Comparing Locomotion Techniques in Virtual Reality for People with Upper-Body Motor Impairments

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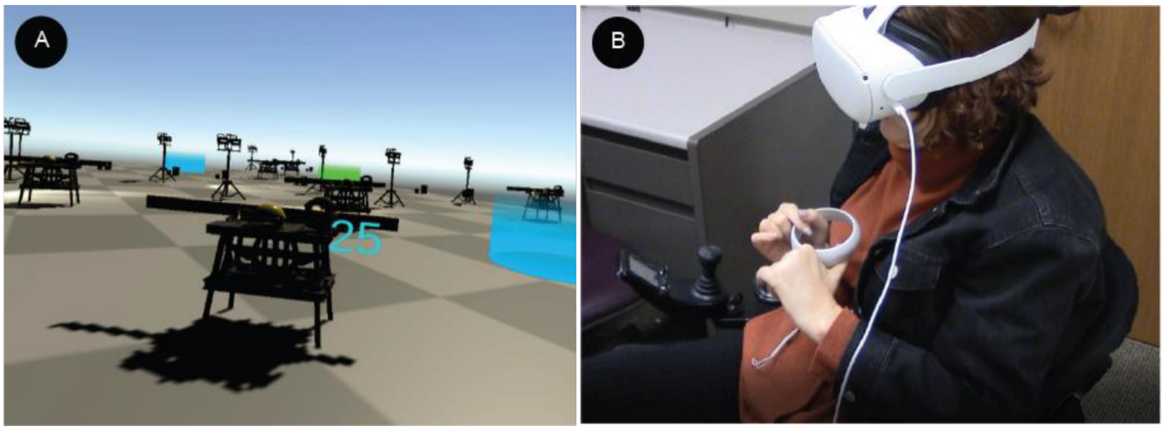

Figure 1: (A) The participant's view of the test environment and 30-second trial countdown. The target that the participant is navigating to is green and other targets in the environment are blue. The participant must also maneuver around the work benches, lighting rigs, and paint cans. (B) A participant performing the task using one hand to stabilize the controller and the other to press the buttons.

ABSTRACT

Although virtual reality (VR) is becoming increasingly popular and many interaction techniques for navigating virtual environments, known as "locomotion techniques," exist, data regarding the accessibility of locomotion techniques for people with upper-body motor impairments do not exist, making it difficult to understand which locomotion techniques work well for users and why. To address this gap, we conducted a study with 19 participants with upper-body motor impairments who completed a navigation task in VR using six seated locomotion techniques. We collected task performance data and elicited participant feedback using questionnaires and interviews. We found that participants performed similarly well with three techniques that required one controller input, little to no upper-body movement, and had a low perceived workload: *Teleport*, *Astral Body*, and *Sliding Looking*. However, *Teleport* was consistently favored in interview responses and could be considered the best technique for this group of participants. On the other hand, participants performed similarly poorly with three techniques that required arm, head, and torso movement and also rated these techniques as having a high workload: *Chicken Acceleration*, *Grab and Pull*, and *Throw Teleport*. However, participants did not necessarily prefer or want to use the techniques with which they performed best or had the lowest perceived workloads. Factors such as enjoyment, exercise, and presence sometimes outweighed accessibility. This finding suggests that accessibility alone should not override all other considerations when designing or recommending locomotion techniques to people with upper-body motor impairments, and that users with disabilities should have a range of accessible locomotion techniques to choose from based on their preferences.

CCS CONCEPTS

• **Human-centered computing** → Accessibility; Empirical studies in accessibility; Human computer interaction (HCI); Interaction paradigms; Virtual reality.

KEYWORDS

Accessibility, Virtual Reality, Upper-Body Impairment, Locomotion Technique

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1 INTRODUCTION

Virtual reality (VR) is becoming a popular consumer technology because of its high engagement, diminishing hardware size, and increasing affordability. VR is also attracting a more diverse user-base than ever before because its focus has expanded from entertainment to social connection, education, and work. Also, VR presents an opportunity for people to virtually "travel" or be together with others in ways that were not possible with other technologies. This opportunity could be especially impactful for people with physical impairments who might be geographically constrained. Because VR is 3-D, interaction techniques are very different from those designed for desktop and mobile devices and are still in their nascent stages of research and development.

One of the most important ways of interacting in VR is navigating virtual environments using *locomotion techniques*. Since VR interaction started becoming a research focus 30 years ago, researchers and designers have developed numerous locomotion techniques. These techniques are varied in terms of their control mechanisms (body movement-based, controller-based, etc.), the parts of the body used to control the techniques (legs, arms, head, etc.), and the level of physical exertion required to navigate a virtual environment. Although a substantial amount of research has focused on designing locomotion techniques that emulate real-world movement, commercial implementations of locomotion techniques have enabled users to move around virtual spaces while seated because of safety concerns and space constraints. This emphasis on seated techniques also benefits people with limited mobility. As a result of designers looking for ways to overcome real-world constraints, over one hundred distinct locomotion techniques exist to this day [23], giving users the ability to choose a technique that suits their abilities and preferences.

Despite the large number of locomotion techniques and the distinct opportunity that VR presents to people with physical impairments, data do not exist regarding which techniques are most accessible, particularly for people with upper-body impairments, making it difficult to know which techniques work best for which users and why. Seated techniques can be accessible for people with lower-body impairments who otherwise have typical mobility in their upper body; however, seated techniques are not necessarily accessible for people with upper-body motor impairments.

This study is a first step in identifying the most accessible seated locomotion techniques for people with upper-body motor impairments. We identified six locomotion techniques that use a range of control mechanisms, parts of the upper body, and physical exertion levels. We then asked 19 participants to navigate to targets in a custom-built virtual environment with these six techniques. We collected data on their performance as well as questionnaire and interview data about their experiences using the techniques.

We found that participants performed similarly well with three techniques that had the lowest perceived workload: Teleport, Astral Body, and Sliding Looking. These techniques required only single-controller input and little upper-body movement. Teleport, however, had the most perceived advantages and was consistently popular compared to all other locomotion techniques in interview responses, suggesting that it was the best technique for this group. We also found that participants performed similarly poorly with three techniques that also had the highest perceived workload: Chicken Acceleration, Grab and Pull, and Throw Teleport. These techniques required arm or torso movement. Yet, participants did not always prefer the techniques with which they performed the best or had the lowest perceived workload. Factors such as entertainment, physical challenge, and presence also factored into the techniques participants said they preferred and would use in VR. Therefore, while accessibility is indeed a critical concern, it cannot be said to override all other considerations for participants regarding their preferences for VR locomotion techniques.

This paper contributes the first empirical study comparing the accessibility, perceived workload, and other user experience factors of locomotion techniques for 19 people with upper-body motor impairments. We contribute: (1) quantitative task performance data, (2) quantitative questionnaire data related to workload, presence, and simulator sickness, and (3) qualitative interview data related to participants' perceptions about the six locomotion techniques they used and how their impairments affected their performance.

2 RELATED WORK

We discuss the current state of accessibility research in VR, locomotion technique taxonomies, and how locomotion techniques are evaluated.

2.1 Physical Accessibility of Virtual Reality

As virtual reality (VR) becomes a mainstream technology, researchers have focused on improving its accessibility for people who use wheelchairs and have upper-body motor impairments. Mott et al. [25] found that people with limited mobility identified several accessibility challenges using a commercial VR system including putting on and taking off the headset, using the buttons, and maintaining a view of their virtual controllers while wearing the headset. A survey by the Disability Visibility Project found that individuals in wheelchairs had difficulty crouching and reaching while using VR [39]. Gerling et al. [10] identified ableist assumptions in the design of VR systems and concluded that the design does not accommodate bodies that do not adhere to an ideal standard.

As a result of these findings, researchers have worked to create systems and techniques that improve the accessibility of VR for people with wheelchairs. WalkinVR[1] is a commercially available game driver that allows users to remap the relationship between their physical and virtual controllers so that they are able to reach and crouch comfortably. Gerling et al. [9] also explored the accessibility of VR for people in wheelchairs by designing full-body VR games.

Researchers have worked to improve VR accessibility for people with upper-body impairments. Franz et al. [7] developed a framework to guide the creation of accessible point-of-interest techniques, with which users can change their view to points-of-interest in the virtual environment using various controller interactions. Yamagami et al. [40] developed a design space that helps designers translate bimanual into unimanual interactions for people who

[1] https://www.walkinvrdriver.com/

only have use of one hand. This work advances accessibility for VR but the accessibility of existing locomotion techniques for people with upper-body motor impairments remains unknown.

2.2 Locomotion in Virtual Reality

There are many ways of moving in a virtual environment. The simplest and most intuitive method is room-scale locomotion, in which the user walks around the physical space to move in a virtual space [32]. However, physical constraints such as the size of the room have resulted in researchers and designers inventing locomotion techniques that do not require a one-to-one mapping of physical to virtual locomotion [27].

There are many locomotion techniques and taxonomies that group these techniques using various attributes including control mechanism, realism, and the metaphor used [2, 4, 24, 29, 34, 41]. Some taxonomies have aggregated locomotion techniques by the level of physical exertion and part of the body used, which can hint at a technique's accessibility [4, 29, 35]. For example, Nilsson et al. [26] grouped techniques in two categories, stationary and mobile. Although some of the stationary techniques they identified still required physical locomotion (e.g., omni-directional treadmills), others could be performed while seated or standing (e.g., hand-based manipulation of the virtual world).

Di Luca et al. [23] looked at how accessible locomotion techniques were in terms of how much motor ability they required and found that the less realistic the technique was, the more accessible it was. Movement-based and room-scale techniques were generally less accessible and more realistic than teleportation or techniques that relied on controller input. However, with greater accessibility also came a trade-off in comfort; more accessible techniques usually induced greater simulator sickness.

The work reviewed in this section offers some guidance for choosing locomotion techniques based on users' desired levels of physical exertion, and whether or not the techniques are seated and stationary, which can all be indicators of accessibility. Yet, this guidance is derived mostly from anecdotal evidence, requiring more formal empirical evidence for the accessibility of locomotion techniques for people with upper-body motor impairments.

2.3 Evaluating Locomotion Techniques

A variety of factors contribute to the user experience of VR locomotion techniques. Such techniques are often evaluated not only in terms of performance (i.e., speed and accuracy) but also by the level of presence and simulator sickness they induce. Other important factors include ease of use, learnability, and spatial awareness [3].

Presence refers to the extent a technique convinces the user that they are physically present in the virtual environment [30]. For example, individuals with ambulatory impairments as a result of multiple sclerosis (MS) felt greater presence in a virtual environment when walking compared to people without MS, suggesting that impairment type might have an effect on presence [12].

Techniques that preserve spatial awareness help users maintain an understanding of the spatial relationships of objects in the environment relative to themselves. Although they were rated as more accessible compared to other techniques, teleportation techniques scored low for spatial awareness because the user jumped to a new location rather than moving smoothly through the space, causing disorientation [23]. Preliminary findings such as these demonstrate that user experience factors could be affected by accessibility design considerations. Yet, there is a gap in the literature systematically investigating how people evaluate the user experience of locomotion techniques when accessibility becomes an important factor. This paper addresses that gap.

3 STUDY METHOD

The purpose of the study was to compare six virtual reality (VR) locomotion techniques across several different measures to understand their accessibility and participants' experiences of the techniques, including perceived workload, presence, and simulator sickness.

3.1 Participants

Nineteen participants with self-reported upper-body motor impairments participated in the study. Eligibility criteria included being fluent in English, 18 years or older, able to provide informed consent, having a permanent or temporary motor impairment that affects the upper body, being able to hold at least one Meta Quest 2 controller, and being able to wear a Quest 2 headset. Four non-binary people, five women, and 10 men participated in the study. The mean age was 40.1 years (*SD*=16.8) and self-reported conditions that caused impairments are listed in Table 1, below. One participant had a high school degree, three completed some college, two had a two-year degree, nine had a bachelor's degree, and four had a master's degree. On a four-point scale from "not proficient" to "very proficient" at using technology, one participant rated themselves as "not proficient," one as "somewhat proficient," five as "average," and 11 as "very proficient." One participant did not respond.

Nine participants had never used VR, six participants had used VR with a headset, and four used VR with a headset and a phone. The first time they had ever used VR ranged from 2016 to 2022. Three participants reported using VR only once before, six reported using it rarely, and one reported using it weekly.

3.2 Apparatus

The apparatus for this study included a custom-built testbed that rendered the virtual task environment and the locomotion techniques.

3.2.1 Custom Testbed. We used a commercial Meta Quest 2 headset and controllers for the VR system, which was connected to an Alienware m15 P79F laptop computer. We developed a custom testbed in C# in Unity 2019.4.17. The testbed environment consisted of a horizontal plane suspended in an empty surrounding world. On the plane were six blue targets, arranged in a circle (see Figure 2A).

3.2.2 Locomotion Techniques. We tested six locomotion techniques selected such that the techniques used different parts of the body (e.g., head, torso, arms, fingers), different control mechanisms (e.g., pointing, controller button manipulation, repetitive movement), and different levels of effort (i.e., low to high). See Table 2 for a breakdown. We used Di Luca et al.'s [23] Locomotion Vault to identify the six locomotion techniques across a range of categories

Table 1: Participants' self-reported upper-body motor impairment conditions.

Participant	Condition
P00	Left hand amputee
P01	Spinal stenosis at 3C level
P02	Ehler's Danlos Syndrome, Beals Syndrome (FBN2 gene mutation) causing progressive muscle weakness
P03	C-5 quadriplegia
P04	Peripheral neuropathy
P05	Osteoarthritis, nerve damage
P06	Hand tremor and weakness
P07	Limb Girdle Muscular Dystrophy Type 2A
P08	Cerebral palsy
P09	Chronic joint pain, ongoing carpal tunnel syndrome
P10	Paralysis, quadriplegia
P11	Tetraplegia
P12	Muscular dystrophy
P13	Muscular dystrophy
P14	C5-C6 incomplete spinal cord injury with functional quadriplegia
P15	Nerve damage, severe muscle spasms, arthritis in neck, sacroiliac joint pain
P16	Arthritis in both wrists, elbows, and shoulders from overuse, right arm fatigues easily
P17	Peripheral neuropathy in all extremities
P18	Transverse myelitis

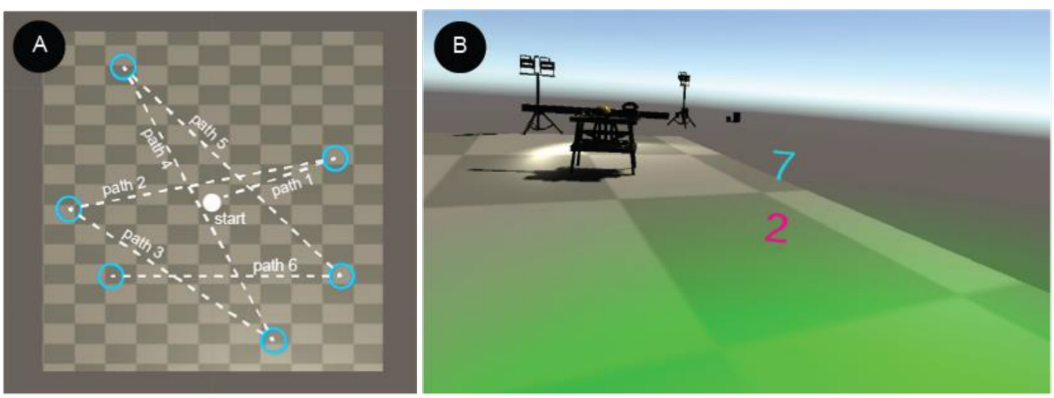

Figure 2: (A) A bird's-eye view of the test environment consisting of six blue targets and paths on a plane. The participant started the task in the center of the plane. The current target would turn from blue to green. (B) The participant's view when they moved inside the current target, which was green. The blue countdown shows the time remaining to complete the trial and the pink countdown shows the seconds the participant must remain inside the target for the trial to be considered a "hit." (This is analogous to dwell-based selection on a touch screen.)

defined in their paper. We ensured that all techniques could be performed while seated and that any two-handed techniques could be performed with one hand as well. None of the techniques required lower-body movement. Participants could perform a stationary turn using the thumbstick for all locomotion techniques except Astral Body, because Astral Body used a third-person perspective. The stationary turn rotated at discrete 45-degree increments. We added the stationary turn mechanism because only two of the first-person techniques, Chicken Acceleration and Sliding Looking, enabled directional control. The stationary turn only had to be learned once because it was consistent across all first-person techniques.

3.2.3 Astral Body. With the Astral Body technique, a participant views their avatar from a third-person perspective looking down on the environment. They control the avatar using the thumbstick by pushing it in the direction that they want the avatar to travel. In the original implementation,[2] the user could switch between third- and first-person perspectives, but we disabled this feature because the first-person locomotion could be considered a different technique and would not make trials comparable among participants. We refer to this technique as *Astral* in the remainder of the paper.

[2]https://vrgamecritic.com/game/alice-mystery-garden

Table 2: The six locomotion techniques tested in our study, instructions for using the technique, the control mechanism for forward movement and direction, and the control mechanism type. The table also presents the body part, effort level according to Di Luca et al. [23], and maximum number of hands required to use the technique. Finally, Di Luca et al.'s categorization of the technique in their taxonomy is included.

Locomotion technique	Instructions	Forward movement	Direction	Control mechanism	Body part	Effort level	Hands	Di Luca et al. [23] category
Astral Body	Use the thumbstick to move the avatar	Thumbstick	Thumbstick	Controller input	Thumb	low	1	Controller
Chicken Acceleration	Lean forward and look in the direction you want to move	Lean forward	Rotate head	Movement	Head and torso	medium	0	Relative position
Grab and Pull	Reach forward, press and hold the trigger, pull the controller back toward you, then release the trigger	Reach and retract	Always forward	Movement, controller input	Arm(s), fingers	high	2	Grab
Sliding Looking	Press and hold the "A" or "X" button and look in the direction you want to move	Press the "A" or "X" button	Rotate head	Movement, controller input	Fingers, head	low	1	Controller
Teleport	Aim the blue circle and press trigger to jump to the circle	Aim and press trigger	Always forward	Aiming, controller input	Arm, finger	low	1	Teleport
Throw Teleport	Press and hold the grip to show a ball. Throw the ball and release the grip to release ball. You will move to where the ball lands.	Aim and throw ball	Always forward	Movement, controller input	Arm(s), fingers	high	2	Teleport

3.2.4 Chicken Acceleration. With the Chicken Acceleration technique, a participant leans forward to move in the direction they are facing, with increasing speed the more they lean. The participant leans back to slow down and stop. The forward direction is controlled by steering with the head (i.e., by looking in the direction the participant wants to travel). This technique does not require any controller input. We refer to this technique as *Chicken* in the remainder of the paper.

3.2.5 Grab and Pull. With the Grab and Pull technique, a participant reaches out with one controller in front of their body, holds down the trigger button, pulls the controller back towards their body, and releases the trigger to grab and pull the ground towards themselves. They can then repeat this movement with one arm or alternate arms, similar to pulling a rope, thereby moving forward continuously. The participant can also grab and pull laterally to the side of their body to move sideways. The participant remains facing forward with this technique unless they change directions using a stationary turn with the thumbstick. We refer to this technique as *Grab* in the remainder of the paper.

3.2.6 Sliding Looking. With the Sliding Looking technique, a participant presses and holds the "A" button (right controller) or, equivalently, the "X" button (left controller) to move forward continuously. They change their forward direction by looking in the direction that they want to move. We refer to this technique as *Sliding* in the remainder of the paper.

3.2.7 Teleport. With the Teleport technique, a participant aims the teleporter, which is an arc emanating from the left or right controller. A blue circle appears at the end of the arc where it intersects with the ground. When the participant presses the trigger, they jump to the location of the blue circle. The participant increases or decreases the distance to the blue circle by tilting the controller up or down, thereby adjusting the height of the arc. Once the participant presses the trigger, they experience an instant change to the new viewpoint. The participant remains facing forward with this technique unless they change directions using a stationary turn with the thumbstick. We refer to this technique as *Teleport* in the remainder of the paper.

3.2.8 Throw Teleport. With the Throw Teleport technique, a participant presses and holds the grip button to activate a ball that appears on top of their controller. The user then tosses the ball with an underhand or overhand motion. They release the grip button when they want to release the ball and are teleported to where the ball lands. Like with the teleport technique, the participant experiences an instant change in viewpoint once they teleport. The participant remains facing forward with this technique unless they change directions using a stationary turn with the thumbstick. We refer to this technique as *Throw* in the remainder of the paper.

3.3 Procedure

After signing the consent form, a participant filled out a demographic questionnaire. The researcher and participant then reviewed the controller buttons required for the task. After the participant felt comfortable with the controllers, the researcher helped the participant put on and adjust the headset. The researcher loaded the testbed and guided the participant to practice using the thumbsticks to perform a stationary turn. After the participant had practiced turning, the researcher launched an empty environment in which the participant could practice using the locomotion technique. The test phase began when the participant felt comfortable using the locomotion technique.

The participant started the test phase in the center of the circle of targets with an initial five second countdown appearing in front of them. Once the countdown finished, they were rotated toward the first target, which turned green, and a 30-second countdown appeared in front of them. They were instructed to move towards the target using the technique they had just practiced, and the countdown, which moved with the participant, indicated how much time they had to move to the target. Once inside the target, a five second countdown appeared indicating how much time was required to stay inside the target before the trial would be considered a "hit" (see Figure 2B). If the participant exited the target before the five-second countdown expired, the countdown disappeared. If they re-entered the target, the countdown restarted at five seconds. The trial was considered a "miss" if the 30-second countdown ended before the participant had stayed inside the target for five seconds. The 30-second countdown was chosen for practical reasons to ensure that the study stayed within a 2.5-hour window.

If the participant failed to move into the target before the 30-second countdown ended, the participant was automatically moved inside the target and rotated towards the next target. We displayed the countdown so that participants were not taken by surprise when they were moved to the next target. If the participant hit the target before the 30-second countdown ended, they were only rotated towards the next target. Participants were rotated toward targets to eliminate the need for visual search. This process repeated for all six targets in the environment and each path between targets was considered one "trial." Six trials were considered one "trial block." For two of the six paths between targets, obstacles appeared, and the participant was instructed to maneuver around them. We introduced obstacles so that participants would have to control their direction, instead of just moving in a straight line. There was no visual, auditory, or haptic feedback if the participant hit an obstacle; they passed through the obstacle and the event was logged. There were 40 obstacles on path 3 and 80 obstacles on path 5 (see Figure 2A). The obstacles were construction materials consisting of workbenches, lighting rigs, and paint cans (see Figure 1A). Obstacles were a range of heights and sizes (e.g., paint cans were small and sat low to the ground while workbenches were wide and at waist height) to reflect a range of obstacles that might appear in a virtual environment.

After completing one trial block, the participant completed a duplicate trial block. The second trial block was the same as the first, with participants navigating to targets in the same order and obstacles appearing on the same paths as in the first trial block. The trial block was repeated twice to get a more accurate estimate of performance measures by averaging out any learning effect.

Next, the participant took off the headset and completed a post-task questionnaire on a laptop. Afterwards, the researcher asked the participant brief questions about their experience using the just-completed technique. Questions included what the participant liked and disliked about the technique, how their impairment affected how they used the technique, how difficult it was to use the technique, and whether they struggled to use the technique at a particular point during the task. After the interview, the user put the headset back on and repeated the process for the next technique. Technique order was counterbalanced via random presentation.

After completing this procedure for all six locomotion techniques, the researcher conducted a final interview in which she asked the participant to compare all six techniques. The participant was asked to choose the most and least comfortable technique, their favorite and least favorite, and the three techniques that they would use in VR consistently. An entire study session took between 2 and 2½ hours.

3.4 Design and Analysis

The study employed a single factor within-subjects design. The factor, *locomotion technique*, had six levels: Astral, Chicken, Grab, Sliding, Teleport, and Throw. Our data set and analysis approaches are explained in the subsections below.

3.4.1 Task Performance Measures. There were three outcome measures per locomotion trial. The first measure was the trial time, in seconds. The second measure was a dichotomous outcome for whether the target was hit or not. The third measure was a count of the obstacles hit. There were 3987 total data points in this study.

Concerning data analysis, mixed models were used to account for repeated measures [21, 22]. Specifically, trial time was analyzed using the nonparametric aligned rank transform procedure [6, 16, 36] with a linear mixed model analysis of variance [8] after verifying the ANOVA assumptions were met. Trial hits (versus misses) were analyzed using mixed logistic regression owing to it having a dichotomous response [11, 31]. Obstacles hit were analyzed using mixed negative binomial regression owing to it having a discrete-count response [17].

3.4.2 Post-Task Questionnaire Measures. The questionnaire consisted of one presence question, which was question #1 from Slater and Steed's [28] presence questionnaire. We only included question #1 because researchers found that this question elicited the most direct response for presence and had high discriminating power [28]. Responses ranged from 1 to 7, with 1 being "not at all" to 7 being "very much" in terms of feeling present. We also included the first question from the Simulator Sickness Questionnaire [19] to measure general discomfort as a result of simulator sickness, and included examples of discomfort (e.g., nausea, dizziness, eyestrain, or vertigo). Responses ranged from 0 being "no discomfort" to 3 being "severe discomfort." Finally, we added five questions from the NASA-TLX workload questionnaire [14]. We excluded the temporal demand question because we did not want the user to focus on the time it was taking for them to complete the task, which might have

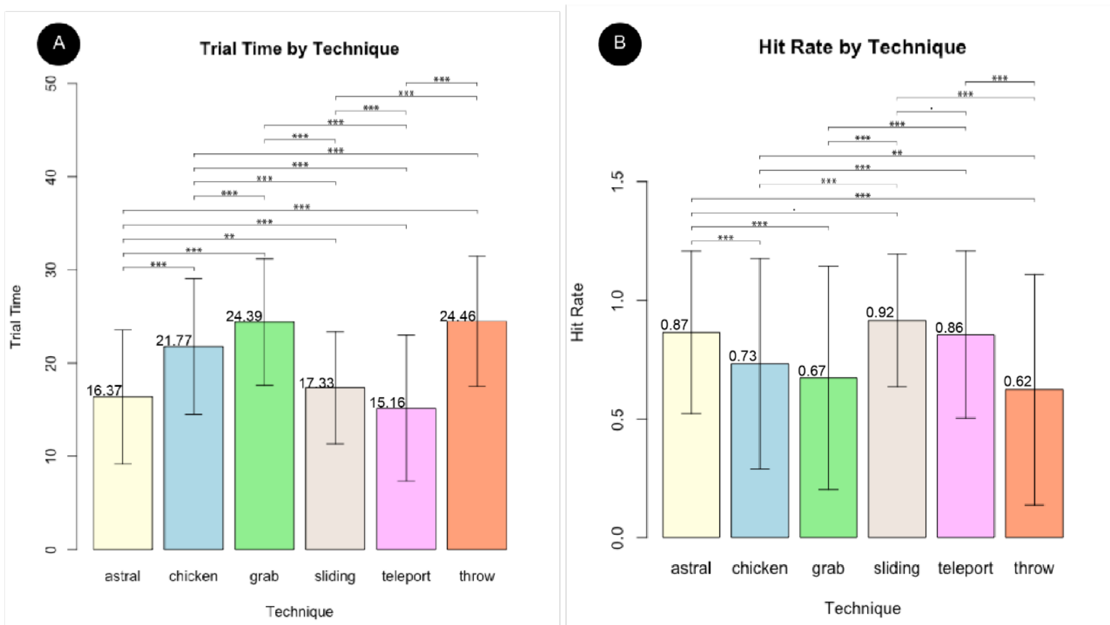

Figure 3: (A) Bar plot of trial time by technique. Lower is better. (B) Bar plot of target hit rate by technique. Higher is better. Means are above the bars. Significance codes: *p*<.001 (***), *p*<.01 (**), *p*<.05 (*), *p*<.1 (.).

induced stress. We adapted the original 21-point scale to a 1 to 7 scale by eliminating the "high," "medium," and "low" increments for each point on the scale to improve readability [13]. There were 114 data points for all questions except presence, which had 112 responses. We analyzed our questionnaire data, all of which were Likert-type scales, using mixed ordinal logistic regression [15].

3.4.3 Interview Data. We conducted post-task and post-study semi-structured interviews with each participant. We transcribed the audio files for the post-task interviews and the final interview for each participant. P09's audio files were unfortunately lost so our results exclude her interview responses. We then performed an inductive thematic analysis by identifying patterns across participant utterances and organizing them by theme [5]. We created eight themes and 51 sub-themes. The third author performed an interrater reliability assessment and achieved a Cohen's Kappa of κ =0.87, indicating strong agreement [20].

4 RESULTS

We report the performance measures, questionnaire responses, and interview responses in this section.

4.1 Performance Measures

We report the results of statistical tests comparing locomotion techniques with respect to trial time, target hits (versus misses), and obstacles hit (a count measure).

4.1.1 Trial Time. To test the normality assumption for a repeated measures ANOVA, an Anderson-Darling test [1] was run on the residuals of a repeated measures full-factorial ANOVA model. The test was statistically significant *(A*=5.62*, p*<.0001), indicating that the residuals did not conform to a normal distribution. Therefore, we used the nonparametric aligned rank transform procedure [16, 36] with a linear mixed model [8] for our trial time analyses.

Figure 3A shows a bar plot for trial times by technique. The fastest technique was Teleport. There was a statistically significant effect of technique on trial time ($F(5, 1277.4) = 161.58$, $p<.0001$). *Post hoc* pairwise comparisons conducted with the ART-C procedure [6], and corrected with Holm's sequential Bonferroni procedure [18], indicated that all pairwise comparisons were significantly different except for Grab vs. Throw ($t(1277.1) = -0.37$, *n.s.*).

4.1.2 Target Hit Rate. Figure 3B shows bar plots for target hit rate by technique. The technique with the highest target hit rate was Sliding. Because targets hit (versus missed) is a dichotomous dependent variable (i.e., it has a value of 0 or 1), we conducted an analysis using a mixed logistic regression model [11, 31]. This test indicated a statistically significant effect of technique on target hit rate ($\chi^2(5, N{=}1209) = 119.76$, $p<.0001$). Pairwise comparisons, corrected with Holm's sequential Bonferroni procedure [18], indicated some significant differences, as shown in the figure.

4.1.3 Obstacles Hit. Figure 4A shows bar plots of obstacles hit by technique. Fewer obstacles were hit with Teleport compared to all other techniques. The data were a count response and followed a negative binomial distribution, so we used mixed negative binomial regression, as is typical for count responses [17]. An omnibus test indicated a statistically significant effect of technique on obstacles hit ($\chi2(1, N{=}1209) = 100.44$, $p<.0001$). Pairwise comparisons, corrected with Holm's sequential Bonferroni procedure [18], indicated some significant differences, as shown in the figure.

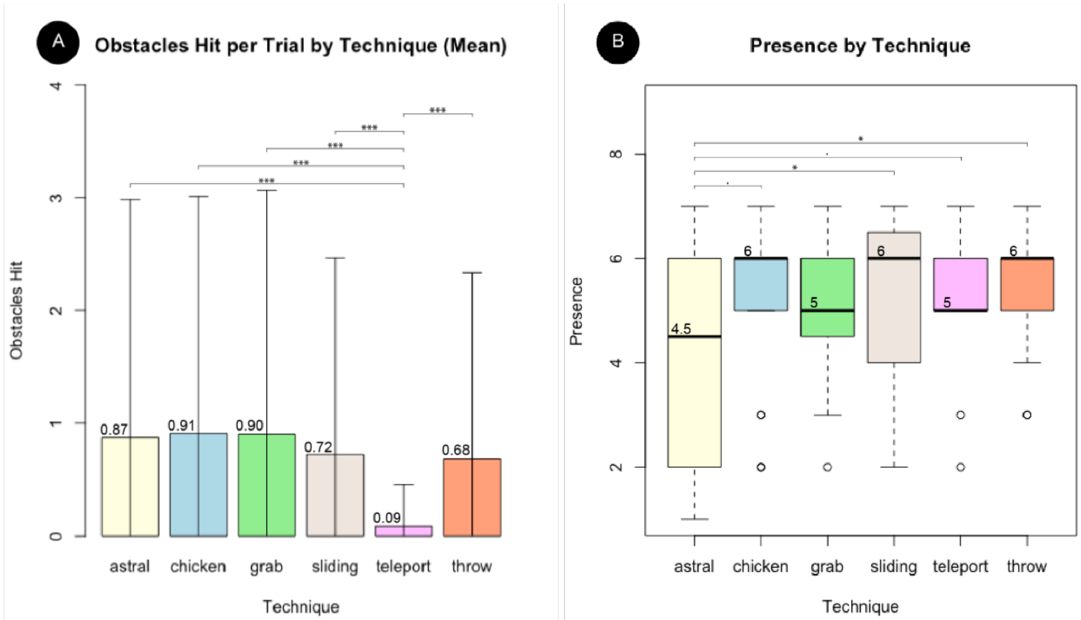

Figure 4: (A) Bar plot of obstacles hit per trial by technique. Lower is better. Means are above the bars. (B) Boxplot of Likert responses for presence by technique. Medians are above and inside the boxes. Higher is greater experienced presence. Significance codes: p<.001 (***), p<.01 (**), p<.05 (*), p<.1 (.).

4.2 Questionnaire Responses

In this subsection, we report the results of statistical tests comparing the locomotion techniques by presence, simulator sickness, mental demand, physical demand, performance, effort, and frustration. All omnibus tests were conducted using an analysis of variance based on mixed ordinal logistic regression [15] and all pairwise comparisons were performed using Z-tests, corrected with Holm's sequential Bonferroni procedure [18].

4.2.1 Presence. Figure 4B shows the distribution of Likert responses (1-7) for presence by technique. Chicken, Sliding, and Throw all had similarly high presence. There was a statistically significant effect of technique on presence ($\chi 2(5, N=19) = 13.70$, $p<.05$). Pairwise comparisons indicated that Likert scores for some comparisons were significantly different, as shown in the figure.

4.2.2 Simulator Sickness. Figure 5A shows the distribution of responses (0-3) for simulator sickness by technique. Grab induced the greatest simulator sickness of all techniques. There was a statistically significant effect of technique on simulator sickness ($\chi 2(5, N=19) = 24.02$, $p<.0001$). Pairwise comparisons indicated that Likert scores for some comparisons involving Teleport were significantly different, as shown in the figure.

4.2.3 Mental Demand. Figure 5B shows the distribution of Likert responses (1-7) for mental demand by technique. Throw had the highest perceived mental demand. There was a statistically significant effect of technique on mental demand ($\chi 2(5, N=19) = 29.71$, $p<.0001$). Pairwise comparisons indicated that Likert scores for some comparisons were significantly different, as shown in the figure.

4.2.4 Physical Demand. Figure 6A shows the distribution of Likert responses (1-7) for physical demand by technique. Grab and Throw had the highest perceived physical demand. There was a statistically significant effect of technique on physical demand ($\chi 2(5, N=19) = 64.67$, $p<.0001$). Pairwise comparisons indicated that Likert scores for some comparisons were significantly different, as shown in the figure.

4.2.5 Performance. Figure 6B shows the distribution of Likert responses (1-7) for performance by technique. Teleport offered the highest perceived performance. There was a statistically significant effect of technique on performance ($\chi 2(5, N=19) = 41.04$, $p<.0001$). Pairwise comparisons indicated that Likert scores for some comparisons were significantly different, as shown in the figure.

4.2.6 Effort. Figure 7A shows the distribution of Likert responses (1-7) for effort by technique. Chicken, Grab, and Throw seemed to require the greatest effort. There was a statistically significant effect of technique on effort ($\chi 2(5, N=19) = 49.48$, $p<.0001$). Pairwise comparisons indicated that Likert scores for some comparisons were significantly different, as shown in the figure.

4.2.7 Frustration. Figure 7B shows the distribution of Likert responses (1-7) for frustration by technique. Chicken, Grab, and Throw were perceived as causing the highest frustration. There was a statistically significant effect of technique on frustration ($\chi 2(5, N=19) = 37.46$, $p<.0001$). Pairwise comparisons indicated that Likert scores for some comparisons were significantly different, as shown in the figure.

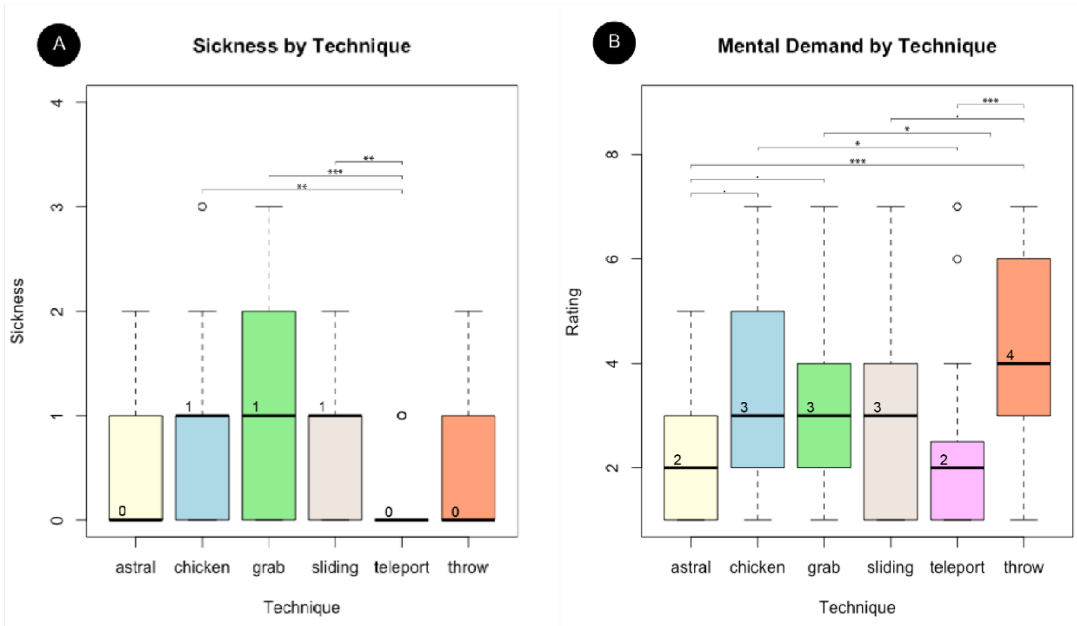

Figure 5: (A) Boxplot of responses for sickness by technique. Lower is less experienced sickness. (B) Boxplot of Likert responses for mental demand by technique. Lower is less perceived mental demand. Medians are above and inside the boxes. Significance codes: *p*<.001 (***), *p*<.01 (**), *p*<.05 (*), *p*<.1 (.).

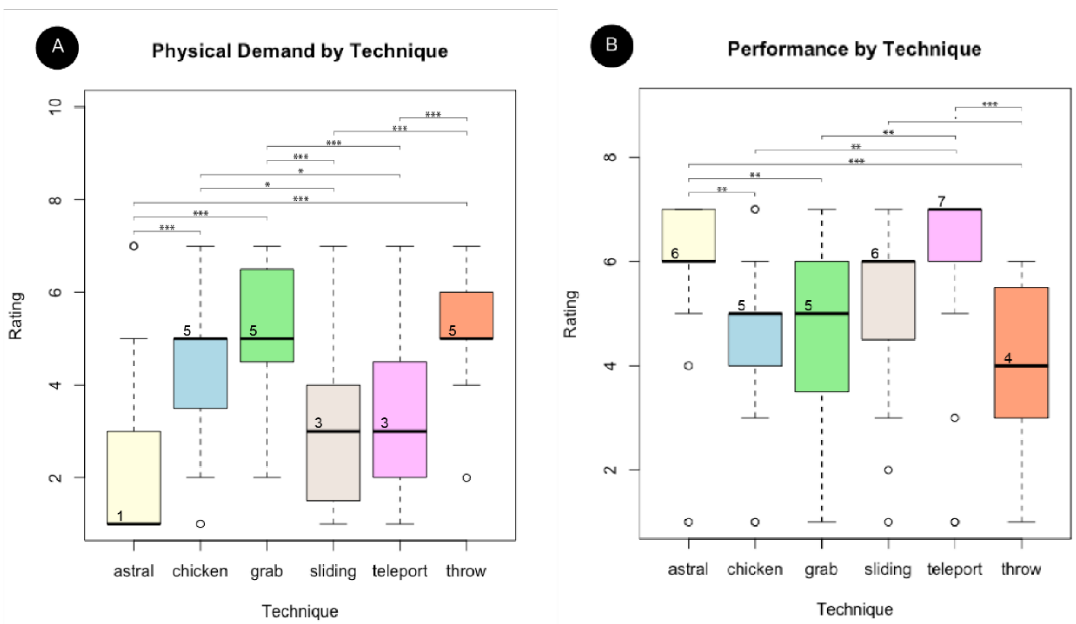

Figure 6: (A) Boxplot of Likert responses for physical demand by technique. Lower is less perceived physical demand. (B) Boxplot of Likert responses for performance by technique. Higher is better perceived performance. Medians are above and inside the boxes. Significance codes: *p*<.001 (***), *p*<.01 (**), *p*<.05 (*), *p*<.1 (.).

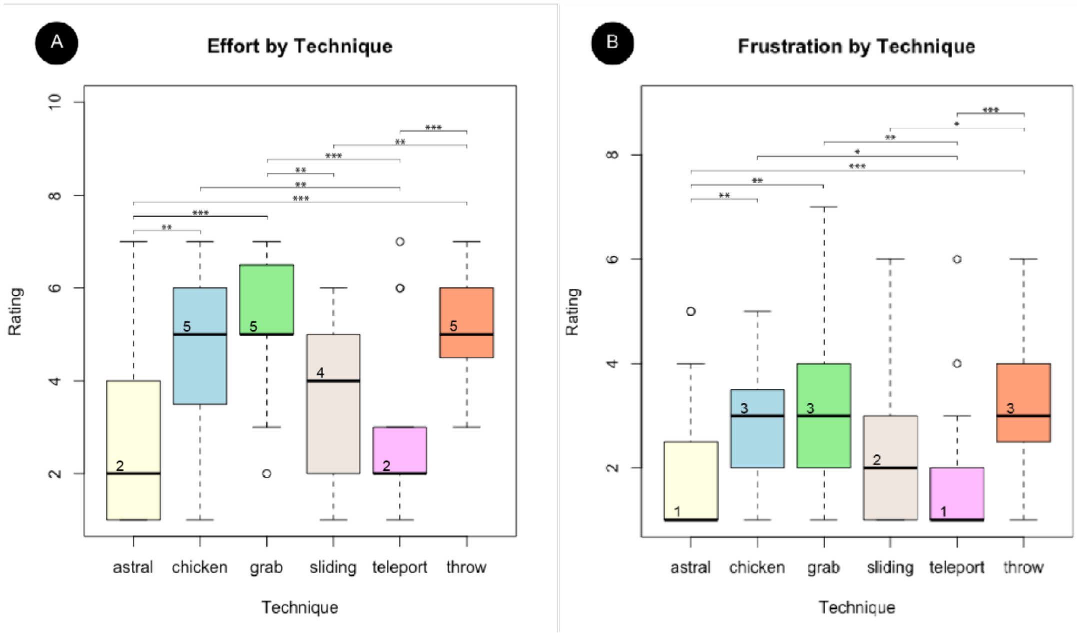

Figure 7: (A) Boxplot of Likert responses for effort by technique. Lower is less perceived effort. (B) Boxplot of Likert responses for frustration by technique. Lower is less perceived frustration. Medians are above and inside the boxes. Significance codes: p<.001 (***), p<.01 (**), p<.05 (*), p<.1 (.).

4.3 Interview Responses

We report interview responses by discussing how participants compared all six techniques, their thoughts on technique accessibility and interaction design, the effect of their impairments on their use of the techniques, their thoughts on overall user experience, and their enjoyment and challenges with the techniques.

4.3.1 Comparison of Locomotion Techniques. Table 3 shows, for each participant, the technique they each felt was most and least comfortable, most and least preferred, and their top three preferred techniques for actual use in virtual reality (VR).

Astral was considered the most physically comfortable technique by most participants (n=8), followed by Chicken (n=4) or Teleport (n=4), and Sliding (n=2). Throw was considered the least physically comfortable technique by the most participants (n=8), followed by Grab (n=6), Sliding (n=3), and Chicken (n=1). Most participants preferred Teleport (n=6) or Chicken (n=6), followed by Sliding (n=3), then Astral (n=2). Most participants liked Throw the least (n=7), followed by Grab (n=5), Chicken (n=5), and Astral (n=1).

Most participants said that they would use Teleport if they were going to use VR (n=7). A smaller group would use Chicken (n=5). Three participants would use Astral and another three would use Sliding. In terms of the technique that they would use second-most, most participants would use Astral (n=7). Other participants would use Sliding (n=5), Teleport (n=3), Grab (n=2), or Chicken (n=1). Finally, most participants would use Throw (n=7) third-most. Other participants would use Sliding (n=4), Teleport (n=2), Astral (n=2), Chicken (n=1), or Grab (n=1). P14 did not like any of the other techniques and would not use a third technique.

4.3.2 Accessibility and Interaction Design. Participants expressed that the controls were easy to use for Astral, Chicken, and Teleport. Astral and Teleport required one button press and Chicken did not require any. Participants also expressed that Astral, Grab, and Sliding gave them a heightened sense of control over navigation. Regarding Sliding, P04 said, "*everything felt a little bit more controlled, and it still felt pretty easy because I was just pressing one button and just moving my head*" (P04). Participants felt that these three techniques were precise, responsive, and made it easy to maneuver around obstacles. Teleport allowed them to navigate the environment particularly quickly and they liked that the teleporter provided visual feedback about where they were going to land after the jump. P12 felt the visual feedback gave her confidence, saying, "*I like the line, like the projection line. That also does help visually, I think. Makes you more confident in utilizing it. Rather than just an arrow showing you where you end up*" (P12).

Some participants expressed that the movements for Chicken and Grab felt natural and intuitive. For Chicken, they liked using their bodies to move forward and control their speed, rather than using their hands. P00 said, "*the more I leaned forward, the faster it went. If I wanted to go to a different direction, whatever direction I looked and leaned, it went to. So, it's so easy*" (P00). Meanwhile other participants expressed that moving forward with their hands felt natural with Grab. For example, P03 said, "*it feels good to virtually move myself without using my wheelchair, but as if I were dragging myself with my arms*" (P03).

On the other hand, participants felt that they had poor control over their navigation with Chicken and Throw. They found it difficult to slow down, stop, and steer with Chicken, while some found it challenging to aim, avoid obstacles, and time the button release with

Table 3: Participant responses to final interview questions comparing the locomotion techniques. "Top 1" refers to the technique they would use most, "top 2" is the second-most, and "top 3" is the third-most.

ID	Most comfortable	Least comfortable	Most preferred	Least preferred	Top 1	Top 2	Top 3
P00	Chicken	Grab	Chicken	Throw	Chicken	Astral	Teleport
P01	Chicken	Throw	Chicken	Throw	Chicken	Sliding	Grab
P02	Astral	Chicken	Teleport	Chicken	Teleport	Siding	Throw
P03	Chicken	Throw	Chicken	Throw	Chicken	Teleport	Sliding
P04	Teleport	Grab	Teleport	Throw	Teleport	Sliding	Chicken
P05	Astral	Throw	Astral	Grab	Astral	Sliding	Throw
P06	Chicken	Throw	Chicken	Throw	Teleport	Chicken	Astral
P07	Astral	Grab	Sliding	Grab	Sliding	Astral	Throw
P08	Sliding	Throw	Sliding	Chicken	Sliding	Grab	Astral
P10	Teleport	Grab	Chicken	Astral	Chicken	Teleport	Sliding
P11	Astral	Sliding	Teleport	Chicken	Teleport	Astral	Throw
P12	Astral	Throw	Astral	Throw	Astral	Teleport	Sliding
P13	Sliding	Astral	Sliding	Grab	Sliding	Astral	Throw
P14	Teleport	Sliding	Teleport	Throw	Teleport	Astral	None
P15	Astral	Sliding	Teleport	Chicken	Teleport	Astral	Throw
P16	Teleport	Grab	Teleport	Grab	Teleport	Astral	Sliding
P17	Astral	Throw	Grab	Chicken	Astral	Grab	Teleport
P18	Astral	Grab	Chicken	Grab	Chicken	Sliding	Throw

Throw. Some participants also mentioned that it was challenging to turn with their heads using Sliding and Chicken. These participants expressed that they could not rotate their virtual body far or fast enough, and that it was difficult to coordinate the head rotation with the thumbstick turn. P07 struggled using these two inputs to change direction with Sliding and said, "*the [head] movements were just very subtle with direction, so I was still very much relying on the thumbstick to change direction*" (P07). Leaning forward to move forward with Chicken felt unnatural for some participants because it did not have a real-life equivalent. Other participants also felt it was unnatural to navigate by throwing a ball with Throw. For example, P17 said, "*it didn't seem fluid. It seemed choppy*" (P17).

The stationary turn with the thumbstick was implemented for all techniques except for Astral because Astral was controlled from a third-person perspective. Many participants struggled to control the stationary turn for a few reasons. First, several participants found the discrete turn disorienting because it instantly changed their viewpoint. Second, other participants wanted finer control over the turn by rotating in smaller increments or continuously. Third, P15 related that since she could only push the thumbstick to the right, she had to push more times and got disoriented during the process. She said, "*if you are impaired going one way, then you have to keep flipping around. And it seems like if you have to move a quarter of a turn to the right and you move the joystick to the right, it seems like it flips you three quarters or one quarter to the left instead of the right. And you have to backtrack. It's kind of weird*" (P15).

4.3.3 Perceived Effect of Impairment. Participants reported that their impairments had an effect on their ability to use all techniques, but particularly on their ability to use Chicken, Grab, and Throw. They discussed either not being able to perform the technique to its maximum capability, or not being able to use the technique how it was intended. For example, P11 used the tilt feature on his wheelchair to mimic leaning back and forth with Chicken. Participants reported that their impairments had little to no effect mainly when using Astral, Sliding, and Teleport.

Some participants could only use one controller because they could not grip it correctly. Instead, they used one hand to stabilize the controller and the other hand to press the buttons (see Figure 1B). As a result, these participants reported difficulty positioning the controller, finding and pressing buttons, as well as preventing their fingers from slipping off buttons. A number of participants noted that the controllers were too heavy, leading to hand-shaking and difficulty performing tasks for extended periods of time. Some participants reported that the headset was heavy and caused discomfort, particularly when using Astral because they had to look down on the environment. P17 reflected, "*the actual exercise of having to look down like that for a long time, especially without a kind of counterweight or just understanding how to have to put it so that it doesn't affect me as much; I still felt out of balance and blurry having to look down*" (P17). Participants felt discomfort in their wrists, arms, shoulders, and necks when using Grab and Throw.

Limited range of motion in the neck affected some participants' ability to use Chicken and Sliding, while limited arm reach and range of motion in the shoulders affected some people's ability to use Grab and Throw. Muscle weakness, especially in the core and arms, also affected some participants' ability to use Grab and Throw. P10 reflected on how core weakness affected her sense of security: "*I don't have a lot of core control, and so the throwing, I think I could have thrown it farther if I felt more secure, like moving more*" (P10).

4.3.4 Overall User Experience. Participants liked that Astral, Chicken, Sliding, and Teleport were not physically demanding. They particularly liked that they had to put in less effort, did not experience pain or discomfort, and only had to use one finger for Astral. P08 liked Astral "*because it was less stressful, less physically demanding. You're just using the thumbstick*" (P08). P04 liked that Chicken was not physically demanding, saying, "*I didn't need to throw my entire body into it. I didn't need to be exerting out of ten in order to get the same response. And so, I like that about it*" (P04).

Participants reported that Astral and Teleport were easy to learn and not mentally demanding to use because they only required one button press to move forward. P12 liked that Teleport required minimal mental effort to plan her route. She said, "*I just know where my destination is after, like, a shorter time, I feel like. So instead of using energy to look for something and decide while I'm moving, I could just decide and then move. [I] feel like it's just faster that way*" (P12).

Some participants verbalized feeling more immersed with Chicken, Grab and Sliding compared to other techniques, even though significant differences did not exist in questionnaire responses. P00 felt more present with Sliding because of the change in visual feedback he experienced when steering with his head. He said, "*I think that the environment is much of a trigger of the visual, and by steering with where you look, it makes you feel like you're in the environment*" (P00). These three techniques were also the only ones that used first-person continuous locomotion in the virtual environment instead of discrete jumps or a third-person perspective. Some participants felt more oriented in space with Astral because they could see all of the environment.

Participants disliked that Grab and Throw were physically demanding, and thought these techniques required too much movement and that the movement was repetitive. Some participants also mentioned feeling like they had not traveled far enough for the level of effort that they put into the technique when using Grab. For example, P15 said, "*It's harder to move. It feels like you should move more per pull*" (P15).

Participants expressed that Chicken, Grab, Sliding, and Throw were difficult to learn, and that they would need time to be able to use the techniques with ease. P00 reflected on Chicken's learnability saying, "*I think there is a little bit of a learning curve. You got to know how to lean and how far to lean. It takes a little bit of adjustment on that, but it's easy once you got the hang of that*" (P00).

A few participants reported feeling less present with Astral and Teleport and likened the experience to playing a traditional video game. With regards to spatial orientation, some participants felt disoriented when using Chicken and Teleport, particularly when they were getting close to the target. For example, about Chicken, P04 said, "*it was sometimes hard for me to tell whether I was successfully in the target, and sometimes I felt like I was sliding out of the target*" (P04). Only three participants discussed simulator sickness, which they felt when using Sliding and Grab.

4.3.5 Enjoyment and Challenge. Some participants enjoyed using Chicken, Grab, and Throw, and said the techniques were entertaining to use. They liked Throw in particular because using it felt like a game and was reminiscent of shooting baskets. For example, P03 enjoyed the physical and mental challenge of Throw, he said, "*the physical activity of it I liked and the challenge of seeing how far I could throw the ball and learning what works better, like a higher arc when throwing the ball. So, figuring out different ways to throw it to get where I wanted to go*" (P03). Participants also liked that these three techniques provided exercise and could be used for physical therapy. For example, P08 liked that he exercised an underused part of his body with Grab: "*It gave me the opportunity to use my left hand more, and I got a good arm workout, obviously, but yeah, it was really good to really manipulate my arms and stuff*" (P08).

Other participants felt exactly the opposite about these same techniques. They said that Chicken, Grab, and Throw were frustrating to use because they moved too slowly, were not mentally stimulating, did not feel a sense of satisfaction, and did not enjoy the repetitiveness of Grab and Throw. A couple of participants mentioned that Teleport was *too* easy to use, which made them feel like they were cheating. P17 said, "*well, it seems like cheating, honestly, because I think the idea is we want our brain to become more keen about visual distance and calculating what we have to do*" (P17).

5 DISCUSSION

Performance and questionnaire data suggest that our six locomotion techniques can be divided into two groups and that techniques within these groups are similar to each other. We discuss these two groups first, then examine how participants ranked techniques, and finally discuss design implications.

5.1 Astral, Sliding, and Teleport are best in terms of performance and workload

In terms of trial time and targets hit, Astral, Sliding, and Teleport were the top three techniques. In terms of obstacles hit, Teleport outperformed all other techniques with the fewest obstacles hit.

The questionnaire and interview data can shed light on why these techniques had the best performance measures. Based on performance and effort responses, participants felt like they needed to work less to be successful using Astral and Teleport. Some participants also explained that the visual feedback of the teleporter helped them avoid obstacles, which is probably why they hit the fewest obstacles with Teleport compared to the other techniques.

Astral, Teleport, and Sliding had significantly lower physical demand scores than Chicken, Grab, and Throw. Participants mentioned that they liked that these techniques required little movement and also caused little to no pain or discomfort. Participants explained that low mental demand scores for Teleport and Astral were a result of only needing to think about a single button input. In addition, the visual feedback of the teleporter helped them aim and plan their route.

Although participants performed well with Sliding in terms of target hit rate, some mentioned that they found it difficult to coordinate the head turn with the thumbstick turn. As a result, they might have rated their performance as worse than it actually was.

Overall, Teleport had the best performance, lowest workload, and was liked for how easy the controls were to use; participants appreciated how fast it was, how easy it was to aim, and how little their impairments impacted their performance. It was also the most popular technique in terms of physical comfort, preference, and the technique that participants would use most in VR. These findings taken together suggest that Teleport was the best technique for this group of participants.

5.2 Chicken, Grab, and Throw are worst in terms of performance and workload

Chicken, Grab and Throw had the worst performance for trial time and target hit rate. They were similarly poor in terms of obstacles hit. Questionnaire and interview data provide insight into why Chicken, Grab, and Throw were the worst in terms of performance. Participants indicated these techniques had significantly greater physical demand than Astral, Sliding, and Teleport. They also reported that their impairments had the greatest effect when they were using these three techniques.

The overall higher workload scores for Grab and Throw might be explained by the fact that participants thought these two techniques were strenuous, slow, and uncomfortable to use. Although participants mentioned that Chicken, Grab, and Throw had a learning curve, only Throw had a significantly higher mental demand score compared to Astral and Teleport. Participants struggled with Throw on many levels, such as coordinating the button release, aiming the ball, and calibrating the distance to throw. All of these challenges could explain the higher mental demand scores for Throw.

5.3 Most comfortable, fastest and least demanding techniques are not necessarily preferred

Participants' responses to the most comfortable technique mostly agreed with the techniques that had the lowest workload and best performance. Teleport was most popular as the most comfortable and preferable as well as the technique most participants would use in VR. Grab and Throw were considered the least comfortable and least preferred by most participants, which also is consistent with performance results and subjective responses.

Despite its poor performance and high workload, however, Chicken was the second most popular technique: it was the most comfortable, preferred, and most-used technique. This finding might be explained by our interview results. Some participants felt that Chicken was easy to use and control because it did not require any controller input or arm movement.

Even though most participants said they would use Teleport most frequently and Astral second-most frequently in VR, which is consistent with performance and questionnaire results, most participants said they would use Throw third-most, even though it was one of the worst techniques in terms of performance and workload. Entertainment might explain why Throw was the most popular choice for this category, since some participants said it felt like a game.

The majority of participants rated Astral as most comfortable but only two chose it as their preferred technique. This result might be explained by the fact that participants felt that the controls were easy to use, but participants also felt less present when using Astral compared to other techniques. Thus, it seems presence affected the preference for a VR locomotion technique.

Seven participants' preferred technique was different than the technique that they thought was most comfortable. Moreover, 10 participants' least preferred technique was different from the technique they thought was least comfortable. This finding suggests that participants weigh trade-offs in accessibility, user experience, and enjoyment when determining their preference for a locomotion technique. While feeling comfortable and performing well are important factors when ranking techniques, other factors can weigh heavily, depending on the participants' individual preferences.

5.4 Design Implications

An implication for locomotion technique design is that using controller button inputs rather than upper limb and torso movement to control the technique would likely lead to better accessibility. Although some participants verbalized difficulty reaching and holding controller buttons, a finding also identified in prior work [25], this challenge did not severely affect performance with controller button-based techniques such as Teleport, Astral, and Sliding. This finding is likely a result of many participants holding one controller with two hands, which highlights the need to enable mapping of bimanual to unimanual interactions [40].

Also, although point and select techniques such as Teleport use some upper limb movement, they are likely to be accessible because, depending on the type of impairment, the user can stabilize their arms while using the techniques. In addition, users can travel further with less input using Teleport compared to other techniques. Some participants liked Chicken because they could control the speed of their virtual movement. Other participants mentioned disliking Grab because they felt like they did not move far with each pull. Designers could add a mechanism to locomotion techniques to control speed or friction so that users feel like they can travel further with less physical exertion, which could improve accessibility. As found in a previous study in which participants with motor impairments struggled to articulate head gestures [33], participants with limited range of motion in their necks struggled to control their direction with Chicken and Sliding. In addition, some participants felt that they were not able to turn quickly enough using their heads. As with speed, designers could enable users to adjust the gain so that a smaller physical head rotation produces a larger virtual rotation.

Another insight is that even though an intended benefit of body movement-based techniques is an improvement in a sense of presence, we did not see this effect. Rather, findings suggest that using third-person perspective negatively impacts presence.

The findings taken together suggest that VR designers should provide an array of accessible techniques for users with upper-body impairments instead of defaulting to the most accessible or best performing techniques. Techniques available to a user should represent a range of mental and physical challenges, presence, and entertainment. Participants' preferences for techniques were based on the task objective and whether efficiency or enjoyment were primary concerns, which has been found in prior work [7, 40]. Identifying where locomotion techniques fall on a range of factors including accessibility requires that researchers and designers evaluate techniques not only on traditional performance, user experience, and workload measures, but also on engagement and entertainment measures. The fact that users evaluate locomotion techniques on multiple dimensions points to an opportunity for personalization. In the future, a system could recommend accessible locomotion techniques to users with impairments based on their abilities and individual preferences, a finding consistent with and endorsed by the concept of ability-based design [37, 38].

6 LIMITATIONS AND FUTURE WORK

Some limitations of this work include that the study setup was simple, limited to seated postures, and limited to controller-based interactions, which could affect the generalizability of results to more intricate setups or complex virtual environments. In addition, even though our qualitative results can point to the effect of impairment on performance, we did not analyze this effect quantitatively. Future work can quantify the effect of impairment type and severity and correlate these measures with performance and preference.

None of the first-person techniques we tested had a built-in mechanism for performing a stationary turn and required the user to push the thumbstick to rotate their view. A main finding from the interviews was that many participants struggled to perform the stationary turn. Some challenges included feeling disoriented after turning, not being able to push the thumbstick, and having difficulty coordinating the thumbstick with other inputs, particularly steering with the head when using Sliding or Chicken. Future work should investigate how stationary turns can be designed for existing locomotion techniques. Design considerations might include which controls to use, how the turn is experienced in the virtual world (e.g., discrete vs. continuous rotation, large vs. small rotation increments, etc.), and how to integrate steering with stationary turning.

7 CONCLUSION

In this work, we compared six locomotion techniques in terms of their accessibility, workload, and other user experience factors. We contribute the first empirical study to evaluate locomotion techniques for 19 people with upper-body motor impairments. Our findings suggest that while participants performed better with some techniques than others, especially the Teleport technique, accessibility was not always the foremost factor when participants chose a technique they preferred and would use in VR—user experience and entertainment factors also played a role. Ideally, designers would be able to recommend a locomotion technique based on knowledge of a user's abilities and preferences and support an extensive range of personalization options to give users the greatest possible flexibility in choice.

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