Exploring Seated Locomotion Techniques in Virtual Reality for People with Limited Mobility

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Abstract: Virtual reality (VR) is often designed as a standing experience, excluding individuals with limited mobility. Given that a significant portion of the population experiences lower-body mobility restrictions, accessible VR locomotion must accommodate users without requiring lower-body movement. To build a comprehensive understanding of suitable locomotion techniques (LTs) for this demographic, it is crucial to evaluate the feasibility of various approaches in virtual environments (VEs). As a starting point, we present our evaluation approach and a user study on the feasibility and potential of selected LTs for accessible seated locomotion in VR. Our findings indicate that common LTs can be adapted for seated stationary VR. Teleportation-based techniques, in particular, stand out as viable options for accessible locomotion. Although our simulated wheelchair was less popular with non-disabled participants, it was well-received by wheelchair users and shows promise as an intuitive LT for this target group.

1 INTRODUCTION

According to the World Health Organization, about 1 billion people (∼ 15% of the global population) live with a disability, with 70 million relying on wheelchairs (World Health Organization (WHO), 2021, 2017). Ensuring accessibility to emerging technologies like Virtual Reality (VR) for individuals with limited mobility is of societal importance. Designing VR applications for this group requires locomotion techniques (LTs) that accommodate seated and stationary users. Existing LTs often depend on costly hardware or physical effort, limiting accessibility (Vailland et al., 2021; Götzelmann and Kreimeier, 2020; Brachtendorf et al., 2020). However, research on accessible LTs for VR is sparse. To address this gap, we pose the following research questions:

Q1: *Are commonly used LTs also feasible in a seated stationary VR setting and therefore in principle accessible for people with limited lower-body mobility?*

Q2: *Which LT with only upper-body control is the most efficient to move through a VE?*

Q3: *Which LT is best suited for a seated stationary VR experience overall?*

We explore digital LTs for seated, stationary VR, requiring no additional hardware. This novel approach evaluates LTs in such settings, emphasizing techniques potentially enhancing accessibility for users with limited lower-body mobility. With this work, we make the following contributions:

- **LT Selection.** Five LTs were chosen based on literature and their potential feasibility for users with limited lower-body mobility.
- **Improved LTs.** We present modified versions of the selected LTs which make them suitable for a

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Figure 1: We compare different locomotion techniques in our evaluation environment: the common *Standard Teleport* (a), a teleport version we call *Volumetric Teleport* (b), a virtual *Wheelchair* (c), *Grab&Pull* (d), and the multi-perspective locomotion technique *Outstanding* (e).

seated, stationary VR setting.

- **Evaluation Environment and Task Design.** To make the selected LTs comparable in a user study, we developed an evaluation environment, including a task design for three tasks that represent different application areas: moving across long distances, on different elevation levels, or around obstacles.
- **User Study.** We present the results of a user study, where all five locomotion metaphors were executed in a seated, stationary position, and give recommendations for accessible locomotion based on our findings.

2 RELATED WORK

Research explores diverse LTs such as natural walking (Langbehn et al., 2017), treadmills (Cherni et al., 2021), walking-in-place (Wilson et al., 2016), teleportation (Weißker et al., 2018), joystick steering (Clifton and Palmisano, 2020), leaning (Buttussi and Chittaro, 2021), and arm-movement (Coomer et al., 2018). Most LTs rely heavily on physical mobility, especially the legs, limiting accessibility for users with disabilities. Accessibility in VR means ensuring VEs accommodate users with diverse disabilities, a challenging task given the wide range of needs. While previous work, such as Soccini (2020); Soccini and Cena (2021); Soccini et al. (2022), explored VR applications for users with physical disabilities, our goal is to enable these users to access experiences designed for non-disabled users. Mott et al. (2019, 2020) identified barriers for users with limited mobility in VR, including setup and cord management. We address these challenges in our study (see Section 3).

2.1 Seated Locomotion in VR

When users' hands are occupied, controller-based LTs in VR become impractical. Solutions like VR Strider (Freiwald et al., 2020), a seated LT using an exercise bike with trackers and feedback devices, offer higher presence, comfort, and better spatial estimation compared to teleportation and joystick locomotion. Similarly, Buttussi and Chittaro (2021) compared teleportation, leaning, and joystick LTs, finding leaning uncomfortable and prone to causing neck and spine fatigue. Alternative methods like pressure sensors on thighs (Ohshima et al., 2016) show promise for wheelchair users but require specialized hardware and lack thorough evaluation. Seated steering LTs, as explored by Clifton and Palmisano (2020), reduce disorientation compared to standing versions and perform similarly in cybersickness metrics, suggesting our seated stationary LTs would align with their standing counterparts. TriggerWalking (Sarupuri et al., 2017) enables walking-like gestures via controller buttons, while Zielasko and Riecke (2020) emphasize that seated users prioritize the sensation of movement in VR over the illusion of walking. Following this, we avoided simulating a standing experience or artificially increasing user height in our approach.

2.2 Wheelchair Locomotion in VR

A unique form of seated LTs involve virtual wheelchairs. Abstract LTs are often more accessible than those mimicking real walking (Di Luca et al., 2021). Studies like Vailland et al. (2021) and Yang et al. (2021) demonstrate VR's potential in training wheelchair users for joystick operation and mechanical propulsion, but these focus on training rather than broader VR accessibility. Specialized hardware is being developed for wheelchair-based VR locomotion. *Whee'llConnect*(Hansen et al., 2019) mounts power wheelchairs onto a stationary setup to translate propulsion into virtual movement. Physical wheelchairs combined with ergometers(Götzelmann and Kreimeier, 2020; Brachtendorf et al., 2020) have also been used for urban planning and force feedback. However, such devices are costly, experimental, and require switching between controllers and wheelchair wheels. Other efforts include a virtual wheelchair simulation using swivel chair rotation (Krösl et al., 2018), which is inaccessible for users with limited

Table 1: List of feasible LTs for people with limited lower-body mobility. The top five LTs were selected for the study and modified for seated stationary locomotion.

Locomotion	Based On
Grab&Pull	Coomer et al. (2018)
Outstanding	Cmentowski et al. (2019)
Standard Teleport	No specific source
Volumetric Teleport	No specific source
Wheelchair	Majetich (2021)
Arm-Swinging	Wilson et al. (2016)
Leaning (Upper Body)	Langbehn et al. (2015)
Swimming	Huang et al. (2019)
TriggerWalking	Sarupuri et al. (2017)
Node-based	Jacob Habgood et al. (2018)
Steering	Langbehn et al. (2018)

lower-body mobility. Research by Gerling et al. (2020) highlighted the importance of adaptable controls, safe interaction, and retaining some physical movement for VR accessibility. Stress from moving real wheelchairs in a room while wearing an HMD is another challenge stationary LTs can address. While Majetich (2021) prototyped a mechanical wheelchair simulation, broader research on this LT remains sparse. We see potential for this approach as an inexpensive, accessible solution for home use, eliminating the need for additional hardware or physical wheelchair movement during VR interaction.

3 LOCOMOTION TECHNIQUES

For our user study, we decided to limit our investigation to LTs for a specific target audience, namely wheelchair users that have a full range of motion in their upper body (hands, arms, head). Based on the limitations of existing solutions as outlined in the previous section, we define the following requirements for the selection of suitable LTs for our user study:

1. **Upper-Body Movement Only.** LTs must rely solely on hand and arm movements, accommodating users with limited lower-body mobility.
2. **Holistic Virtual Movement.** LTs must support seated, stationary 3D navigation, including virtual rotation and exploration of uneven terrain and altitudes.
3. **No Additional Hardware.** LTs must function using only standard VR equipment: a HMD and two controllers.

LTs that meet the above requirements are listed in Table 1. We selected five of them and LTs that do not fulfill all three requirements are considered infeasible. To prevent sickness-inducing movements (Langbehn et al., 2018), we excluded LTs with continuous

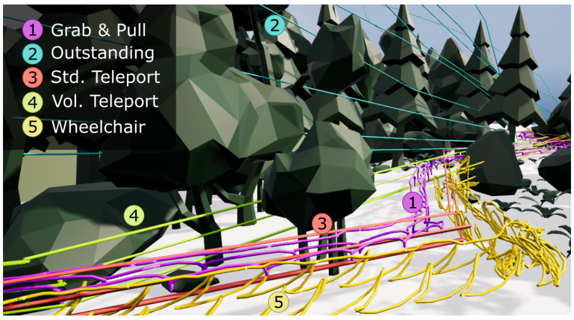


Figure 2: A comparison of how users move with the different LTs. VE colors are simplified for better visibility.

Steering or joystick control and only included those enabling unrestricted movement in a VE without preselected nodes (*Node-based* LTs). Our goal was to select a range of LTs with different archetypes: *Teleport* is a widely used LT. *Outstanding* offers a continuous version for long-range travel. From similar LTs like *Grab&Pull*, *Swimming*, and *Arm-Swinging*, we selected *Grab&Pull* for its independence between movement direction and camera orientation and its ability to function with one hand. We included *Wheelchair* as an LT that closely mimics real-world movement for people with limited lower-body mobility. *TriggerWalking* was excluded due to complexity, and *Leaning* was excluded for comfort issues (Buttussi and Chittaro, 2021). We adapted the selected LTs to ensure usability for individuals with limited mobility (Figure 2 visualizes hand and head movements in the VE, following Kloiber et al. (2020)). The LTs and evaluation environment were implemented in Unity 2021.3.0f1 using the XR Interaction Toolkit 2.0.1. To address VR accessibility barriers (Mott et al., 2020), we used the Oculus Quest 2, a standalone HMD with inside-out tracking requiring only an HMD and controllers.

Grab&Pull. This continuous LT, based on *Point-Tugging* (Coomer et al., 2018), involves users grabbing the air to pull or push themselves through the VE. It relies on upper-body movements and enables continuous navigation.

Outstanding. A continuous multi-perspective LT where users control an avatar by selecting target points (Cmentowski et al., 2019). Users can switch between first- and third-person views to traverse large distances (Figure 1e).

Teleport. A discontinuous LT where users select a target point and "jump" there, guided by trajectory or volumetric indicators. This LT is widely used due to its reduced likelihood of motion sickness (Langbehn et al., 2018).

Wheelchair. Drawing on Majetich (2021), this LT simulates a mechanical wheelchair. Users push virtual wheels using VR controllers, eliminating the need for additional equipment or hand tracking (Figure 1c). Since the wheelchair is physically based, this LT requires a lot of movement from users, and may exhaust them. However, since the target audience are people who use mechanical wheelchairs and perform this movement daily, this LT might not feel as strenuous to them.

3.1 Modifications and Implementations

To maximize accessibility for stationary, seated locomotion, we adapted all chosen LTs to enable orientation changes while sitting.

Grab&Pull. This LT builds on the concept by Coomer et al. (2018), with modifications informed by informal user tests. To address the slow pace of movement, we added a multiplier (m in Eq. 3) to enable covering greater distances efficiently. A multiplier of 2.0 proved effective, avoiding noticeable jitter in initial testing. Attempts to integrate rotation directly into the grabbing motion caused jitter and nausea. To resolve this, we separated position changes from rotation, allowing orientation adjustments via joystick control. Vertical movement (y-axis) was incorporated realistically by interpolating between the user's camera height (cam_h) and the controller height (con_h) at the grab point (Eq. 2), with interpolation determined by hand movement (t, Eq. 1). The updated position ($NewPos$) is calculated using Eq. 3, where $dist_{max}$ represents the maximum controller movement distance in the x-z plane.

$$t = clamp\left(\frac{dist_{current}}{dist_{max}}\right) \in [0,1] \tag{1}$$

$$y = t \cdot con_h + (1-t) \cdot cam_h \tag{2}$$

$$NewPos = \begin{pmatrix} current_x + (grab_x - con_x) \cdot m \\ y \\ current_z + (grab_z - con_z) \cdot m \end{pmatrix} \tag{3}$$

To mitigate potential user fatigue from extended hand positions, the grabbing mechanism operates at any point in space. However, this flexibility can influence the relative movement distance achievable from a grab point.

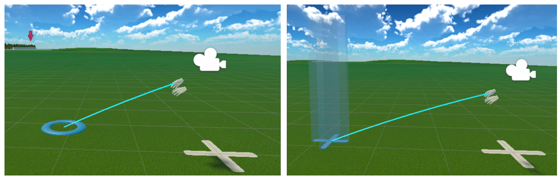


Figure 3: Left: *Standard Teleport* indicator. Right: translucent *Volumetric Teleport* indicator.

Outstanding. Cmentowski et al. (2019) provided the source code of their LT *Outstanding* for our study, including the basic functionality of zooming out, selecting a target via a trajectory, and allowing the avatar to follow a path (using Unity AI Navigation) to reach the target point.

We modified the first-person camera to account for height differences in the VE and added a continuous rotation feature, enabling the user to adjust their viewing direction. This adjustment replaces the original LT's reliance on physical rotation in the real world.

Standard and Volumetric Teleport. Teleport is a promising LT, but seated users may face occlusions in VEs with obstacles. We tested two variants: *Standard Teleport* (Figure 3, left; Figure 1a) with a flat circle indicator and *Volumetric Teleport* (Figure 3, right; Figure 1b) using a translucent cross for better visibility. Following Weißker et al. (2018), both teleports use a pointing method, operate in vista space, and provide visual feedback with instant transitions. Users activate teleportation with the primary button (*A* on the right Oculus Touch Controller) and release to execute. Discontinuous snap-rotations (45° increments) were added for in-place orientation using the right joystick.

Wheelchair. Our wheelchair LT builds on Majetich's VR wheelchair implementation (Majetich, 2021) and uses a 3D model based on the Meyra Budget 2 (Model 9.050[1]). Each wheelchair component exists as both a visual 3D object and a physics instance, synchronized to move the player with the wheelchair. Users grab the large wheels (60cm diameter) to push or pull, creating a grab point that disappears if they let go or exceed a set distance. When stopped, braking is simulated by increasing the negative torque of the wheel based on its angular velocity. If released without braking, motion gradually slows due to physics, with inclines requiring more effort than flat surfaces. We fine-tuned the physics parameters (Majetich, 2021) through informal user testing

[1]Mechanical wheelchair: Meyra Budget 2, Model 9.050, https://www.fruehwald.net/mobilitaet/rollstuehle-u-elektrorollstuehle/standardrollstuhl/57~PRODUKT/42124/meyra-budget-2-modell-9050

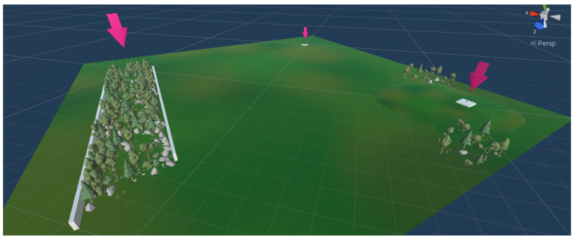


Figure 4: The ground plane of the VE with all three tasks active.

for improved usability. Haptic feedback on the controllers indicates successful wheel grabs, reducing the need to look down while interacting.

4 EVALUATION ENVIRONMENT AND TASK DESIGN

To test the accessibility of our chosen LTs, we designed a custom VE with three tasks (*T1, T2, T3*) addressing key aspects of stationary seated locomotion:

(T1) **Differences in Altitude.** *T1* features a hill with an $\sim 10^\circ$ incline to evaluate the usability of LTs for reaching positions at varying heights.

(T2) **Long Distance.** *T2* includes a 200-meter-long straight path to assess the performance of LTs over extended distances.

(T3) **Obstacle Course.** In *T3*, users navigate a course with static obstacles to test precise position adjustments without collisions. The course layout was consistent across all LTs.

They were positioned at the corners of a 200 by 200 meter plane, equidistant from the center (see Figure 4). The starting point was placed at the fourth corner, with tasks arranged such that the distances from the starting point to *T1* and *T3* are equal, while the distance to *T2* is longer. Each task requires users to navigate the environment and locate a target marked by a black pillar with a *task-button* on top, which must be pressed to complete the task. A large pink arrow highlights the target's location in the VE. To form a continuous path for three tasks in any order, a replica of the ground plane is placed so the new starting position aligns directly beneath the previous target (see Figure 5). Each added ground plane displays only one task. In our VE, obstacles like trees and stones (see Figure 2) have reliable colliders. However, there is no feedback when a collision occurs except that the *Wheelchair* cannot move through it. To enhance the user's sense of movement with the continuous LTs, we use a grass texture on the ground instead of a plain green color.

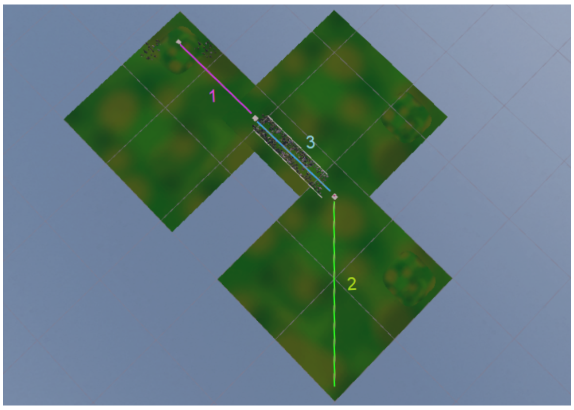


Figure 5: One of six possible task orders (2, 3, 1) in the VE. *T1* is marked in magenta, *T2* in green, and *T3* in blue.

5 USER STUDY

Our goal is to facilitate the design of inclusive LTs for VR, specifically for users with limited mobility. To achieve this, we identified LTs suitable for stationary, seated settings through a literature review and tested them first with non-disabled individuals to evaluate feasibility. In the second part of the study, qualitative feedback was collected from two wheelchair users. For the first part, we employed a within-subject design where 15 non-disabled participants (seven female, eight male, aged 26–55, $M = 33.5$, $SD = 4.7$) tested all five LTs across three tasks. Participants varied in VR experience: one had no prior experience, four had tried it once, seven multiple times, and three were regular users. Tasks were completed in a consistent environment using the same hardware and a stationary non-swivel chair for all LTs. In the second part, two wheelchair users provided qualitative feedback. P1 (male, 24) regularly uses a mechanical wheelchair and has prior VR experience. P2 (female, 27) alternates between a mechanical wheelchair at home and an electrical one outside, with limited VR experience. P1 used his mechanical wheelchair, while P2 used her electrical wheelchair during the study.

5.1 Experiments with Non-Disabled Participants

5.1.1 Procedure

Our evaluation environment and tasks were designed to accommodate an arbitrarily large user study with an a-priori unknown number of participants. The system automatically randomized the order of experimental conditions (LTs) and tasks within each condition. Since counterbalancing would require knowledge of the expected participant count, it was not implemented. The procedure lasted approximately 45 to 60 minutes and consisted of the following steps:

1. **Introduction.** Participants were briefed on the study procedure and signed a consent form.
2. **Demographic questionnaire.** Participants provided information on gender, age, wheelchair usage, and VR experience.
3. **Hardware introduction.** Participants were introduced to the Oculus Quest 2 setup and the evaluation environment.
4. **Testing phase.** Each set of three tasks began with a test scene where participants were introduced to the current LT while wearing the HMD. They could try out the controls and were shown the task-buttons, targets, and indication arrows. Once comfortable, participants initiated the tasks by pressing the task-button. After completing the three tasks described in Section 4, participants removed the HMD and completed the VR Sickness Questionnaire (VRSQ). If sickness symptoms arose, extended breaks were taken, and the study continued only with the participant's consent.
5. **Questionnaires.** After completing all LTs, participants filled out the System Usability Scale (SUS) questionnaire and answered additional questions about each LT. This process allowed for comparative feedback across all LTs.

Participants could skip tasks or scenes if they felt too exhausted, motion-sick, or frustrated. All questionnaires were completed regardless of task completion to capture participants' opinions. Breaks of any length were allowed, and participants could end the experiment at any time. The study did not focus on learning time for operating an LT. During testing, participants were given unlimited time to familiarize themselves with the controls. Path memorization was unnecessary as targets were always marked with a red arrow, minimizing the impact of potential learning effects.

5.1.2 Data Collection

We recorded data on task completion time, HMD and controller positions, collisions with obstacles, and instances where participants skipped tasks.

Virtual Reality Sickness Questionnaire. We evaluated the feasibility of the chosen LTs for seated, stationary VR by assessing nausea potential using the VRSQ (Kim et al., 2018).

System Usability Scale. To evaluate the usability of our LTs, we used the adapted SUS from Bangor et al. (2008). While the NASA-TLX assesses workload, we chose the SUS as it better distinguishes between usable and unusable systems, making it more appropriate for our study. We excluded two statements from the SUS: statement 4, as traditional technical support is not applicable in our VR setting, and statement 5, as our LTs do not have diverse functionalities requiring integration. The SUS score calculation was adapted to reflect these changes.

Additional Questions. After completing all 15 trials (three tasks per LT), participants rated each LT on a 7-point Likert scale and indicated their overall preferred technique, providing reasons for their choice. Additionally, they were asked to describe any differences they noticed between tasks when using the same LT and to provide general feedback not addressed by other questions. We did not include questions about presence or immersion, as these topics have been extensively studied in prior research (Jacob Habgood et al., 2018; Cmentowski et al., 2019; Wolf et al., 2020; Buttussi and Chittaro, 2021) and are outside the scope of our study.

5.2 Experiments with Wheelchair Users

In the second part of the study, feedback was collected from wheelchair users. The procedure included: (1) an **introduction** to the study and hardware, (2) a **testing phase** with a thinking-aloud protocol, (3) a **demographics questionnaire** with a 7-point Likert scale to rate LT preferences, and (4) a **semi-structured interview** with the following questions:

- *Which was your favorite LT?*
- *What would be the ideal LT for you or how would you improve your favorite LT?*
- *Do you find it important that there are adapted LTs like the ones you just experienced?*
- *Did you ever have the problem that you were not able to use a VR app because of your limited mobility?*
- *Would you describe the wheelchair LT as intuitive for you? What were the positive/negative aspects of that LT for you?*

6 EVALUATION

To address research question **Q1** on the feasibility of LTs in a seated, stationary VR setting, we surveyed

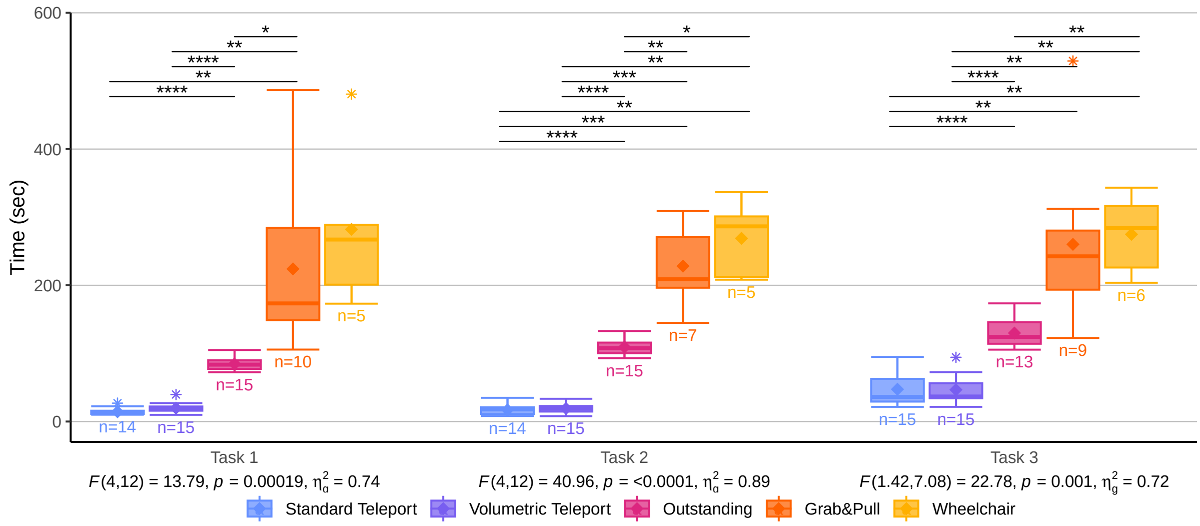


Figure 6: Boxplot of the completion time per task per LT (♦ mean, ∗ weak outlier). Statistically significant relations according to pairwise t-tests are connected on top with the number of stars indicating the significance level. The number of participants per group after outlier-removal is reported bellow each box. One-way repeated-measures ANOVA results are reported bellow each Task.

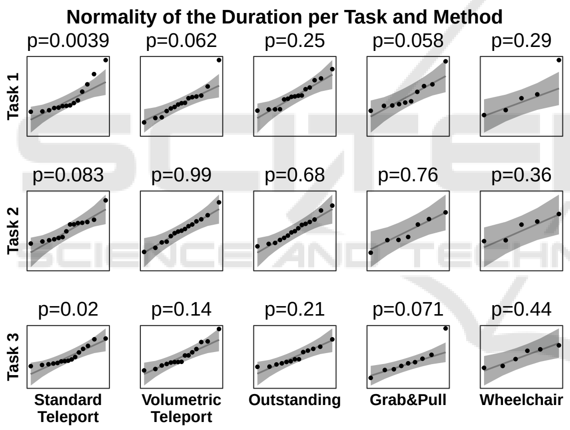


Figure 7: QQ-Plots and Shapiro-Wilk test results for the completion time.

the literature and then tested the usability of our five selected LTs, with the following hypothesis:

H1: *All LTs reach an adapted SUS score > 50.*

To find the most efficient LT (**Q2**), we formulated these hypotheses:

H2: *Continuous LTs cause more collisions.*

H3: *Discontinuous LTs result in faster task completion.*

H4: *Different LTs produce different movement paths.*

Finally, to overall determine the most suitable LT for seated, stationary VR (**Q3**), we tested:

H5: *Volumetric Teleport is better in cluttered environments.*

H6: *LTs with less sickness symptoms and higher usability scores will be preferred.*

H7: *The wheelchair LT is more intuitive to use for regular wheelchair users.*

We use the standard $\alpha = 0.05$ for all statistical tests and, in case of multiple testing, report adjusted p-values after applying Bonferroni correction. As effect sizes, we report Cohen's d, Wilcoxon's r and Kendall's W ($< .5$ small, $.5 - .8$ medium, $> .8$ large), and generalized eta squared η_g^2 ($< .06$ small, $.06 - .14$ medium, $> .14$ large). As the same participant experienced every LT, we use paired or repeated measure methods to address the dependency of the individual measurements on the subject. An a-priori power analysis with $\beta = .8$ indicates a required sample size of $n = 8$ for a one-way ANOVA with a medium effect, and $n = 15$ for a paired, two-sided t-test with a large effect. Greenhouse–Geisser correction is applied, if the sphericity assumption is violated. Result figures use the IBM colorblind-safe palette (IBM, 2018).

6.1 Results from Non-Disabled Participants

Not all participants completed every task; some skipped individual tasks, and three users had to abort testing the *Grab&Pull* and *Wheelchair* LTs due to motion sickness. As a result, the number of measurements per parameter or task varies.

6.1.1 Objective Data

Collisions. Collisions were recorded only in the obstacle course (*T3*). Since *Outstanding* uses Unity's AI Navigation pathfinding, which does not produce collisions, it is not evaluated here. Most participants caused no collisions, but one participant created 42 with *Grab&Pull*, possibly due to not recognizing small plants as obstacles. *Grab&Pull* had the most collisions, and *Wheelchair* the least. Due to the aforementioned extreme outlier and non-normality of the data, we applied a non-parametric Friedman test, which yielded no significant result ($\chi^2(3) = 4.53$, $p = .21$, $W = .28$). Therefore, we reject **H2**.

Task Completion Time. We tracked task completion time as a primary measure of efficiency. Two extreme outliers from the *Standard Teleport* LT were removed. Shapiro-Wilk tests revealed violations of normality for the first and third tasks using *Standard Teleport*. However, the Quantile-Quantile (QQ) plots depicted in Figure 7 suggest that the data approximately follows the linear reference line. Thus, we consider all times normally distributed. A two-way ANOVA reveals a significant influence of the LT used ($F(4,4) = 15.694, p = .01, \eta_g^2 = 0.896$), but a negligible effect of the task ($F(2,2) = 16.665, p = .057, \eta_g^2 = 0.332$). Subsequent one-way ANOVAs for each task and pairwise comparisons using two-way t-tests show substantial differences between most LTs (Figures 6), but no significant difference between *Grab&Pull* and *Wheelchair* (*T1*: $p = .54$, $d = 1.54$; *T2*: $p = 1$, $d = 1.14$; *T3*: $p = 1$, $d = .044$) or between the *Teleport* variations (*T1*: $p = .34$, $d = .63$; *T2*: $p = 1$, $d = .157$; *T3*: $p = 1$, $d = -.026$). *Grab&Pull* and *Wheelchair* were on average the slowest, followed by *Outstanding*, which is restricted by the preset avatar's speed. Discontinuous *Teleport* variations were statistically significantly faster than most LTs, except *Wheelchair* at *T1*, probably due to the small sample size, as the min-max intervals are distinctly not overlapping. Given the evidence that discontinuous LTs lead to faster completion times, we accept **H3**. Next to the standard list-wise deletion for missing data, we additionally fitted a linear mixed-effects model combined with conditional multiple imputation ($N = 100$, MICE based on Bayesion regression), to predict missing values. The conclusions remained consistent with the original analysis.

Movement Paths. Most movement paths for the *Teleport* variations showed inaccuracies, as participants prioritized speed over accuracy, resulting in differently sized loops around the target. In *T3*, some

Table 2: Descriptive statistics of the questionnaire results.

	VRSQ			SUS		
	Mean	SD	Median	Mean	SD	Median
Std. Teleport	2.89	6.72	0	92.7	10.1	96.9
Vol. Teleport	3.34	6.99	0	93.3	8.17	96.9
Outstanding	5.56	5.27	3.34	77.1	22.2	87.5
Grab&Pull	21.89	15.88	19.2	66.7	21.7	68.8
Wheelchair	25.00	11.75	22.5	42.9	21.6	37.5

participants found small openings to project their teleport trajectory through, allowing faster movement through the obstacle course (see Figure 2, 4). *Grab&Pull* and *Wheelchair* paths showed more zigzag patterns, possibly contributing to participants' aversion to these LTs. Additionally, the *Wheelchair* required realistic rotation of the virtual wheelchair, increasing effort on corners (see Figure 2, 5, lower right). These findings demonstrate that different LTs result in different movement paths, supporting **H4**.

6.1.2 Questionnaires

Virtual Reality Sickness Questionnaire. The VRSQ score (0-100) indicates sickness, with higher scores reflecting greater sickness. *Volumetric Teleport*, *Standard Teleport*, and *Outstanding* had low scores, while *Grab&Pull* and *Wheelchair* had higher ones (Table 2). A Friedman test ($\chi^2(4) = 46.3$, $p < .001$, $W = .772$) found significant differences between LTs. Pairwise Wilcoxon signed rank tests showed *Grab&Pull* and *Wheelchair* had significantly higher scores than the others ($p \leq .011$, $r \geq .851$). Participants reported *Discomfort*, *Fatigue*, and *Fullness of Head* with *Grab&Pull* and *Wheelchair*, while *Teleport* and *Outstanding* caused fewer symptoms, mostly *General Discomfort* and *Fullness of Head*.

System Usability Scale. Bangor et al. (2008) consider SUS scores above 70 as good and below 50 as unacceptable. Since we used a modified SUS with fewer questions and adjusted calculations, our results are not directly comparable to standard SUS ratings, but serve as general usability indicators for comparing our LTs. A Friedman test indicates significant differences between LTs ($\chi^2(4) = 40.6$, $p < .001$, $W = .677$). Table 2 shows that both *Teleport* variations received high scores (*mean* > 90), affirming their popularity. Pairwise Wilcoxon signed rank tests demonstrate significant differences between the *Teleport* variations and all other LTs ($p \leq .046$, $r \geq .761$). *Outstanding* achieved a mean score of 77.08, while *Grab&Pull* scored 66.67, which we both interpret as acceptable despite mixed ratings ($SD > 20$). The *Wheelchair* LT scored lowest on average (42.92), highlighting the need for rigorous improvement despite some high ratings. Thus, while **H1** (SUS > 50

for each LT) holds for both *Teleport* LTs, *Outstanding*, and *Grab&Pull*, it does not for the Wheelchair LT, leading us to reject **H1**.

Preference and Enjoyment. We asked participants about their preferred LT and overall enjoyment of each LT. Contrary to our hypothesis that *Volumetric Teleport* is better for seated VR in cluttered environments, nine out of 15 participants preferred *Standard Teleport*, while only five favored the *Volumetric Teleport*, rendering **H5** false. One participant preferred *Outstanding*, and none voted for *Grab&Pull* or *Wheelchair*. Participants stated ease of use, speed, and intuitiveness as reasons for preferring the teleport variations, with *Volumetric Teleport* users highlighting the easier to see volumetric indicator compaired to the flat one of *Standard Teleport*. Figure 8 illustrates LT enjoyment ratings: *Wheelchair* was rated worst, *Grab&Pull* received mixed feedback, *Outstanding* had mostly positive ratings, and both *Teleport* variations scored highest. There is a significant inverse correlation between the VRSQ and SUS score (Spearman's $\rho = -0.643$, $p < .0001$) and task completion times (VRSQ: $\rho \geq .6117$; SUS: $\rho \leq -.5$; $p < .0001$). Differences between participants' best-scored LT and their preferred LT (VRSQ: 3; SUS: 3, no overlaps) showed no significant deviation from zero (VRSQ: $p = .1814$; SUS: $p = .149$; one-sided Wilcoxon signed rank test), indicating alignment between ratings and preferences. Thus, LTs with the lowest sickness symptoms and highest usability scores are preferred, supporting **H6**.

6.1.3 Additional Questions

Finally, participants provided free-text feedback, noting task-specific differences. Opinions on *Outstanding* varied: Some appreciated the third-person view for the obstacle task *T3*, while others found the view-switching tedious. *Grab&Pull* was criticized for its slow speed and therefore limited suitability for long distances, but praised for precise navigation in *T3*. Speed was also a drawback when using the *Wheelchair*, with difficulties reported when navigating uphill (*T2*) or on uneven terrain.

6.2 Results from Wheelchair Users

Figure 9 shows responses on a 7-point Likert scale from P1 and P2 to the question "*Did you like/enjoy this Locomotion Technique?*" and the time they spent with each LT.

Teleport. P1 preferred *Teleport* LTs, despite spending the least time with them, due to their speed, ease of use, and familiarity with gaming. In contrast, P2 also used to fast gaming interactions, rated them as *neutral*, stating, *"I didn't enjoy the teleport, none of them, because it was easy and you didn't have to move"*. P1 generally prefers joystick movement in VR, self-reporting no motion sickness, and noted, *"It's relatively easy and it is equally usable for everyone* [non-disabled people and individuals using wheelchairs]*, there are no pros or cons when everyone can use the same* [LT].*"*.

Outstanding. P1 found *Outstanding* slower than *Teleport* LTs, although otherwise preferring walking characters in games. P2 rated *Outstanding* slightly above *neutral*, noting, *"Outstanding works for me just because I am a very patient person. It wouldn't work for people with no attention or no patience."*

Grab&Pull. P1 found *Grab&Pull* unsuitable in his wheelchair, stating, *"Since I don't have trunk stability, I fall forward the moment my arms are extended."*, and explaining that sitting on a stable chair or couch would improve this by allowing to lean back without losing stability. Finding the LT too exhausting, P1 considered combining it with *Outstanding* a suitable solution, stating, "[This] *would definitely be the ideal* [LT] *from this selection* [of LTs].".

Wheelchair. Both participants liked the *Wheelchair* LT and spent similar amounts of time using it. P2 rated it the highest and selected it as her favorite, valuing its visual representation over other, more abstract LTs (e.g., pulling an invisible rope). She found the representation crucial for immersion. Conversely, P1 became deeply immersed, noting, *"[...] I wouldn't even be able to tell, if the breaks of [his] wheelchair are on."* P1 initially struggled with the movement, explaining, *"I intuitively do the upper-body movements as I would have to, when moving in my real wheelchair to not fall off. This means I move my upper body forward and backward. [...] So, the intuitive movements do not work, because I just sit there [while moving the virtual wheelchair]."* However, he eventually found that the virtual wheelchair's movement closely matched that of a physical wheelchair. With time, he realized that reaching further back to grab the virtual wheels, as in real life, allowed him to generate more movement. Similarly, P2 noted that users might require time to understand the LT's mechanics. Both participants enjoyed the *Wheelchair* LT but found it physically demanding. P2 compared the upper-limb exhaustion to playing sports. While she

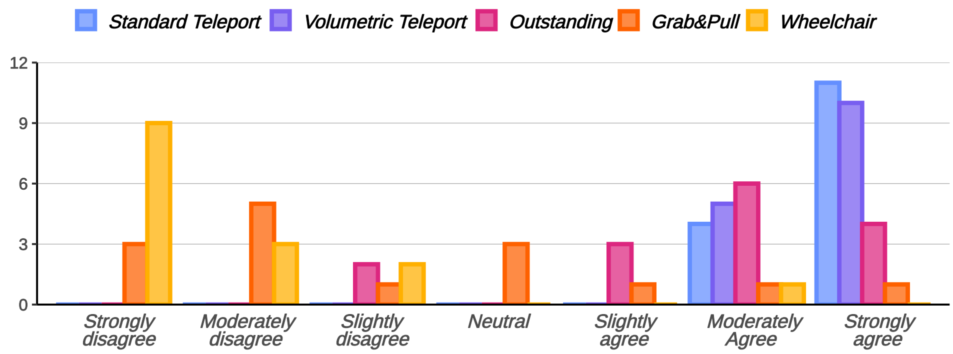
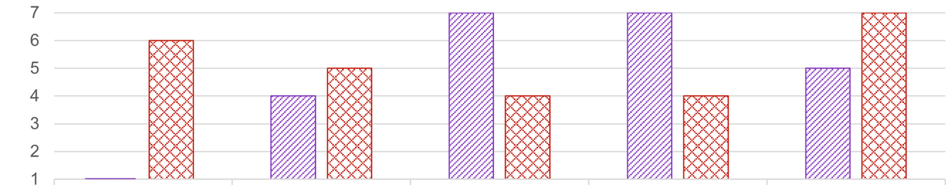


Figure 8: Participants' responses to the question "*Did you like/enjoy this locomotion technique?*".



	Grab&Pull	Outstanding	Standard Teleport	Volumetric Teleport	Wheelchair
P1	2 min.	5 min.	> 1 min.	> 1 min.	10 min.
P2	5 min.	27 min.	5 min.	7 min.	11 min.

Figure 9: Preference ratings and time spent exploring an LT of the wheelchair users.

appreciated the controls, she suggested less strenuous arm movements could improve the interaction design, remarking, *"It would be nice for example to put my arms up and down to move."* P1 acknowledged simpler alternatives for moving through a VE but noted he might prefer using his physical wheelchair for such tasks, provided the controllers were integrated effectively. P1 concluded, *"It's something that needs time getting used to. In real life, I also need time to get used to a wheelchair, since every wheelchair is different and this [virtual] one is also manageable after some time."* Feedback from both participants inspired potential improvements for the *Wheelchair* LT. For instance, P2 suggested, *"I would change the look of the wheelchair. I would add some colors or make it look like a spacecraft or a motorbike."* Their positive reception, compared to non-disabled participants, supports **H7**, though a larger study with more wheelchair users is required for a definitive evaluation.

7 DISCUSSION

By looking at our quantitative and qualitative data and observations made during the experiments, we gained the following insights.

Speed. Discontinuous LTs were generally faster than continuous ones (**H3** = true). Some users struggled with height differences using the *Wheelchair*, as reflected in the outliers for *T1* (involving altitude changes) in Figure 6. While expected, these findings highlight considerations for designing accessible LTs.

Accuracy. Collisions were observed with the *Teleport* variations during rapid movement, potentially impacting precision when aiming between obstacles. Unexpectedly, the *Wheelchair* LT resulted in few collisions (**H2** = false). This may be due to our instructions encouraging conscious movement or because users were fully immersed in the VE and maintained a natural distance from obstacles, as they would in the real world.

Motion Sickness. As expected, the *Teleport* variations resulted in low sickness levels (assessed with VRSQ). In contrast, *Outstanding* caused nausea in a few participants, the same individuals who struggled with *Grab&Pull* and *Wheelchair* due to sickness. *Grab&Pull* showed the highest *Fatigue* scores on the VRSQ, aligning with participants' qualitative feedback labeling it as too exhausting. Some participants reported HMD jitter during movement, which may explain the elevated scores in other VRSQ segments for this LT. The poor VRSQ scores for *Wheelchair* and *Grab&Pull* likely stem from a mismatch between visual and vestibular information, consistent with prior findings on continuous joystick movements (Langbehn et al., 2018; Clifton and Palmisano, 2020).

Usability. The *Volumetric Teleport*, *Standard Teleport*, *Outstanding*, and *Grab&Pull* all received SUS scores above 50, with the *Teleport* variations scoring above 90. This high usability may be attributed to the familiarity of *Teleport* as one of the best-known LTs and its simplicity, requiring only pointing, pressing one button, and joystick rotation. Conversely, the *Wheelchair* LT scored below 50 among non-disabled participants, likely because they were not regular wheelchair users and required time to adjust to its mechanics. However, both wheelchair users favored the *Wheelchair* LT despite its physical demands. They found it accurate, usable, and enjoyable (**H7** = true), experiencing no motion sickness or tracking issues. P1 even experimented with faster movement by extending further back with the controllers, akin to his real-life wheelchair use, without encountering HMD tracking problems. Since *Outstanding* and *Teleport* also performed well with wheelchair users, combining *Wheelchair* for precise navigation with *Teleport* or *Outstanding* for efficient long-distance movement could be a promising avenue for future research.

7.1 Research Questions

Q1. Informed by our literature survey, we proposed three requirements for LTs to be accessible to individuals with limited lower-body mobility: (1) *only upper-body movement*, (2) *holistic virtual movement* (including virtual rotation), and (3) *no additional hardware* beyond standard VR equipment. Based on these requirements, we identified all LTs listed in Table 1 as suitable for accessible locomotion when modified to include virtual rotation. Our quantitative evaluation of five modified LTs showed acceptable usability (SUS scores) for all but low usability for the *Wheelchair*(**H1**). As discussed in Section 2, the use of a mechanical wheelchair simulation as an LT in VE remains uncommon and relatively unexplored in research. While improvements are likely needed, our wheelchair users generally appreciated this LT. To address **Q1**, many commonly used LTs are feasible in a seated, stationary VR setting if modified to account for the lack of physical rotation, making them, in principle, accessible for people with limited lower-body mobility.

Q2. Since locomotion should be fast, easy to use, and maneuverable, we evaluated the efficiency of LTs primarily by task completion times, as well as motion paths and the number of collisions as measures of accuracy. Given that we accepted **H3**, the *Teleport* variations emerged as the most efficient LTs, with the lowest task completion times. Although the *Teleport* variations recorded a slightly higher absolute number of collisions, these results were not statistically significant (**H2** = false). Regarding movement paths (accepted **H4**), the *Teleport* variations appeared subjectively more efficient for navigating the VE due to their discontinuous movement between target points. To address **Q2**, our findings suggest that among LTs with only upper-body control, a *Teleport* LT is the most efficient for navigating a VE.

paragraph**Q3.** As shown, all our modified LTs are suitable for seated stationary VR (**Q1**). The *Teleport* variations were the most efficient and preferred LTs in our study (**H6** = true), achieving the highest SUS and lowest VRSQ scores. We hypothesized that *Volumetric Teleport* would perform better in cluttered VEs (**H5**). While this was true for five participants who preferred *Volumetric Teleport*, the majority favored *Standard Teleport*, leading us to reject this hypothesis. *Outstanding* combines some benefits of *Teleport* while remaining continuous. Users rated it well across categories but found precise movements challenging. In its original version, Cmentowski et al. (2019) paired it with real walking for finer adjustments. Future research could explore combining *Outstanding* with *Grab&Pull*, as the latter excels at precise positioning but is unsuitable for long distances. One wheelchair user also considered this combination ideal for accessible LTs. While the *Wheelchair* LT was poorly received by non-disabled participants, wheelchair users found it potentially effective for their needs (**H7**). To answer **Q3**, the optimal LT for a seated stationary VR experience depends on the target group. However, *Teleport* variations are generally well-received by both non-disabled participants and wheelchair users.

8 CONCLUSION AND FUTURE WORK

While many LTs exist, their suitability for seated, stationary VR settings remains underexplored. Based on a literature review, we proposed a set of requirements for accessible LTs for individuals with limited mobility and identified potentially viable LTs for seated, stationary locomotion (Table 1). To evaluate these, we developed an evaluation environment and task design, conducting a user study with 15 non-disabled participants and two wheelchair users. The *Teleport* variations outperformed other LTs in efficiency, usability, and user preference among non-disabled participants.

For wheelchair users, the *Wheelchair* LT was equally favored, alongside the *Teleport* LTs. *Outstanding* received good ratings among continuous LTs from both groups. *Grab&Pull* caused exhaustion, motion sickness, and low usability, while the *Wheelchair* LT had similar results for non-disabled users. However, wheelchair users were less affected and generally appreciated this LT. Based on current findings, we recommend a *Teleport* variation for an inclusive design-for-all approach, supporting both non-disabled users and those with limited lower-body mobility. Future work aims to refine the *Wheelchair* LT based on feedback from wheelchair users, as it showed promise for this target group. Additionally, we tested *Teleport* LTs with implicit orientations. Given their versatility, follow-up studies could explore specialized tasks and alternative orientation methods (e.g., Mori et al. (2023)) to better understand their advantages.

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