usage metrics, established through Steam, Meta, Oculus, SideQuest, and Viveport platform ranking listings and application download reports. Usage metrics were selected in order to identify the locomotion techniques that are most likely to be experienced by users of consumer-level HMD devices, in turn providing a representative overview of mainstream VR practices. This section will begin by addressing the key research questions this review is exploring, followed by explanations of application inclusion criteria, platforms, inputs, and taxonomy choices.

3.1. Research questions

This data collection and subsequent systematic software review aims to explore the following key research questions to provide a clearer historical and state-of-the-art understanding of industry practitioner locomotion technique adoption:

- RQ_1: Which locomotion techniques are most and least explored by industry practitioners?
- RQ_2: How have industry practitioners utilised locomotion haptic cues?
- RQ_3: Where do academic and industry practitioner locomotion adoption rates align and diverge?

Results for RQ_1 categorise locomotion both at a broader analysis level, with similar techniques placed together amongst a group of top-level categories, as well as at a more in-depth analysis level, with every locomotion technique presented in each application categorised following a data-driven attribute analysis approach (Di Luca et al., 2021).

Haptic cues are vital both for increasing immersion (Kudry & Cohen, 2022), along with potentially increasing locomotion accessibility (Wee et al., 2021), with results for RQ_2 laying the foundation for further accessibility-related VR locomotion research by revealing current haptic usage and presenting potential gaps. Finally, although locomotion has been extensively explored in academia, the high-level abstraction metaphor-based findings for RQ_3 for the first time allows for direct comparisons between academic and practitioner adoption rates, adding scientific rigour to the inclusion choices in future locomotion work with empirically evidenced exploration results.

The use of the unsupervised machine learning k-means clustering algorithm (Hartigan & Wong, 1979) allows for mapping of industry practitioner exploration levels across locomotion categories and techniques, as well as direct comparisons to locomotion exploration rates in academia with reference to the results from the systematic academic locomotion review conducted by Martinez et al. (2022).

3.2. Application inclusion criteria

Representative overview inclusion criteria were specified to ensure the most used VR applications since 2016 were analysed, chosen due to the release of the first wave of sensor-based 6DoF tracking consumer-level HMDs in the Oculus Rift and HTC Vive systems (Cook et al., 2019), with a mixture of applications from each year until 2023 as seen in Table 1. Due to the usage inclusion criteria the number of applications analysed for each year are not identical, with more recent applications potentially underrepresented due to having less time to satisfy usage metrics. Additionally, due to the data collection period commencing in August 2023, applications released after the August 2023 cut-off date that may have met the usage inclusion criteria were excluded from the data set, such as the "Assassin's Creed Nexus VR" game from Ubisoft Entertainment (2023).

Five application platforms were selected for data collection, representing all major PC VR and standalone VR application platforms. This includes the two largest VR storefronts, with 100 applications from Steam (Valve, 2023d), chosen as it is the largest PC VR platform, and 100 applications from the Meta Store (Meta, 2023g), the largest standalone VR platform associated with the market leading Meta Quest series of HMDs. The remaining three platforms include fewer applications due to representing smaller entities in the VR space. Firstly, 50 applications from the Oculus Store (Meta, 2023c) were chosen due to the historical significance of the Oculus tethered PC VR HMD devices, such as the Oculus Rift, prior to the shift from Oculus/Meta to standalone HMDs in 2019. Sideloading is possible with the majority of consumer-level HMDs, with recent Google Ventures investment in the space (Siegler, 2022) showcasing wider industry interest in the practice, therefore warranting the inclusion of 50 applications from the largest independent sideloading and early access VR application platform SideQuest (2023). Finally, although representing only a small portion of the VR application market, and therefore with only 30 applications included, the largest VR application subscription service Viveport Infinity from the HTC Corporation (2023) was included to ensure complete coverage of all the ways PC VR and standalone VR applications can be accessed.

Table 1. Number of analysed applications per year.

Year	Number
2016	29
2017	39
2018	35
2019	50
2020	54
2021	50
2022	51
2023	22
Total	330

In total, of the 330 applications analysed, 261 were games, 42 were general applications, and 27 were media-related, with the large representation of games reflecting the prominent gaming focused marketing for the current generation of consumer-level HMDs (Meta, 2023h). General applications included education resources such as a virtual museum (MOR Museum Inc., 2023), design tools focusing on for example three-dimensional painting (Google, 2016), utility applications such as PC desktop mirroring (Bigscreen Inc, 2021), fitness applications (FitXR, 2023), and social applications (McVeigh-Schultz et al., 2018). Finally, media included three-dimensional films (ARTE, 2016) and VR media players (Meta, 2023c).

To fully understand the state-of-the-art and ensure a representative mainstream overview of commercial VR practices, usage was the primary inclusion criteria. Only early access or fully released applications were included, with demos and prototypes excluded, such as the narrowly focused prototypes often created for controlled academic research. VR-only titles were selected, with post-launch VR compatible applications, such as the highly owned "No Man's Sky" game (Hello Games, 2023), excluded from the data set. This is in line with previous VR application analysis (Foxman et al., 2020; Zhao et al., 2019), allowing for comparisons between locomotion design decisions made specifically for sensor-based consumer-level HMDs rather than potentially analysing locomotion techniques designed primarily for non-VR devices. For analysis of locomotion techniques requiring the use of additional hardware, such as treadmills or smart bicycles, the associated locomotion technique was only noted when explicitly adjustable at a software-level, for example with in-application configuration options for the specific hardware. Devices that work at a system level across multiple applications, such as treadmill input replacing controller joystick bindings, were not counted as compatible with each individual joystick-based application.

There are no common evaluation methods for quality assessments with VR applications, with quality thresholds applicable to traditional academic systematic review procedures (Kitchenham, 2004) not suitable for commercial applications. Similarly to Prinz et al. (2022), where locomotion taxonomy quality assessment procedures did not exist, quality criteria were not enforced during the VR application assessment phase beyond assumed quality based upon usage metrics.

For Steam, multiple methods were used to ensure all of the most accessed VR-only applications were included. Selections were made amongst the current “VR Only” global top sellers from the platform itself (Valve, 2023e) in August 2023, from the list of titles tagged “VR only” with over 100,000 owners documented on the Steamspy website (Galyonkin, 2023c), all of the top 50 most user reviewed VR titles of all time on the Steam platform (VR.Space, 2022), and the current most accessed “VR Only” titles by live user count at the time of data collection in August 2023 (VRLFG.net, 2023). Of the 100 applications selected from Steam, 30 were free and 70 were one-time fee paid titles. For the 100 Meta applications, the combined 50 “Most popular” free experiences in the games, applications, and entertainment categories on the Meta Store (Meta, 2023a) were selected provided they were not originally found in the Steam search. Similarly, the combined 50 top selling paid experiences were selected from the games, applications, and entertainment categories (Meta, 2023b). A comparable method was used with the Oculus Store selections, although for this platform all category types were included in a single list, with 25 of the “Most popular” free PC VR experiences (Meta, 2023d) and 25 of the top selling PC VR paid experiences (Meta, 2023e) selected. For SideQuest, selections were made from the “All apps” category sorted by “Top”, with a mixture of sideloaded and Meta App Lab early access applications chosen to cover both sideloading installation methods (SideQuest, 2023). Finally, for Viveport Infinity, all titles provided in the “Infinity” subscription service (HTC Corporation, 2023) were selected when the same application listed on the Steam platform had over 100 reviews.

3.3. Platforms

Steam and Viveport Infinity titles are available on PC VR headsets, with support for standalone HMDs via tethered USB or WiFi connection. Oculus Store applications meanwhile are available to the Oculus Rift PC VR product line, with tethered standalone access official support for the Oculus/Meta Quest HMD devices. Finally, the SideQuest and Meta platforms support the standalone Quest headsets only. For Steam, Meta, and Oculus platforms all listed applications are available to download directly from the storefront either for free or following a one-time purchase. Meanwhile, all applications included in this data set from Viveport Infinity are available for PC download for Infinity subscription holders. The majority of listings (179) on the SideQuest platform contain a link to the associated Meta Store or App Lab storefront page, with the remaining 12 listings including APK and OBB file downloads for the associated application. Data were recorded on the available platform(s) for each application, with Table 2 displaying the number of applications listed on each platform. Results show widespread cross-listing of titles, with 213 (64.5%) of applications available across multiple platforms.

Table 2. Total number and percentage of applications from the data set available on each platform, with the number and percentage of exclusive applications.

Platform	Total	Exclusive
Meta Store	219 (66.4%)	54 (16.4%)
Oculus Store	175 (53%)	18 (5.5%)
SideQuest	191 (57.9%)	4 (1.2%)
Steam	240 (72.7%)	41 (12.4%)
Viveport Infinity	119 (36.1%)	0 (0%)

If a cross-listed application met the inclusion criteria but had already been selected from a prior platform search, the succeeding listed application was selected. Specifically, the next top selling or most popular application on the Meta (2023a, 2023b) and Oculus Stores (Meta, 2023d, 2023e), the subsequent top listed application on the SideQuest platform (SideQuest, 2023), and the next Viveport Infinity application with over 100 Steam reviews available on the subscription service (HTC Corporation, 2023). All 330 titles in the data set are unique, with no repeated cross-listed application selected after the initial platform selection.

3.4. Input criteria

The primary and optional supported inputs for controlling locomotion were recorded, with hardware inputs including bimanual handheld controllers, gamepads, computer keyboards, and any additional devices that are supported at a software-level, such as 3D Rudder foot control hardware (Di Luca et al., 2021). Additionally, low-friction input modalities allowing for locomotion control without additional hardware requirements were recorded, consisting of head-based, freehand, and speech-based input (Spittle et al., 2022). Primary inputs were noted where locomotion within the application is controllable via the input on first time usage without the need for selection or configuration, whilst optional inputs were noted where explicit selection or configuration options were included at a software-level, most commonly within application menus.

3.5. Taxonomy selection

Locomotion techniques were categorised following two separate locomotion taxonomies best suited for the specific research questions to be explored. The Locomotion Vault (Di Luca et al., 2021) was selected to explore RQ_1 and RQ_2, whilst the locomotion survey of existing taxonomies presented by Al Zayer et al. (2020), with techniques organised following the taxonomy categorisation first introduced by Bowman et al. (2004) and later updated by LaViola Jr et al. (2017), was used to explore RQ_3.

The Locomotion Vault online database was chosen for the comprehensive review of categories, techniques, and haptic cues due to both the multifaceted unifying scheme categorising attributes from existing taxonomies (Di Luca et al., 2021), along with the inclusion of a large number of specific and timely techniques. Earlier established locomotion taxonomies such as those from Slater and Usoh (1994), Mine (1995), and Bowman et al. (1997), whilst historically important in academic locomotion analyses, are often situated at a higher level of abstraction (Prinz et al., 2022) than the Locomotion Vault techniques, potentially obscuring key differences between similar techniques, for example the different arm movements required for climbing and swimming actions.

The use of a taxonomy at a higher-level of abstraction however is important to allow for direct comparison with academia, where the majority of examinations of VR locomotion are situated at a high abstraction level (Boletsis, 2017). The overview of existing taxonomies presented by Al Zayer et al. (2020), largely influenced by the metaphor-based taxonomy first introduced by Bowman et al. (2004), was therefore chosen for RQ_3 to allow for direct comparisons with existing systematic reviews of locomotion in academic literature. The specific high-level abstraction metaphor-based taxonomy derived from the work by Bowman et al. (2004) was selected due to having historically had the greatest impact in taxonomy research (Prinz et al., 2021), with the metaphor-based cluster of taxonomies furthermore being the most prominently used cluster in academia since 2017 (Prinz et al., 2022). The use of the comprehensive survey from Al Zayer et al. (2020) helps to address potential timeliness issues found in the original taxonomy from Bowman et al. (2004), with additions to the original taxonomy covering unaddressed novel techniques such as arm swinging (Calandra et al., 2019; Khundam & Nöel, 2021). Other proposed high-level abstraction academic taxonomies were not selected either due to focusing too specifically on set groups of locomotion techniques, such as walking (Nabiyouni & Bowman, 2016) and teleportation (Weißker et al., 2018), or due to being potentially unsuitable for the complexities of commercial applications, for example the issue with distinguishing between techniques that may integrate components from two or more proposed techniques in the influential taxonomy from Boletsis (2017).

3.6. Data extraction

Data were extracted non-automatically from all applications, with locomotion attributes assigned for each application based primarily upon first author testing. Subsequent web searches on official websites, application platforms, online wiki pages, review websites, and video sites allowed for full categorisation of techniques not immediately available during first-hand testing, such as techniques presented later in gaming applications only after extended progression. All locomotion techniques were noted, with primary and optional techniques separately labelled within the database. Similar to hardware input categorisation, primary locomotion techniques consist of the available techniques upon first-time application usage without the need for selection or configuration at a software-level, whilst optional techniques were noted where explicit selection or configuration is required within the application.

Categorisation of locomotion techniques were primarily based upon analysis of technique attributes in relation to the selected taxonomies. Labelling of application category and genre meanwhile were based primarily upon platform data, whilst release years reflect initial launch dates of applications across all available platforms. To further illustrate the data extraction process, Table 3 presents a sample of applications with their corresponding locomotion-specific attributes based upon the Locomotion Vault categorisation scheme (Di Luca et al., 2021). A selection of applications from each year of the data collection period is included, with titles from the game, general application, and media-related categories all demonstrated.

4. Results

The following results will explore locomotion usage by industry practitioners categorised in line with the Locomotion Vault database, showcasing overall industry adoption and historical trends. This will be followed by accessibility results as categorised by Di Luca et al. (2021), based upon motor impairment accessibility levels. The lack of locomotion classification work comprehensively assessing the accessibility of techniques beyond physical effort, posture, or overall motor ability levels (Di Luca et al., 2021) currently restricts in-depth understanding of locomotion accessibility in relation to cognitive and sensory impairments, limiting the applicability of these results for wider audiences. Following the accessibility results, haptic cues associated with locomotion will be presented. The current industry focus on handheld haptics in VR applications, as seen both in the continual introduction of high-definition handheld controller hardware (Heaney, 2022; Nishino, 2021; Valve, 2019a), as well as in the release of the Meta Haptics SDK for industry practitioners (Meta, 2023i), emphasises the importance of understanding how hardware input and haptic cues associated with locomotion are currently implemented in order to inform future research and design directions. Finally, academic trend results highlighting industry interest in the high-level abstraction metaphor-based locomotion techniques introduced by the seminal academic locomotion taxonomy from Bowman et al. (2004) will be presented.

4.1. Locomotion categories

4.1.1. Overall category exploration

Figure 1 presents the overall adoption of each Locomotion Vault based category, with the total number and percentage of applications containing at least one technique within each category displayed in the data labels and the k-means cluster highlighted on the vertical axis, with the silhouette coefficient and elbow point identified via the kneed Python package suggesting three clusters for the categories.

The combination, gesture, and treadmill categories (Di Luca et al., 2021) are within the least explored cluster, with each unexplored within the applications that meet the inclusion criteria. The combination category contains two very specific techniques applicable to single applications (Valve, 2023a; 2023c), whilst the gesture category contains three techniques based upon narrowly focused non-commercial prototypes (Guy et al., 2015; Huang et al., 2019;

Table 3. Sample data extraction from each year for the primary and optional locomotion vault attributes.

Application	Category	Primary	Optional
The Lab (2016)	Game (Action)	Teleport (Teleportation); Teleport Presets (Teleportation); Architectural Portals (Teleportation); Room-scale (Roomscale); TV Screen (Addon); Snap Turn (Addon); Haptic Feedback (Addon)	Dash Joystick (Controller)
L.A. Noire: The VR Case Files (2017)	Game (Adventure)	Arm Swinger (Movement): Fading – Cinematic Blink (Controller); Third Person Teleport (Teleportation); Vehicle VR (Vehicle); Room-scale (Roomscale); Snap Turn (Addon)	Sliding Joystick (Controller); Sliding Pointing (Controller)
In Death (2018)	Game (Action)	Teleport Throw (Teleportation); Room-scale (Roomscale); Snap Turn (Addon); Haptic Feedback (Addon)	Sliding Joystick (Controller); Sliding Pointing (Controller)
Mission: ISS: Quest (2019)	Media (Education)	EVA Thrusters (Vehicle); Grab + No Gravity (Grab); Room-scale (Roomscale); Snap Turn (Addon)	None
Meta Horizon Worlds (2020)	Application (Social)	Unconstrained Teleport (Teleportation); Teleport Presets (Teleportation); Room-scale (Roomscale); Tunneling (Addon); Snap Turn (Addon); Haptic Feedback (Addon)	Sliding Joystick (Controller); Sliding Pointing (Controller); Dash Pointing (Controller); Teleport Reorient (Teleportation)
SURV1V3 (2021)	Game (Shooter)	Sliding Joystick (Controller); Room-scale (Roomscale); Snap Turn (Addon)	Arm Swinger (Movement); Sliding Pointing (Controller); Fading – Cinematic Blink (Controller); Unconstrained Teleport (Teleportation); Teleport Reorient (Teleportation); Tunneling (Addon)
Arkio (2022)	Application (Design)	Focal Point VR (Grab); Dash Joystick (Controller); Room-scale (Roomscale); Tunneling (Addon); Snap Turn (Addon); Haptic Feedback (Addon)	None
Tea For God (2023)	Game (Adventure)	Redirected Walking (Roomscale); Passive Move (Vehicle); Haptic Feedback (Addon)	Sliding Joystick (Controller); Sliding Pointing (Controller); Tunneling (Addon); Snap Turn (Addon)

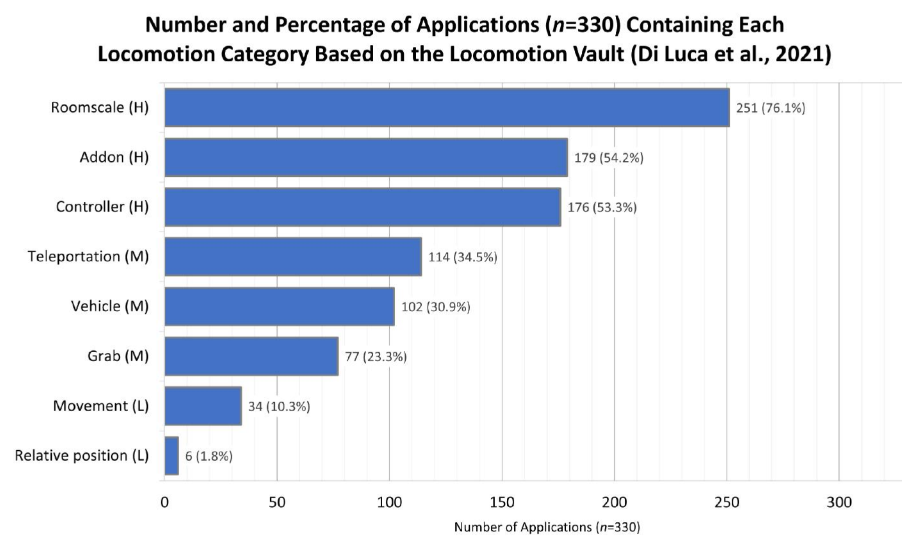

Figure 1. Number of applications exploring each Locomotion Vault based category (categories with zero instances excluded) with clusters of exploration level (highly (H), moderately (M), and least (L) explored).

Skarredghost, 2020). Although the treadmill category contains a mixture of techniques covering both academic prototypes as well as commercially available treadmill devices, such as the KAT VR (2023) omnidirectional treadmill, as no application contained hardware selection or configuration options this category was deemed not explicitly supported on an individual application level. Relative position (6) and movement (34) are both also within the least explored category cluster. The low relative position result does not correlate with recent wider exploration of the category, where the introduction of original relative position techniques has outpaced all other categories except for movement since 2015, whilst the sustained focus in exploring novel movement techniques above all other categories for almost 30 years (Di Luca et al., 2021) is similarly not reflected in practitioner adoption rates.

Grab has historically seen a constant decline in the number of newly explored techniques per year, consistently being the second least explored category in terms of novel locomotion introduction (Di Luca et al., 2021), with the availability of controller and hand tracking provided by the 6DoF tracking sensors of consumer-level HMDs not resulting in a sustained increased development of novel grab techniques. Despite this lack of innovation, industry practitioner interest in implementing the grab category is growing at a fast rate, resulting in an overall moderate industry adoption level with

77 total applications including grab locomotion. The teleportation (114) and vehicle (102) categories meanwhile have both seen a moderate increase in novel introduction in recent years (Di Luca et al., 2021), with a similar overall moderate adoption rate amongst industry practitioners.

Addon (179), controller (176), and roomscale (251) are the most explored categories by commercial practitioners. Techniques within the addon category are largely not associated with viewpoint motion control (Di Luca et al., 2021), with the majority of addon techniques used in combination with motion control methods from alternative categories, such as sliding joystick controller travel combined with the addon tunneling technique to reduce the FoV during motion (Fernandes & Feiner, 2016). Meanwhile, the two earliest established locomotion categories in VEs (Di Luca et al., 2021), the controller and roomscale categories, are also the two most adopted viewpoint motion control categories by industry practitioners. This reflects the overall trend that technical innovation is generally not reflected in industry practitioner adoption, where more established and less novel categories have generally received a larger practitioner implementation focus.

4.1.2. Category temporal analysis

The largest temporal trend in industry practitioner adoption of locomotion categories is in the increasing number of categories explored in applications since 2016. This can be seen in Figure 2, with a general yearly increase in the percentage of titles that contain either primary or optional locomotion exploration in a number of the categories. The number of applications with controller locomotion for example, although already the third most explored category in 2016 within 38% of applications, has seen a yearly increase in exploration in all but two years, with over 50% of applications containing controller locomotion each year since 2018. Grab locomotion meanwhile has seen a dramatic increase in exploration, from almost unused in 2016 within just 3% of applications, to over 30% of applications in each of the prior three years, with an increase in practitioner adoption every year. Except for dips in use in 2020 and 2023, movement has seen a similar, albeit less dramatic, yearly increase in adoption, from again 3% in 2016 to over 10% of applications in each of the prior three years.

Although the overall number of explored categories is generally increasing, adoption rates have not increased in every category. Relative position has remained almost unexplored throughout, whilst the roomscale and vehicle categories have remained largely flat. Teleportation meanwhile has seen a decrease in usage in all but one year, from the second most explored category amongst practitioners in 48% of applications released in 2016, to the sixth most explored category in 2022 and 2023, with fewer than 25% of applications including the teleportation category in these prior two years.

4.2. Locomotion techniques

4.2.1. Overall technique exploration

The k-means clustering silhouette coefficient and elbow point identified via the kneed Python package suggested six clusters for the 109 individual Locomotion Vault techniques

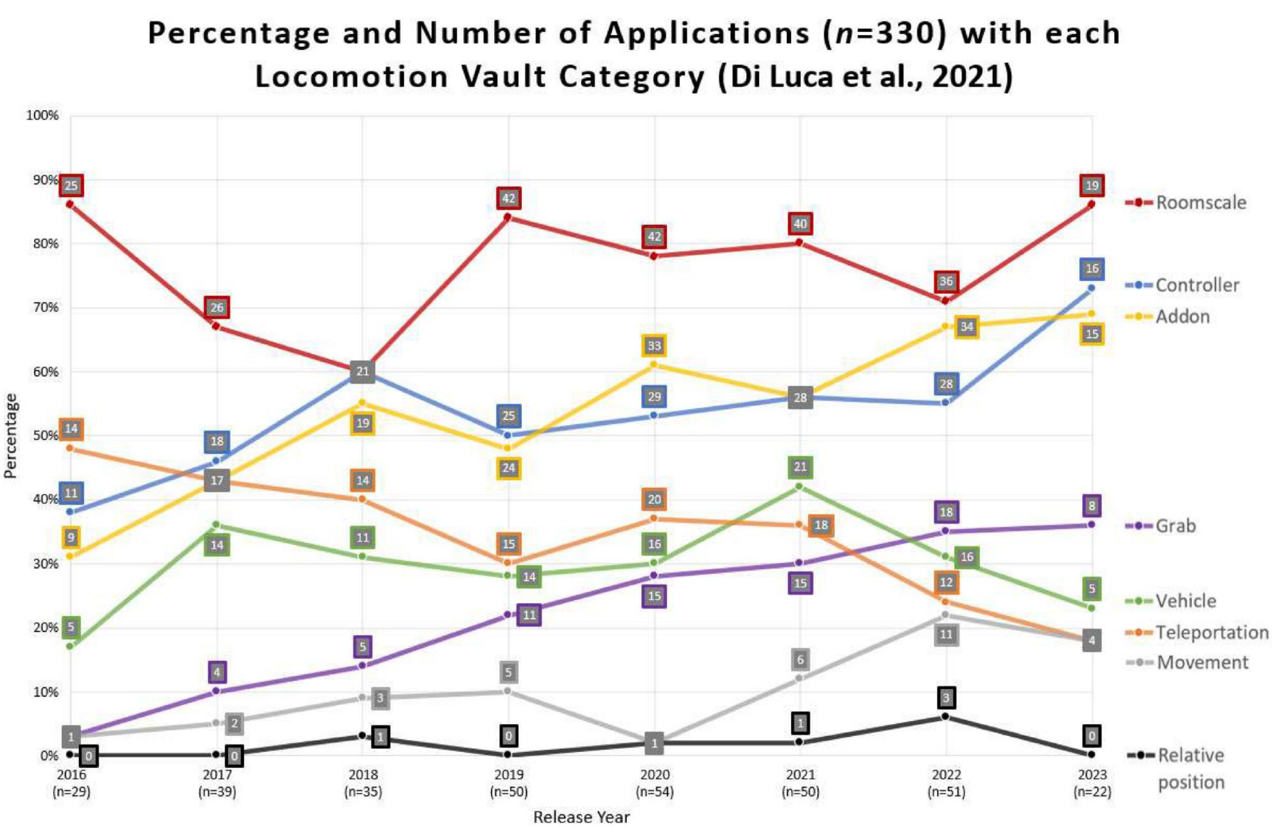

Figure 2. Percentage of applications released each year which explore each locomotion category. Actual number of applications released each year highlighted with the data labels.

Table 4. Exploration clusters of locomotion techniques, from very limited to extensive usage.

Cluster	Technique	Number	Percentage
Very limited	Hand Rockets	8	2.4
	Room-scale Vehicle	8	2.4
	Teleport Preview	10	3
	Dash Forward	11	3.3
	Flying Vehicle	11	3.3
	Hand Walking	11	3.3
	Swimming	11	3.3
	Dash Pointing	13	3.9
	Vehicle VR	13	3.9
	Grappling Hook	14	4.2
	Third Person	14	4.2
	Fading – Cinematic Blink	15	4.5
	Sliding Looking	16	4.8
	Flying	17	5.2
	Teleport	17	5.2
	Arm Swinger	20	6.1
	Dash Joystick	20	6.1
	Grab and Pull	20	6.1
	Teleport Reorient	21	6.4
	Local Area	23	7
Low	Passive Move	28	8.5
	Unconstrained Teleport	40	12.1
	Running on Rails	42	12.7
	Teleport Presets	43	13
	Climbing	46	13.9
Moderate	Sliding Pointing	72	21.8
	Tunneling	82	24.8
	Haptic Feedback	105	31.8
High	Sliding Joystick	130	39.4
	Snap Turn	166	50.3
Extensive	Room-scale	248	75.2

(Di Luca et al., 2021). Table 4 presents the five clusters containing techniques that are included in over 2.3% of the applications, with all 77 additional techniques appearing in the Locomotion Vault database (Di Luca et al., 2021) but not included in Table 4 being placed in the least used cluster. Techniques in this least used cluster include the historically extensively explored redirected walking (Nilsson et al., 2018) and walk in place (Slater et al., 1995) techniques, with redirected walking appearing in only two titles (Johansen, 2021; void room, 2019), whilst walk in place is completely unused commercially beyond the walk in place emulation of joystick locomotion afforded by the "Natural Locomotion" utility application (Valve, 2023c).

Unsurprisingly, due to the 6DoF inside-out spatial tracking afforded by sensor-based consumer-level VR HMDs, the room-scale technique (248) is in a category by itself as the most explored technique. Sliding joystick (130) and the snap turn (166) techniques meanwhile are both highly explored, with sliding joystick the most conventional input method closely matching the joystick locomotion in non-VR gaming applications. The moderately used cluster includes the sliding pointing (72) controller technique, again closely matching conventional non-VR gaming controller locomotion, with the addition of pointing for turning (Clifton & Palmisano, 2020) afforded by the spatially tracked handheld VR controllers. The two addon techniques included in the moderately explored cluster include haptic feedback associated with locomotion (105) and the comfort focused tunneling (82) technique, where the FoV is reduced during travel acceleration to limit sickness issues (Chang et al., 2020; Fernandes & Feiner, 2016; Lin et al., 2002). This moderate offering of tunneling and high exploration of viewpoint snap turn rotation techniques reflects the propagation of academic sickness mitigation guidelines to industry practice (Farmani & Teather, 2018; Sargunam & Ragan, 2018).

Although within the very limited use cluster due to the low overall exploration level, further analysis suggests a growing level of practitioner exploration in the grab category hand walking (11) technique (Another Axiom, LLC, 2022), with 11.8% of applications released throughout 2022 and 13.6% of applications released in 2023 containing this form of locomotion, suggesting inclusion of this technique may be required in future research to uncover technique specific usability and accessibility insights.

4.2.2. Technique temporal analysis

There has been a general increase in the number of techniques offered in an average application, as seen in Table 5. Apart from 2018 to 2019, the total number of locomotion techniques offered in an average application has stayed level (2021 to 2022) or increased year-on-year, from a total of 3.9 different locomotion techniques in an average application released in 2016, to a total of 5.95 techniques in an average application released in 2023.

Similarly to overall category trends as seen in Figure 1, the two most dramatic technique temporal differences are found in the grab and teleportation categories. The number of different grab techniques offered in an average application released in 2016 was virtually unused at 0.03, to an average of 0.59 and 0.77 grab techniques in 2022 and 2023 respectively, whilst the number of individual teleportation techniques has decreased from 1.17 in 2016 to below one in the previous five years, including 0.53 teleportation techniques in 2022 and 0.36 in 2023.

4.3. Accessibility

Results in Table 6 show the yearly average motor accessibility level, as defined by Di Luca et al. (2021), of the

Table 5. Number of locomotion techniques in an average application released in each year.

Category	2016	2017	2018	2019	2020	2021	2022	2023
Addon	0.9	1.13	1.54	1.62	1.8	1.66	2.08	2.18
Controller	0.69	0.79	1.09	0.82	1.11	1.18	1	1.36
Grab	0.03	0.13	0.17	0.22	0.28	0.4	0.59	0.77
Movement	0.03	0.05	0.11	0.1	0.02	0.16	0.24	0.18
Relative position	0	0	0.03	0	0.02	0.02	0.06	0
Roomscale	0.86	0.69	0.6	0.88	0.78	0.84	0.71	0.86
Teleportation	1.17	0.95	1	0.72	0.91	0.84	0.53	0.36
Vehicle	0.21	0.51	0.34	0.28	0.31	0.48	0.37	0.23
Primary	3.24	3.59	4.11	3.7	4.2	4.34	4.38	5.09
Optional	0.66	0.67	0.77	0.94	1.02	1.24	1.2	0.86
Total	3.9	4.26	4.88	4.64	5.22	5.58	5.58	5.95

Table 6. Motor accessibility level (Di Luca et al., 2021) of the primary, optional, and total techniques of an average application per year (from 1 least accessible to 3 most accessible).

Category	2016	2017	2018	2019	2020	2021	2022	2023
Primary	2.25	2.29	2.39	2.2	2.37	2.26	2.15	2.09
Optional	2.88	3	2.74	2.93	2.98	2.79	2.91	3
Total	2.37	2.41	2.45	2.35	2.49	2.38	2.29	2.22

locomotion techniques presented within all analysed applications, with findings showing that optional techniques are universally more motor accessible than primary techniques.

Further analysis highlights how optional techniques consist largely of the sickness mitigation tunneling (40 optional) and snap turn (35 optional) techniques, with these results revealing how where practitioners include alterations to locomotion, they appear to widely provide addon techniques which make the application more visually accessible in terms of sickness, rather than allowing for selection of viewpoint motion control techniques in alternative categories. Applications containing choices between motion control categories include 23 primary teleportation titles which allow for selection of one or more techniques within the controller category, as seen in "The Lab" (Valve, 2019b), the "Meta Horizon Worlds" (Meta, 2023f) social application, and the "In Death" (Solfar Studios, 2016) action game, all of which can be seen in Table 3. Meanwhile, a further 15 applications provide teleportation selection options for primarily controller-based locomotion titles, including "SURV13" (Candymakers, 2021) in Table 3. Whilst discrete locomotion techniques such as teleportation can mitigate simulator sickness (Habgood et al., 2018), the combined average motor accessibility level of all teleportation techniques in the included applications is 2.92, with controller category techniques virtually identical at 2.93, suggesting that providing alternatives between these two categories does not meaningfully impact motor accessibility levels.

Other alternative category choices can allow for alteration of technique from the least to most motor accessible level, however these selections are rarely provided. These limited options include three applications with primary arm swinger locomotion which provide accessible controller category alternatives, including "L.A. Noire: The VR Case Files" (Rockstar Games, 2024) in Table 3, two applications with alternative controller techniques for arm tracked grab category locomotion, and one application, "Tea For God" (void room, 2019) in Table 3, allowing for sliding controller locomotion choices in the place of roomscale redirected walking. These results demonstrate how only a handful of applications with the least motor accessible locomotion techniques provide alternative accessible optional locomotion choices.

4.4. Supported inputs

For hardware-based inputs, bimanual handheld controllers are the most supported device, with 326 applications supporting them as the primary input method, one providing optional support, and just three freehand only input titles not allowing for handheld controller input. Of the total 327 supported applications, 272 contain at least one locomotion technique supporting bimanual handheld controller input, whilst the remaining 55 contain no handheld controller locomotion input, such as applications with static viewpoints or roomscale only locomotion. Gamepad input meanwhile is included in 49 applications, of which 19 include primary gamepad input, with 39 of the total 49 supported titles containing gamepad input for at least one locomotion technique. Finally, 23 applications allow for some form of computer keyboard input, of which all but one are as an optional device, with 15 applications containing at least one locomotion technique supported by keyboard input. Figure 3 highlights the locomotion trends of these three main input hardware devices, with results showing a slight increase in the number of applications which contain at least one bimanual controller locomotion technique, minimal support for keyboard locomotion each year, and declining gamepad locomotion input support since 2018.

Other hardware-based input devices for locomotion control include two flight simulators with flight rudder pedal support, one fitness application with smart bicycle locomotion-control,

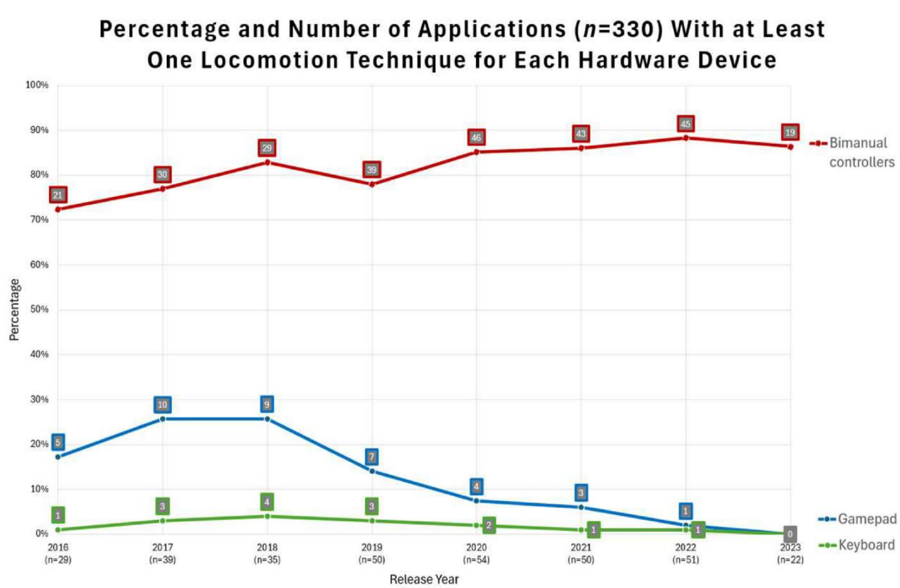

Figure 3. Percentage of applications released each year which contain bimanual controller, gamepad, and keyboard locomotion input techniques. The actual number of applications released each year is highlighted with the data labels.

and one action game with software-level optional 3D Rudder hardware configuration. In terms of non-hardware locomotion input support, freehand tracking is supported in 25 applications, with freehand locomotion provided in 11 of these titles. Head direction based input meanwhile is included in 19 applications, with 12 providing head based locomotion control. Finally, some form of software-level speech-based input appears in seven applications, although no application provides voice input locomotion support.

4.5. Haptic feedback

As seen earlier in Table 4, results show a total of 105 applications contain at least one haptic feedback cue associated with locomotion. Table 7 shows that the most used locomotion haptic feedback cue, with high interest as indicated by the k-means clustering algorithm, is environmental contact haptic cues (39) when the user controlled viewpoint or avatar makes contact with VE objects during locomotion, most commonly associated with wall collisions. This locomotion focused cue differs from environment-based haptics associated with hand gripping actions, such as picking up a virtual object from within the VE, which is explored in 195 applications, making it the most used haptic feedback in VR above and beyond any locomotion haptic cue.

Table 7. Number, percentage, and exploration cluster (high (H), moderate (M), low (L)) of locomotion haptic cue types.

Cue	Number	Percentage	Cluster
Automated motion	13	3.9	L
Environment contact	39	11.8	H
Footsteps	6	1.8	L
Hand walking	10	3	L
Teleportation	27	8.2	M
Vehicle	19	5.8	M

4.6. Academic trends

For direct academic comparison, techniques used by industry practitioners were placed within one of the walking-based, steering-based, selection-based, manipulation-based, or automated categories (Martinez et al., 2022). These five metaphor-based categories are further comprised of 29 individual techniques. Locomotion within the walking-based category relies upon body movements, with techniques including human walking gait cycle components (Nabiyouni & Bowman, 2016). Steering-based techniques meanwhile rely upon continuous control of travel direction, whilst selection-based techniques allow users to select a target destination or travel route (LaViola Jr et al., 2017), manipulation-based techniques allow for manual control of positioning, orientation, or scale within the VE using hand gestures, and automated locomotion includes fully or semi automated travel (Al Zayer et al., 2020).

Figure 4 presents the exploration levels of each of these high-level abstraction metaphor-based locomotion categories, with the k-means cluster, the total number of utilised techniques within each category, and percentage of overall techniques displayed in the data labels. Results show the walking-based (65) category is the least explored in commercial applications, with selection-based (161), manipulation-based (117), and automated (136) categories moderately adopted, whilst the steering-based (365) locomotion category is highly explored.

Table 8 summarises the extent to which each of the 29 high-level abstraction techniques across the five categories have been explored in commercial applications.

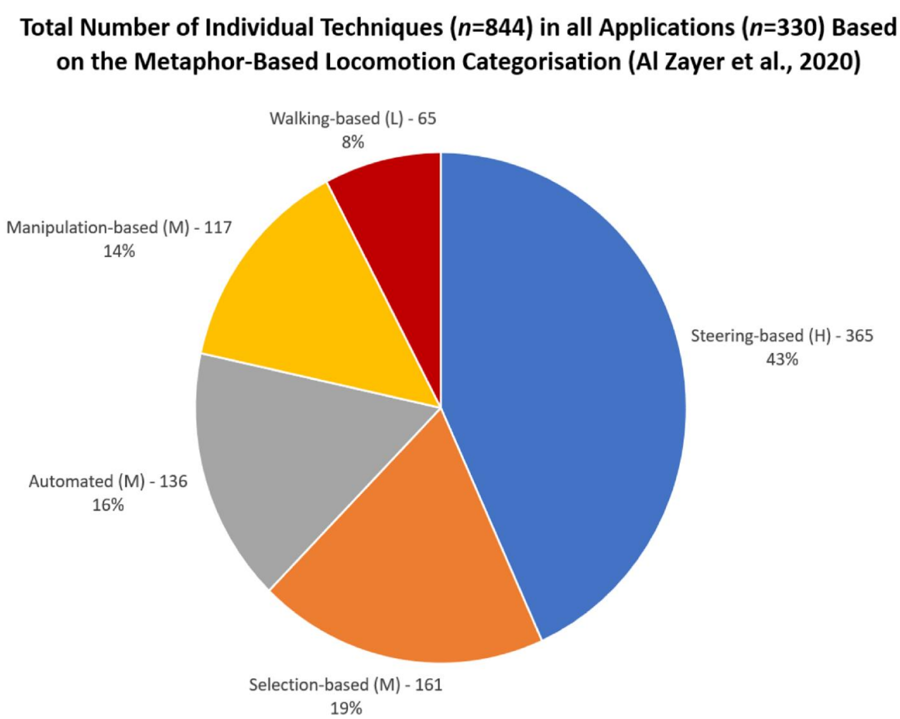

Figure 4. Number of explored techniques within each metaphor-based category of locomotion with clusters of exploration level (highly (H), moderately (M), and least (L) explored).

Table 8. All metaphor-based locomotion categories, techniques, total number of applications, percentage, and exploration cluster (highly (H), moderately (M), or least (L) explored).

Category	Technique	Number	Percentage	Cluster
Walking-based	Real Walking	19	5.8	L
	Redirected Walking	4	1.2	L
	Scaled Walking	3	0.9	L
	Walking-in-Place	0	0	L
	Arm Swinging	37	11.2	M
	Squatting	0	0	L
	Low-Friction Surface	0	0	L
	Unidirectional Treadmill	0	0	L
	Omnidirectional Treadmill	0	0	L
	Step-based Device	2	0.6	L
Steering-based	Head-directed Steering	133	40.3	H
	Hand-directed Steering	80	24.2	M
	Lean-directed Steering	4	1.2	L
	Other Spatial Steering	1	0.3	L
	Joystick-directed Steering	130	39.4	H
	Mouse-directed Steering	17	5.2	L
Selection-based	Point-and-Teleport	108	32.7	H
	Point-and-Walk	5	1.5	L
	Point-and-Motion	36	10.9	M
	Look-and-Motion	12	3.6	L
Manipulation-based	Manipulate-to-Steer	76	23	M
	Camera-in-Hand	0	0	L
	Scene-in-Hand	15	4.5	L
	World-in-Miniature	4	1.2	L
	Dragging	22	6.7	L
Automated	Automated Steering	52	15.8	M
	Semi-automated Steering	26	7.9	L
	Automated Teleport	15	4.5	L
	Semi-automated Teleport	43	13	M

Arm swinging (37) is moderately implemented in commercial applications, whilst all other walking-based techniques are less utilised. For steering-based techniques, results show a high level of interest in the spatial head (133) and non-spatial joystick-directed (130) steering methods, a moderate interest in spatial hand-directed (80) steering, and low interest in all other steering-based methods. The selection-based point-and-teleport (108) technique meanwhile is highly adopted, with the point-and-motion (36) technique moderately explored, and both the point-and-walk (5) and look-and-motion (12) selection-based techniques less explored. Finally, the manipulate-to-steer (76) technique is moderately utilised, with all other manipulation-based techniques less explored, whilst automated steering (52) and semi-automated teleport (43) techniques are moderately adopted in the automated category, with semi-automated steering (26) and automated teleport (15) both less explored.

5. Discussion

In this section, results are discussed in terms of overall locomotion trends to explore RQ_1, followed by analysis of accessible locomotion results, hardware input support, and haptic cues covering RQ_2, before finishing with the RQ_3 academic comparison discussion.

5.1. Locomotion trends

Review results indicate that the locomotion categories which have received the highest focus in novel exploration, such as the post-2015 resurgence in the relative position category (Di Luca et al., 2021), has not translated to widespread practitioner adoption. As seen in Figure 1, the most explored practitioner category cluster includes the roomscale (251) and controller (176) categories, which in turn contain the most explored and earliest invented (Di Luca et al., 2021) room-scale (248) and sliding joystick (130) techniques. This highlights how the novel techniques made possible by the 6DoF body tracking of sensor-based consumer-level HMDs, such as the movement category swimming (11) technique (Di Luca et al., 2021), has not resulted in widespread industry exploration, suggesting a potential gap in the market for industry practitioners to implement more novel techniques within the relative position (6) and movement (34) categories. Furthermore, although the extended tracking ranges afforded by HMD inside-out sensors has resulted in a large interest amongst industry practitioners in the room-scale (248) technique, this technique is currently most often combined with other locomotion techniques in the controller, teleportation, or grab categories (Di Luca et al., 2021). All historically extensively explored redirected walking roomscale techniques (Langbehn et al., 2017; Nilsson et al., 2018), such as the moving platforms technique (Di Luca et al., 2021) found solely within the “Eye of the Temple” application (Johansen, 2021), remain surprisingly underexplored by practitioners, suggesting another potential gap for industry practitioners within the redirected walking roomscale category.

Temporal analysis results challenges the often assumed (Funk et al., 2019; Langbehn et al., 2018; Sayyad et al., 2020) industry focus on the teleportation (114) category, with the continued decrease in the inclusion of teleportation techniques, as seen in Figure 2, suggesting claims that teleportation is the de-facto standard in industry (Matviienko et al., 2022; Müller et al., 2023) are no longer true. Temporal results, as seen in Table 5, furthermore suggest that the grab (77) category, historically amongst the least explored categories in terms of novel technique exploration (Di Luca et al., 2021), may require a renewed academic research focus in line with the growing industry adoption, in turn potentially uncovering locomotion usability insights of the more novel grab techniques such as hand walking (11). The motion tracked hand and arm movements required for grab techniques additionally requires accessibility-related research to ensure potentially difficult to perform bimanual grabbing motions are flexible and adaptable to varied needs (Yamagami et al., 2022).

These representative overview and real-world technique implementation results can inform future research agenda by highlighting locomotion categories and techniques that may require further academic research focus. Future research addressing these potential gaps in knowledge may uncover vital new insights about commercially widely adopted techniques, playing a vital role in the establishment of best practice guidelines that have the potential to further drive mainstream adoption of VR.

5.2. Accessibility

As seen in Table 4, the moderate exploration of the tunneling (82) and high exploration of the snap turning (166) techniques demonstrates the successful transfer of academic visual-based sickness mitigation knowledge to industry practices. Other academically explored techniques beyond visual adjustments for reducing sickness are less explored by practitioners however, including body movement techniques such as walk-in-place (Lee et al., 2017; Tan et al., 2022), with the corresponding locomotion technique (Di Luca et al., 2021) appearing completely unused commercially. Haptic stimulation cues which may reduce sickness, such as footstep (6) synchronized haptic cues (Peng et al., 2020), are also largely overlooked.

Practitioners providing modifications to locomotion largely offer visual tunneling (40 optional) and snap turn (35 optional) techniques rather than alternative viewpoint travel category selections, suggesting that industry practitioners are largely not adhering to recommendations suggesting disabled users should be given flexibility in tailoring locomotion to their abilities and preferences (Franz et al., 2023). More work must be done to encourage practitioners to include optional accessible viewpoint travel motion techniques, with the establishment of widely acknowledged guidelines and accessibility focused practitioner tools vital to spread awareness and support practitioners in implementing accessible locomotion alterations (Dudley et al., 2023; Heilemann et al., 2021).

The narrow categorisation within existing taxonomies on the accessibility of locomotion techniques from simulator sickness and motor ability levels (Di Luca et al., 2021) suggests that further research is needed to explore the accessibility of locomotion in VR from alternative perspectives. The reliance on stereoscopic visual and binaural sound feedback, with limited locomotion haptic cue exploration as seen in Table 7, in particular emphasises the need for research with sensory impaired individuals, an audience that is largely overlooked by both academia and industry (Piçarra et al., 2023). Along with the inclusion of participants with a wider range of abilities in novel technique research, further work is required to explore the accessibility barriers present in existing locomotion techniques, with the BVI social VR locomotion study from Collins et al. (2023) for example highlighting potential non-visual comprehension challenges when utilising snap turning. These potential accessibility trade-offs within commercially highly explored visual sickness mitigation techniques must be more fully explored, with a continued exploration of locomotion techniques from alternative disability perspectives in turn allowing for more nuanced accessibility categorisation in future locomotion taxonomies.

5.3. Input

Temporal hardware input results, as seen in Figure 3, showing both an increase in the number of applications supporting bimanual tracked controller locomotion and a decrease in non-spatially tracked hardware such as gamepads, together with the locomotion technique trend results showing a continual increase in arm tracked techniques such as climbing (46), suggest that advances in hardware tracking capabilities may be influencing practitioner exploration of spatially tracked locomotion. Further work however is required to analyse commercial VR at a headset hardware-level to understand this potential interplay between hardware development and locomotion exploration by industry practitioners beyond the software-level scope of this current review.

Overall results highlight the large input inflexibility in commercial VR, with data showing no software-level support of treadmill devices, along with little support for third-party locomotion hardware such as 3D Rudder foot motion controllers (1). Whilst gamepad (39) and keyboard (15) hardware devices are more widely supported for locomotion input, temporal results, as seen in Figure 3, suggest that applications are increasingly requiring virtual locomotion input from tracked bimanual controllers (272) only, suggesting that this hardware inflexibility may be increasing. Furthermore, few titles support low-friction non-hardware based locomotion, with results showing for example no applications containing potentially accessible landmark-based hands-free speech locomotion (Hombeck et al., 2023). This input inflexibility is concerning from an accessibility perspective, with combined hardware and low-friction input results further reinforcing locomotion technique accessibility results by highlighting how users are largely unable to tailor locomotion to their own abilities (Franz et al., 2023).

5.4. Haptic cues

A large difference exists between the number of applications which offer locomotion and interaction haptics, with no locomotion associated haptic cue, as seen in Table 7, contained in more than 12% of the total applications, whilst interaction haptic feedback such as hand gripping cues are included in 59% of applications. This suggests that haptics associated with locomotion may be largely underexplored by industry practitioners, with locomotion feedback haptic cues associated with continuous travel techniques, such as footsteps (6), in particular appearing underexplored when considering the potential benefits to spatial orientation performance these feedback cues may provide (Feng et al., 2016).

Although headset manufacturers such as Meta are primarily focused on how haptics designed by industry practitioners can increase immersion (Meta, 2023j), previous research showcasing the importance of haptic feedback in improving accessibility in VR (Wee et al., 2021), combined with BVI participant preference results for hand-based haptic feedback in VR guidance tasks (Wedoff et al., 2019), highlights the importance of continuing to explore how usable haptic feedback may be in assisting with VR locomotion.

5.5. Academic comparison

There are numerous individual locomotion techniques where practitioner and researcher exploration levels are misaligned, with the most dramatic overall contrast found in the high-level abstraction walking-based category. Whilst being the most researched academic category (Martinez et al., 2022), as seen in Figure 4, the walking-based category (65) is in a cluster by itself as the least explored by industry practitioners. Results furthermore show a large practitioner difference in the exploration of the historically extensively academically researched (Razzaque et al., 2002; Steinicke et al., 2008) redirected (4) and walking-in-place (0) techniques, suggesting a large gap in the market may exist for practitioners to implement best practice findings from this extensive history of walking-based research.

In terms of steering-based locomotion, there is an overall high interest in both industry (363) and academia (Martinez et al., 2022), with industry exploration, as seen in Figure 4, far higher than any other category. For individual techniques, academic research also correlates with industry practitioner exploration in the low interest in lean (4), other spatial steering (1), and mouse-directed steering (17) techniques, with a similar high adoption found within the joystick-directed steering (130) technique. Head-directed steering is moderately explored in academic research (Martinez et al., 2022) in contrast to the high commercial application (133) usage rate, whilst hand-directed steering is moderately implemented in commercial applications (80) but less explored in academic research (Martinez et al., 2022), suggesting that both head and hand-directed steering techniques may be slightly underexplored in academia.

For selection-based locomotion, there is an overall moderate interest in both academia and industry (161), whilst manipulation-based techniques are less explored in academia (Martinez et al., 2022) but moderately adopted by industry practitioners (117). Finally, the moderate industry exploration of automated techniques (136) differs from the low academic research focus, with all four of the automated techniques amongst the least explored in academia (Martinez et al., 2022). These results suggest that further research may be needed in the automated travel category, in particular to investigate the potential accessibility benefits for motor impaired users in the provision of automated steering (Dudley et al., 2023).

6. Limitations and future work

Although inclusion criteria were designed to include the most used VR applications, the precise usage levels of each individual application is not a factor in this analysis, therefore making it difficult to accurately analyse the total number of users potentially exposed to each technique. For example, the highly accessed social VR application “VRChat” (VRChat Inc., 2023) is estimated to have between 10–20 million Steam owners (Galyonkin, 2023b), whilst the action game “In Death” (Solfar Studios, 2016) is estimated to have between 100,000 and 200,000 owners (Galyonkin, 2023a). In this review however these differences in ownership statistics, which may help to more fully understand user locomotion engagement, were unaccounted for.

The inclusion criteria of VR-only titles, although chosen to allow for direct comparisons of locomotion techniques designed specifically for sensor-based VR inputs, may have omitted certain highly used applications that would more accurately represent industry practices. It appears for example that the prevalence of vehicle-based applications in industry was underrepresented due to the frequency of applications exploring vehicles being ported to VR post-launch, such as the highly accessed “Microsoft Flight Simulator” (Microsoft, 2023) and “Assetto Corsa” (Kunos Simulazioni Srl, 2023) vehicle-based simulators. In future VR-only and post-launch VR titles may be a valuable variable to explore, both to ensure a more representative inclusion of the most accessed VR applications, as well as to understand to what extent locomotion in post-launch titles may differ to locomotion presented in VR-only applications.

As software can be updated on all analysed VR platforms, separation of applications by release year may not always accurately reflect when specific locomotion techniques were introduced to an application, potentially negatively impacting the accuracy of the temporal analysis. For example, although “Rec Room” (2023) was released in 2016 with teleportation and short teleportation (Di Luca et al., 2021) locomotion options, controller sliding joystick and optional sliding looking techniques were patched into the application two years post-launch (Rec Room, 2018), whilst the action game “The Lab”, included as the 2016 release in Table 3, added dash joystick locomotion in 2019 (Valve, 2019b). Whilst accounting for the exact dates when updated locomotion techniques were added to each application would more accurately reflect the historical state of locomotion in each year, it would not as accurately reflect the dynamic nature of commercial VR software.

Due to the complexity of modern VR applications, certain locomotion techniques may have been missed during data collection. This may include for example techniques that first appear only in the later stages of lengthy games, which may not have been experienced during first author testing, and additionally may have been missed during subsequent web searches. Unclear and unfinished entries in the Locomotion Vault database (Di Luca et al., 2021) may have also led to miscategorisation, in particular for techniques with a large amount of similar or overlapping implementation design points.

As this review analysed temporal trends in hardware input support at a software-level, further analysis is required to examine the potential interplay between the development in headset hardware, such as tracking sensor capabilities, and the adoption of locomotion techniques, in turn potentially highlighting locomotion trends in relation to HMD hardware capabilities. This will allow for further understanding for example on the potential interplay between the increases in the adoption of spatially tracked locomotion techniques at an industry practitioner level mapped against hardware technology advances.

Since the current data collection is focused solely on commercial applications, with academic results based largely upon the existing data set from the systematic academic locomotion review conducted by Martinez et al. (2022), visualising the differences between practitioner and academic results is not currently possible. Additionally, the lack of detailed information in existing academic reviews about the range of purposes explored in academia may limit the direct comparability of these results. The large industry interest in games (261) for example may not be reflective of the prototype diversity found in academic research, in particular due to results suggesting that academic locomotion user studies are largely focused on the performance of a limited number of techniques for narrowly defined tasks (Buttussi & Chittaro, 2021; Franz et al., 2023; Suma et al., 2010). Results highlighting a growing increase in the number of techniques in an average application, as seen in Table 5, however suggest that exploring the effects of combining locomotion techniques may be an important future research direction in line with wider industry trends. This may be particularly relevant in accessibility focused locomotion research to understand the preferences of diverse audiences within the context of specific, and potentially complex, application categories. For example, the free exploration of a number of techniques in the BVI social VR application research from Collins et al. (2023) highlighted key differences between blind and low vision participant locomotion requirements in a dynamic social VE. Further research is needed to explore the interplay between locomotion preferences and potentially complex application contexts for all audiences.

Locomotion accessibility analysis overall requires further in-depth research, with categorisation of individual techniques beyond the existing motor accessibility considerations used by existing taxonomies (Di Luca et al., 2021) urgently required. Accessibility exploration of highly used locomotion techniques from cognitive and sensory impaired perspectives in particular is essential to understand locomotion usability from a comprehensive range of ability perspectives.

6.1. Implications for VR locomotion design

The following list contains the key findings and future research directions from the current review:

- The most explored practitioner techniques include the earliest invented room-scale and sliding joystick techniques. Novel techniques made possible by the positional tracking of consumer-level HMDs, such as arm swinging locomotion, meanwhile appear underexplored by industry practitioners.
- Although room-scale locomotion is the most widely explored technique overall, applications most often combine the technique with more conventional controller sliding locomotion rather than utilising roomscale walking-based techniques, highlighting a large industry gap.
- Claims that teleportation is the standard locomotion technique in VR, whilst largely accurate in 2016 and 2017, no longer hold true, with the category as a whole continuously decreasing in usage.
- The continuous growth in grab technique exploration, combined with the often precise motion tracked arm movements required for inputs such as climbing, emphasises the urgency needed in further accessibility-related research to ensure locomotion is usable, flexible, and adaptable to varied needs.
- The number of locomotion techniques in an average application has increased from 3.9 in 2016 to 5.95 in 2023, suggesting that further research is needed to explore the impact of this increasing locomotion complexity.
- Industry practitioners appear to largely not be offering alternative viewpoint motion control category choices. Optional locomotion techniques consist mostly of the visual sickness mitigation snap turn and tunneling techniques, suggesting that users are largely not able to tailor locomotion to their own abilities.
- Simulator sickness and motor accessibility are currently the only considerations in accessibility categorisation schemes. Research is urgently needed to further explore locomotion accessibility from alternative perspectives, such as with cognitive and sensory impaired individuals.

7. Conclusion

The historic focus on academic sources within VR locomotion research has led to a large gap in the understanding of industry practitioner adoption, with the lack of an understanding of real-world locomotion implementation weakening justifications for technique inclusion in research studies. These representative overview results highlight the divergent interests between industry and academia, showing for example the dramatic declining exploration of teleportation in commercial applications, from 48% of the applications released in 2016 to 18% of those released in 2023, suggesting that practitioners are less interested in teleportation than previously often assumed. Temporal analysis furthermore suggests that academically underexplored techniques, such as hand walking within the grab locomotion category, may require renewed research focus in order to potentially uncover technique specific usability and accessibility insights. These in-depth results provide a vital source of continued academic engagement with the VR industry, with empirical evidence of current adoption, historical trends, and gaps between industry and academic exploration highlighting potential future industry and academic directions.

The high practitioner usage levels of sickness mitigation techniques such as snap turning indicates that practitioners have widely implemented many of the best practice findings from the extensive history of accessibility focused academic sickness research. Sickness however is not the only accessibility barrier presented by locomotion in VR, with the increasing complexity of locomotion in commercial applications, as shown both in the rising number of techniques in an average application, and the growing focus on precise arm movement based techniques such as climbing, emphasising the urgent need for further research to ensure locomotion is accessible for all audiences.

The combination of specific and detailed locomotion technique analysis with high-level abstraction academic metaphor-based comparisons allows this review to support the needs of both academic researchers and industry practitioners, with the numerous trends and gaps identified adding scientific rigour to future VR locomotion selections across both domains. Potential key future research directions include the exploration of locomotion accessibility beyond physical effort metrics, in particular with cognitive and sensory impaired audiences. Finally, the current low exploration within mainstream applications in the extensively academically explored walking-based locomotion category suggests a potential industry market gap, whilst the growing practitioner adoption of grab techniques suggests that the grab category may require further academic research focus to uncover potential usability and accessibility insights.

Ethics statement

The study received ethical approval from the Birmingham City University Faculty of Computing, Engineering & the Built Environment Research Office Ethics Committee (#12046).

Disclosure statement

No potential conflict of interest was reported by the author(s).

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