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WriArm: Leveraging Wrist Movement to Design Wrist+Arm Based Teleportation in VR

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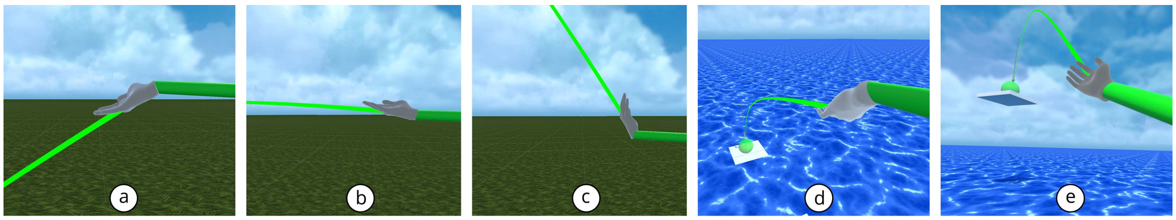

Figure 1: WriArm teleportation technique. (a-c) Third-person views show users' wrist and arm movements to control the parabolic pointer for teleportation in VR. (d-e) A user is using WriArm to teleport to different locations

Abstract

Teleportation, a widely used locomotion technique in Virtual Reality (VR), is used to move users through a virtual environment. Until recently, handheld controllers have been used for teleportation, where users use controllers to point to a location and perform an action (e.g., button press) to be instantly moved to the targeted location. Recent advancements in VR hand tracking enable users to move through and interact with the virtual world without controllers. This opens the opportunity for compelling alternatives to explore hand tracking-based teleportation techniques for more natural, intuitive and immersive interactions. Prior work mostly explores using arm movement for teleportation as an alternative to using the controller. In this paper, we design and evaluate WriArm, a VR locomotion technique that leverages both wrist and arm movement for VR teleportation. We first conduct a design study to find suitable hand gesture sets that can be mapped to teleportation activities such as activation, pointing, confirmation and cancellation for WriArm and arm-based techniques. Based on the results, we conduct a study comparing users' performance while navigating tasks with the two techniques and three gesture sets. Results show that WriArm improves navigation efficiency by allowing users to navigate the environment quickly. We conclude with design guidelines for arm and wrist-based teleportation in VR.

Index Terms: Human-centered computing—Human computer interaction—Interaction paradigms—Virtual reality; Human-centered computing—Human computer interaction—Interaction techniques—Gestural input

1 Introduction

Interaction in Virtual Reality (VR) environments commonly requires users to navigate through a large virtual space while staying fixed in a limited physical space, such as an indoor or tracked area. Locomotion, defined as a self-propelled movement in VR [23], allows users to navigate virtual spaces effectively by minimizing users' movement in their physical spaces. Researchers have explored different locomotion techniques [5, 18, 31, 38, 42, 46, 48], and teleportation has been reported as one of the primary techniques for VR locomotion due to its minimal impact on motion sickness and its general ease of use. Teleportation in VR applications is commonly performed with a physical controller [8], where users point to a teleportation spot with an parabolic pointer (emanating from the controller) and press a button to be instantly relocated [8]. However, prior research showed that holding a physical controller limits natural and immersive interactions, such as manipulating objects in VR, and makes the overall experience less intuitive [9, 51].

Hand tracking capabilities on VR devices, which have improved considerably, enable users to interact with the virtual environment without needing a controller. Consequently, researchers explored controller-free hand-based interactions in VR that offer a natural, intuitive and immersive experience to interact with virtual environments [39, 44]. Prior work explored controller-free locomotion techniques leveraging hand tracking solutions that rely primarily on arm movement to point towards the intended teleportation destination [8, 22, 27, 28, 45, 52]. They also reported that the arm movement limits the teleportation activities, especially when it requires users to be teleported to a higher elevation (e.g., stairs), and impacts overall users' performance [8, 35].

To address this issue, we develop WriArm: a novel teleportation technique that leverages wrist angle in combination with arm movement to provide users with improved control over the movement of the parabolic pointer. More specifically, users can use arms for coarse pointer movements while leveraging wrist angles for fine controlling of the parabolic pointer, thus adding more flexibility for precise control over the pointer for teleportation (see Figure 1). While designing WriArm, we found no prior work exploring suitable hand gestures for initiating and executing key teleportation activities, including pointer activation, pointing, confirmation, and cancellation. Therefore, we first conduct a study with designers exploring suitable hand gestures for WriArm and arm-based teleportation activities. We collect a set of 25 gestures for each teleportation activity and refine the set further by selecting the top three gestures preferred by designers. We further run a user study evaluating the performance of WriArm and arm-based pointing in teleportation tasks with three gestures. We used tasks where users are required to navigate a VR environment with varying distances, directions and

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heights. Results show that WriArm is significantly faster than the arm-based technique.

Our paper has three major contributions. The first contribution is WriArm, a novel hand-based implementation for teleportation in VR. In WriArm, a user can leverage their wrist movement (i.e., flexion/extension, radial/ulnar deviation) to control the teleportation parabola - which has not been explored in the context of VR teleportation. Our second contribution is the exploration of suitable gesture sets for hand-based teleportation. We are the first to propose a set of gestures that can be used as an alternative to controllers for teleportation sub-activities: activation, pointing, confirmation and cancellation. Our third major contribution is the investigation of Arm and WriArm in conditions where targets are placed at varying distances, elevations, and angles in combination. To our best knowledge, combining all three factors to explore hand-based teleportation has not been explored in previous work.

2 Background and Related Work

We review prior work that has explored ways to design locomotion in VR, which we review first. We then review gesture- and teleportation-based locomotion in VR. These earlier projects inspired the design of our WriArm.

2.1 Locomotion in Virtual Reality

Locomotion is considered one of the most common tasks in VR [6]. Researchers explored different locomotion techniques allowing users to navigate large spaces in VR environments in a limited physical space. For instance, Slater et al. [46] proposed *Walking-in-place* technique that allows users to travel inside the VR environment by moving their feet up and down without moving around in their physical environment. They showed that *Walking-in-Place* provides a higher sense of immersion than *Flying* technique, where locomotion is done by pushing a button to fly in the direction the hand is pointed at. Usoh et al. [48] proposed a technique called *Real walking*, where the participants were able to walk freely in a 10m $\times$ 4m physical environment where their movement was mapped 1:1 to the VR environment. They conducted a user study to evaluate users' perception of presence where the study results showed that *Real walking* offered better immersion compared to *Walking-in-place* technique. They also reported that users had to adjust the virtual space with a controller when they reached the end of the physical space to continue navigating in the virtual world (while reorienting themselves for walking in the physical world). To make unlimited walking possible in a limited physical environment, Razzaque et al. [42] proposed *Redirected walking*, where users implicitly walk in a circular path to navigate in the virtual environment. Results from a user study showed that *Redirected walking* allows users to turn more naturally compared to *Real walking*. Rietzler [43] proposed a modified redirected walking technique, *Telewalk*, which enables unlimited walking in a room-scale environment (3m $\times$ 3m), whereas the previous redirected walking methods required larger than room-scale environments.

Bozgeyikli et al. [8] introduced *Point & Teleport* in VR, which is an adaptation of the *Jumper metaphor* [5]. In this technique, a user points in a straight line (i.e., linear pointer) to a destination in VR and waits two seconds to be instantly moved to that location. They conducted two user studies comparing their techniques to other existing techniques, where results showed that their technique is intuitive and easy to use for locomotion in VR. Though the linear pointer showed benefits, the curved parabolic pointer became the most commonly used standard locomotion technique for commercial and general-purpose VR experiences and games [22, 35].

In a recent work, Cherni et al. [12] compared 22 locomotion techniques and found that *Teleportation* with hand gestures and *Real Walking* were the most preferred locomotion techniques based on immersion and motion sickness. In another work, Rietzler et al. [43] revealed that *Teleportation* has a lower level of motion sickness and requires less time to reach the final destination compared to *Redirected walking* [43]. This is also confirmed in [21], where they revealed that *Teleportation* causes the least motion sickness and provides users with an equal level of spatial information in VR [50] compared to other locomotion techniques. Consequently, in our work, we focus on facilitating a controller-free *Teleportation* technique for locomotion.

2.2 Gesture-based Locomotion in Virtual Reality

VR devices are now equipped with cameras that can track a user's hands and environment. Consequently, researchers leverage hand-tracking solutions to explore hand-based interaction as an alternative to the physical controller for VR locomotion. Mine [37] proposed one of the earliest works on hand gesture-based navigation techniques, where the user's hand position and orientation are used to set the direction and orientation of the user's movement in VR. Pie et al. [39] showed that the hand-based locomotion technique produces less motion sickness and lower task load while having a similar level of naturalness and immersion as *Walking-in-place*. Researchers also revealed that gesture-based locomotion techniques are more intuitive than using physical controllers such as a joystick [28].

Researchers also explored different hand gesture-based locomotion techniques in VR. For instance, Ferracani et al. [19] designed and compared four gesture-based locomotion techniques: *Walking-in-place*, *Swing*, *Tap* and *Push*. Their study results showed that Tap, where the index finger is used to point and walk in a particular direction in VR, provides higher accuracy, lower fatigue and higher perceived immersion than other explored techniques. Chastine et al. [11] investigated a gesture-based navigation technique where users' movement in VR depends on the relative distance between their palms and a Leap motion device. With a user study, they found that the gesture-based technique performs poorly compared to Keyboard+Mouse and Gamepad. In addition, participants expressed their concerns about maintaining the index finger pointed for a prolonged time. Zhang et al. [52] used the Oculus Rift along with a Leap Motion sensor to implement a double-handed gesture-based navigation technique, allowing users to turn easily while walking. However, compared to the gamepad-based navigation and *Portal* (i.e., gamepad-based teleportation), the gesture-based navigation technique did not perform well when considering the mean travel time.

The effectiveness of a hand-based interaction in VR depends on various factors such as fatigue level, naturalness, gesture speed and gesture accuracy [1]. Intuitiveness, learnability and ease of use are also essential factors [47] for designing an appropriate gesture to perform a task. Cissé et al. [14] worked with designers to elicit 64 mid-air hand gestures for locomotion in VR. They evaluated the gestures based on five criteria to design a suitable design for a gesture set to perform two-handed locomotion. Sampson et al. [44] took into account the limitations of Leap motion sensors and designed a hand gesture set for navigation and interaction in VR environments. They suggested using gestures distinct from unconscious movement so that they do not trigger an unintended action (i.e. the Midas touch problem) [44]. Researchers explored ways to solve this issue by using a delimiter, which is a specific action to define the start and end of a gesture [36]). However, to our best knowledge, there are no formal studies exploring different navigation-related activities such as activation of teleportation (i.e., delimiter), navigation, confirmation of teleportation and cancellation, which are common in locomotion. Consequently, we run a design study exploring suitable gestures for navigation-related activities.

2.3 Teleportation-based Locomotion Techniques

Currently, teleportation is widely used for locomotion in VR applications [3]. Bolte et al. [5] first introduced the concept of teleportation with a *Jumper metaphor*, where users look at a location for 500 milliseconds to initiate the *Jump* to the desired location. Bozgeyikli et al. [8] introduced a locomotion technique called *Point & Teleport* that tracks a user's hand and shoulder to determine where the user is pointing. Once the user points at a location for 2 seconds, they are teleported to that location. The authors compared *Point & Teleport* with existing walk-in-place and the gamepad-based locomotion techniques. Results showed that *Point & Teleport* causes less motion sickness than the other two techniques. In a follow-up study, Bozgeyikili et al. [7] compared different locomotion techniques, which included *Gamepad*, *Walking-in-place*, *Redirected walking*, a *Stepper*, *Trackball* and hand gesture-based techniques. The study showed that *Gamepad* and *Point & Teleport* are the two preferred techniques based on user ratings. Langbehn et al. [30] compared *Gamepad*, *Teleportation* and *Redirected walking* in a Virtual Environment, and they revealed that *Teleportation* and *Redirected walking* are preferred over Gamepad as it causes motion sickness. Although *Walking-in-place* methods improve the presence of the user, it is less efficient (i.e., higher task completion time) than other locomotion techniques based on the study results. Funk et al. [22] redesigned two novel teleportation techniques based on *Point & Teleport* while using a curved trajectory and compared it with *Linear Teleport* and *AngleSelect Teleport* [8]. The results showed that the new techniques reduced users' need to reorient themselves but had a higher task completion time. Schäfer et al. [45] compared one-handed and two-handed teleportation techniques and concluded that the one-handed technique had a lower task completion time and required less teleportations to reach a destination. Therefore, we decided to explore one-handed teleportation in our work.

In a more recent work, Matviienko et al. [35] compared three variations (i.e., instant, interpolated and continuous) of linear and parabolic pointing-based teleportation. Instant transitioning with linear pointing achieved the highest accuracy and the lowest completion time. Rietzler et al. [43] reported that users experience spatial disorientation in instant teleportation. However, they referred to a prior work [13] highlighting that the participants reported minimum disorientation with instant teleportation compared to gaze-directed and continuous locomotion. Therefore, we include instant teleportation in our design. However, we argue that linear pointing will be ineffective in most virtual reality scenarios that include elevation (e.g., Mountainous terrain, stairs). In addition, the current implementation of arm-based teleportation is not flexible enough to navigate an environment with different elevations (e.g., stairs) [35]. Consequently, we designed a new technique, WriArm, allowing users to navigate an environment with varying distances and altitudes.

3 Design Study

The goal of our work is to explore controller-free hand-based teleportation techniques for VR. While exploring teleportation in VR with the standard controller, we observed the following common teleportation sub-activities:

- Activation: refers to the action that initiates the teleportation process. Once an action is performed, the controller emits a ray from the device, indicating that the user can start teleportation in the VR environment.
- Pointing: in VR, locomotion is commonly done with virtual ray casting, where the controller controls the origin, destination and orientation of a ray in a similar way to manipulating a laser pointer. By changing the controller's position and orientation, a user can adjust the destination (i.e., where to teleport).
- Confirmation: is the action that causes the user to teleport to the destination defined by the ray casting pointer. The user can commonly issue a confirmation by pressing a button on the controller. Once a confirmation action is triggered, the user is teleported to the destination.
- Cancellation: is the action to deactivate the ray that is initiated during the activation process. Once the cancellation is triggered, the user has to activate the ray again to continue navigating. On a controller, cancellation is commonly performed by pressing a button.

We found that arm-based teleportation was used widely in previous work [7, 8, 13, 45] and thus used it in our exploration. Our key goal was to explore hand-based teleportation in VR without requiring handheld controllers. We explored controller-free hand-based teleportation as next-generation headsets (e.g., Cambria [2]) have begun including hands-only control for tasks, which warrants further investigation into this form of input for VR teleportation.

We are unaware of any prior work that generates a catalog of hand gestures designed explicitly for the above teleportation sub-activities. Therefore, we first explore hand gestures that can be used for controller-free teleportation in VR.

Wrist and hand movements can offer many gesture options that can be mapped to teleportation activities. To limit the number of options, we reviewed prior work [10, 15–17, 32, 34, 41, 44, 49] focusing on user elicited hand and finger gestures for mobile, AR and VR interactions. Consequently, we come up with a set of 21 hand and finger gestures that are commonly reported in prior work. We then elicited designers' input to gain initial insights on gestures suitable for controller-free teleportation.

Figure 2: Selected gesture sets for teleportations after the design study

3.1 Participants and Procedure

In order to determine suitable gestures for teleportation sub-activities, we first ran a design session. For recruiting participants, we sent invitations to HCI/Interaction design and media studies-related labs at a local university. Eight graduate students (ages 21 to 32, 1 Female, mean age 28.13, SD 3.48) who have experience with designing and developing AR/VR applications, participated in the study. We selected this group as they are familiar with design theory and its processes. None of the participants were aware of the design of the study. Due to the surge of the Omicron variant of Covid-19, sessions were conducted online via Zoom as a precautionary measure. Each session lasted around 30 minutes.

Instead of having participants rate each and every option, we let the participants produce three gesture sets, each set containing four gestures – one for each teleportation sub-activity. They were asked to try different gestures by themselves first and decide on gestures that they would prefer to use for the teleportation sub-activities. Participants were also instructed to add any new gestures if they did not find a desired gesture on the slides. We structured the design session in two phases.

In the first phase, we explained the goal of the session, how teleportation sub-activities work and how these activities are commonly performed with the standard controller. We then presented participants with slides showing the possible gestures via Zoom. Textual descriptions (e.g., “Fist” or “Pinch”) of each of the gestures were also displayed. We instructed them to perform a gesture and its possible variants before selecting it as the preferred gesture for a navigation sub-activity. In the end, each participant provided us with a minimum set of three gesture sets, each containing four gestures – one for each navigation sub-activity. Their gesture preferences were collected using a Qualtrics form. Each session took approximately 20 minutes to complete.

We collected a total of 25 gesture sets from the participants. As we want to evaluate users’ performance with the gesture sets for teleportation activities, we took steps to find a small set which can be investigated further with a user study. Two authors analyzed all the submitted responses from participants to find a small gesture set by (i) removing the repeated gestures for the same sub-activity, (ii) eliminating the gestures that cannot be captured with the VR headset’s embedded cameras while avoiding any detection issues (e.g., occluded fingers) and (iii) avoiding sets that require significant hand/finger adjustment to switch between navigation sub-activities. For example, flipping the arm and closing the fingers to switch from pointing to confirmation requires considerable changes in the arm/fingers and are thus ignored. Figure 2 shows the five gesture sets selected during the process. In the second phase, we sent these 5 gesture sets to the eight participants who participated in the first phase. We asked them to first perform the set by themselves, then provide their preference of the gesture sets on a 5-point Likert scale and add a justification of their ratings in a Qualtrics form.

3.2 Results

Figure 3 shows participants’ preference ratings across the gesture sets. We conducted a Friedman test where the results showed no significant differences on ratings across the gesture sets ($\chi^2(4, N = 8) = 4.61, p = 0.33$).

However, we found that Set 3 (mean 3.50), Set 4 (mean 3.25) and Set 1 (mean 3.00) had higher user ratings than Set 2 (mean 2.25) and Set 5 (mean 1.75). Participants commented on Set 2 and Set 5, expressing their concerns with these two sets. For instance, one participant commented, *Set 5 feels like it requires a lot of effort and forethought*. Another participant mentioned, *Set 5 was tough to remember*. In addition, one participant commented, *[for set 2] it feels like initialization and navigation are switched for what is intuitive*. Therefore, we decided to move forward with Set 1, Set 3 and Set 4 and explore users’ performance with these sets.

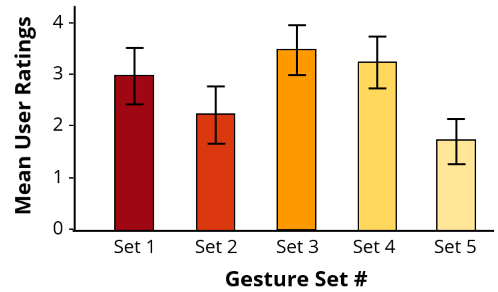

Figure 3: Participants’ preference ratings across the gesture sets

4 Techniques

There are several ways to display the teleportation pointer; the most common is showing the ray as a straight line or a parabola. As the parabolic pointer is the standard in most commercial applications and widely used in pointing techniques [4, 12, 20] in controller-based methods, we use it for designing controller-free hand-based teleportation techniques.

For manipulating the position of the parabolic pointer in the VR environment, we considered multiple controller-free input sources. In the exploratory phase, we examined the gaze, arm, wrist and the tip of the index finger as the pointer manipulation source. During pilot sessions, we found that consistently holding the finger stable in mid-air for precise pointing is difficult due to jitters. In addition, the gaze pointer caused nausea and motion sickness. Therefore, we excluded these two sources from our exploration.

Prior work on hand-based teleportation relies on arm movement [7, 13, 28, 52] to point towards the intended teleportation destination. Researchers revealed that only arm-based solutions are not optimal for teleportation, especially when it requires users to move to a higher elevation (e.g., stairs), and impacts overall users’ performance [7, 35]. Wrist input can act as a complementary input to arm input while extending the ability to control the angle of the parabolic pointer using the wrist’s angle. In addition, we noticed that the wrist offered more control for precise pointer movements, while the arm provided rapid and larger pointer movements. Consequently, we decided to explore the combination of both wrist and arm for controlling the pointer. Finally, we narrowed down our exploration to the following two techniques:

- Arm: In this technique, the arm’s position (from a reference point) is used for moving the teleportation pointer. To allow users to reach a positive or negative elevation, we use the height of the arm from a base position (i.e., the arm in a position with the elbow at a 90° angle) to create an angle to calculate and draw the parabola. Once the arm is in the base position, we consider the angle as 0°. As the arm moves up or down from the base position, we increase or decrease the angle values. With a pilot study, we find a suitable mapping between the arm height and the angle values, making it possible to reach the most heights and distances while the arm position is still comfortable. If the arm is lower than the base position, the parabola source is pointed downwards, allowing for teleportation to low or short destinations. Conversely, if the arm is higher than the base position, the parabola is pointed upwards, allowing for teleportation over elevated or farther destinations (see Figure 4).

- WriArm: In this technique, the arm’s position is only used as the position for the source for the parabolic pointer. Therefore, lifting or lowering the arm is used to control the height of the

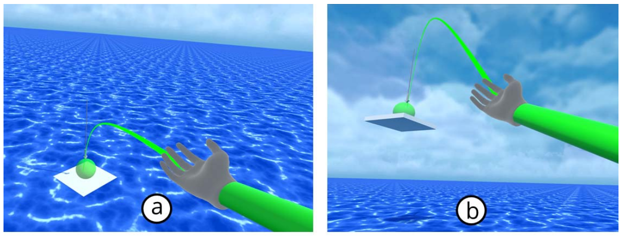

Figure 4: (a-b) Arm-based teleportation technique.

pointer. Wrist here acts as a secondary input, further extending the ability to control the angle of the parabolic pointer using the wrist's angle itself. We consider the straight wrist being parallel to the ground as the 0° (i.e., base position). Once users move their wrists upward (i.e., extension), downward (i.e., flexion), left (i.e., radial deviation) or right (i.e., ulnar deviation), we calculate the angle of the wrist from the base position and use this angle to determine the source angle of the parabolic pointer. With this added angle, comfortable adjustments of the pointer can be made using the wrist angle, and higher and lower destinations can be reached without lifting or lowering the arm. In essence, the arm controls broad pointer movements, and the wrist angle controls the angle of the pointer origin, thus assisting in reaching higher and lower elevations and precise pointer movements.

We calculated the points using the following formula to draw the parabola:

$$y = \frac{1}{2}at^2 + v_0t + y_0$$

y = height, t = time in seconds, a = acceleration due to gravity, v0 = initial (starting) velocity, y0 = initial (starting) height. We used Unity's built in physics engine to set the angle at which the projectile that represents the pointer is initially launched.

We took some additional steps to improve the usability of the parabolic pointer. We observed that controlling pointers with the arm and wrist trigger jitters due to unintentional arm and hand movements in mid-air. To tackle this issue, we first applied moving average filters to make the pointer movement smooth without any noticeable delay. More specifically, we took the four most recent frames from the height of the arm and six from the wrist angle for the filter. Then we apply a threshold to this data to filter out small jitters from the data. In addition, performing the confirmation gesture naturally produces some sudden movement of the pointer, which can potentially cause users to teleport to a different location than their intended destination. As this movement is sudden and creates a rapid spike in the data, we ignore this movement by checking the historical data (i.e., the last two seconds of tracking data) to find the last stable position of the pointer before the sudden movement. We further use this information to teleport the user to the previous stable pointer position.

5 User Study

The goal of this study is twofold: (i) compare our wrist-based navigation technique, i.e., WriArm, to the standard arm-based technique, Arm, and (ii) find a suitable gesture set for teleportation. With knowledge of three preferred gesture sets from the design study, we then evaluated these three gesture sets as well as the two techniques for teleportation in a VR environment.

5.1 Participants

We recruited 12 participants aged between 20 to 41 (M = 27.5, SD = 5.92), of which 2 were female. Participants were recruited through word-of-mouth from a local university. 10 out of 12 participants reported that they had prior experience using Virtual Reality Headsets. We ran the user study in person in early May 2022 when we saw a return to "normalcy" after Covid-19.

5.2 Apparatus

We used the Oculus Quest 2 as the head-mounted display for our study. Instead of using marker-based or external motion tracking solutions for hand tracking, we used headset cameras to track the hand. We used MRTK SDK with Oculus SDK for hand tracking. We used Unity 3D (2020.3.33f1) as the primary development software with C# scripting to design and develop the gesture sets, techniques, and the virtual environment. We used the MRTK to track the position of key points on users' hands, such as knuckles or fingertips, in real-time. We used this information to implement three gesture sets selected in the design session. An Oculus link cable was used to run the application on a computer during the development phase. However, the studies were conducted directly on the Quest 2 headset itself, with the application running on the headsets, without any cables or computer connections, representing real-world usage. The data logged during a study session was automatically transferred from the Oculus Quest 2 to a Cloud-Firestore data base.

5.3 Tasks and Procedure

Our study involved each participant standing in an empty 3×3 metre space using a Quest 2 with no controllers. Participants were instructed to stand in the centre of the space and remain there while performing the study. Participants performed a set of teleportation tasks where they were required to use a gesture set and a technique to navigate in the VR environment. Each teleportation involved participants navigating from their current location to the next location. The next location was determined based on the following:

Distance: Prior work used different teleportation distances for investigating teleportation techniques. For instance, in Skyport [35], authors used 7m, 14m and 21m distances to represent an average, a distant and a very distant point (requires multiple teleportations) to teleport to. In *Point & Teleport* [8], the authors used 2m and 4m distances, as their goal was only to evaluate the usability of the technique. For hand gesture-based teleportation, Schafer et al. [45] used a fixed distance of 10m. Note that none of these prior works included heights as a parameter while designing their study. With a pilot study, we found that 5.5m is a suitable near distance, and 11m is a far distance that can be reached via a single teleporation considering different heights. Therefore, we included 5.5m and 11m teleportation distances in this study. Note that we did not include a distance that required multiple teleportations as we were interested in exploring the performance of the techniques with a single teleportation, and multiple teleportations is the repetition of a single teleportation multiple times.

Height: Most of the previous works did not explore height as a factor for teleportation activities. Recently, Matviienko et al. [35] explored heights as a factor in their study where the teleportation destinations were positioned vertically up or down. Our study considered height and distance in conjunction, allowing the teleportation destination to be placed in more realistic positions. We did another pilot study where results showed that users could comfortably reach up to 5m height when the destinations are placed at the maximum distance (i.e., 11m). Therefore, we used the heights of 2.5m and 5m.

In our study, we used teleportation tasks where users were required to traverse on the same plane (heights from 0m to 0m), going up (from 0m to 2.5 or 0m to 5m) and going down (from 2.5m to 0m or 5m to 0m). Use used these heights in combination with horizontal distances (i.e., 5.5m and 11m).

Teleportation Angle: Instead of showing the destination points directly in front a users' view, we placed them at random angles between -45° and +45°. We placed the teleportation destinations to the left or right (i.e., negative and positive angles) while ensuring that no two consecutive teleportations were placed in the same direction to reduce directional bias. We also made sure that users had to move their heads a maximum of 45 degrees to locate the next teleportation point quickly.

We used a red semi-transparent sphere (in Figure 4) of 1m in diameter to represent the teleportation location (i.e., target location). We placed an arrow above the sphere pointing down towards it to make the location more visible from a distance. In addition, we added a white 1.5m×1.5m platform to give the user the feeling of standing on a platform instead of floating in space which is unrealistic and can trigger some users' fear of heights. The combinations of height and distance were randomly selected to display the next target location while ensuring every combination appeared with equal frequency and the random angles always went left to right and vice versa. Only one target location was visible to the user at a time, with the next checkpoint only appearing after a successful teleportation.

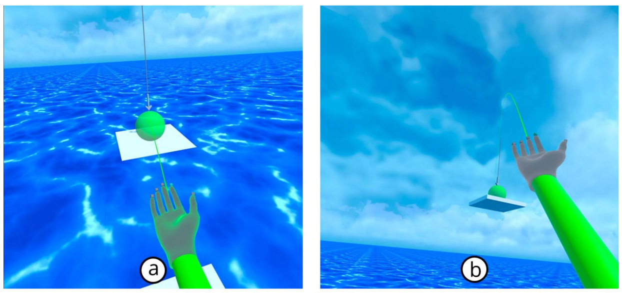

Figure 5: Teleportation height and distance. (a) The user needs to teleport from 0m to 0m height with a distance of 5.5m and (b) from 0m to 5m height with a distance of 11m.

5.4 Design

Each trial involved the participant teleporting from their current location to the target location. Participants began on an initial flat platform where they were asked to use a technique and a gesture set to teleport to the target location. Participants were instructed to point at the sphere and use a confirmation gesture to teleport to the target location. When participants aim the parabolic pointer at the sphere, the color of the sphere and the parabolic pointer change from red to green, indicating that they are successfully aiming at the target. They can now use the confirmation gesture to teleport to the target location. Assigning confirmation gestures to the non-target locations was disabled (similar to VR games). Performing the confirmation gesture triggers audio feedback to users, teleports them to the location and makes the next destination point visible.

We used a within-subject design with two independent variables: *Technique* with 2 levels (Arm, WriArm) and *Gesture Set* with 3 levels (Gesture Set 1, Gesture Set 3, and Gesture Set 4). As mentioned before, *Distance* and *Height* were randomly selected and we used 2 *Distance* (i.e., 5.5m and 11m) and variations of five *Height* (from 0m to 0m, from 0m to 2.5m, from 0m to 5m, from 2.5m to 0m and from 5m to 0m). Both distances were repeated for each height to create 10 unique teleportation destinations. We randomized the presentation order of the teleportation destinations to avoid any order bias. However, we ensured that there were no inconsistencies in heights for two consecutive teleportations. For instance, once a user teleported from 0m to 5m, the next teleportation was always started from 5m (See Figure 5). Each destination was repeated eight times – generating 80 teleportation tasks (i.e., 80 trials) per *Technique* × *Gesture Set* combination. The presentation order of *Technique* was counterbalanced across participants and *Gesture Set* was selected randomly. Otherwise, for a fully counterbalanced presentation order consisting of two techniques and three gesture sets, we would have had to recruit a large number of participants. Thus, for practical reasons we only counterbalanced on the key factor, i.e., Technique.

Each participant was first given a brief introduction to the study, which provided an explanation of the basic concepts of locomotion, teleportation and the hand gestures. We then explained the first *Technique* × *Gesture Set* combination assigned to the participants and provided a set of practice trials (i.e., 20 trials) with the assigned combination. After finishing the practice trials, they were given 80 trials with the combination. We provided them with a 1-minute break after 40 trials to avoid any substantial arm fatigue. After completing the trials (i.e., 80 trials), they were provided with a 3-minute break. We repeated this process with the next *Technique* × *Gesture Set* combination until they had finished all the combinations. Each participant completed 2 *Technique* × 3 *Gesture Set* × 10 *Distance-Height* Combination × 8 repetitions = 480 trials. We arrived at this number by running a pilot study, where we ensured that the entire study could be completed within a reasonable time (i.e., 1 hour), without hand and arm fatigue, while collecting a decent data set. Once they were done, participants were asked to fill out a questionnaire to collect their demographic information and feedback on the *Technique* and *Gesture Set*. In addition, we used the Virtual reality sickness questionnaire (VRSQ) [29] to evaluate the techniques. We collected feedback from the participants using the questionnaires after finishing all the combinations – allowing participants to compare and contrast the techniques – which is used in many prior works [24, 25, 40] but adapted to our work. Note that each session lasted approximately 1 hour.

5.5 Results

We used trial time as the dependent variable in our study, where trial time is the time taken to teleport from a location to the destination. In addition, the questionnaire provided subjective measures of the participants' preferences, perceived speed, accuracy, fatigue and ease of use on each gesture set and technique, along with the VRSQ providing insight into any motion sickness or simulator sickness caused by the techniques.

5.5.1 Trial time

We used a two-way repeated measures ANOVA and post-hoc pairwise comparisons to analyze the mean trial time. Results showed that *Technique* had significant effects on checkpoint time ($F_{1,11} = 6.42$, $p < 0.05$, $\eta^2 = 0.37$). Figure 6a shows the mean trial time (in seconds) across *Technique* × *Gesture Set*. Results showed that users were significantly faster at teleporting with WriArm (mean 2.35s) than Arm (mean 2.59s).

Results also revealed that *Gesture Set* had significant effects on trial time ($F_{2,22} = 4.69$, $p < 0.05$, $\eta^2 = 0.30$). Post-hoc pairwise comparisons between gesture sets showed that users were significantly faster with gesture set 4 (mean 2.38s) than with gesture set 1 (mean 2.64s) and gesture set 3 (mean 2.39s). There were no other pairwise statistically significant differences.

Figure 6b shows the mean trial time (in seconds) across *Technique* × *Height*. In general, users were faster with WriArm than Arm when traversing straight, going up or down, except for going from 0m to 5m. We observed that Arm (mean 2.52s) and WriArm (mean 2.52s) had comparable performance when going up from 0m to 5m. We also found that both techniques required more time when going down from 5m to 0m. We believe that these are due to the maximum height (i.e., 5m) used in the study. In addition, we did not find any significant differences in the VRSQ total score according to the techniques. In the subjective feedback, participants did not report any issues related to motion sickness.

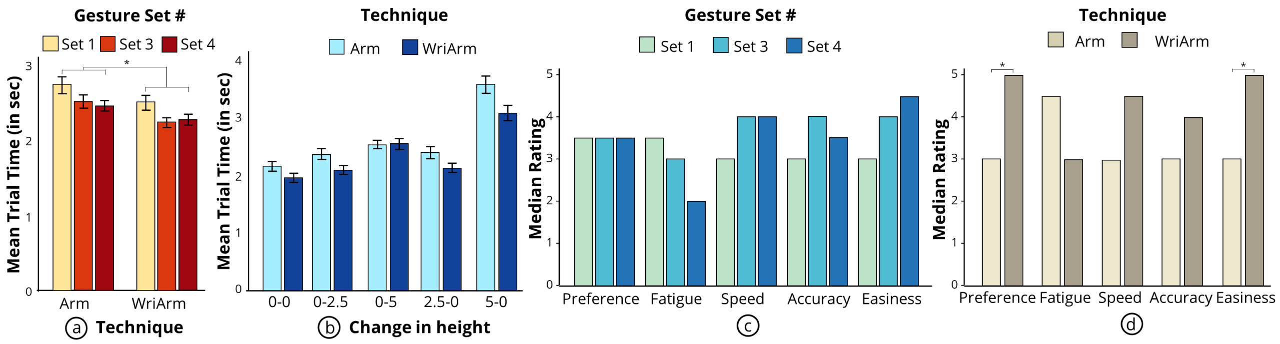

Figure 6: Study results. Mean trial time (a) across the techniques and gesture sets. Results showed that *Technique* had significant effects on trial time where users were faster at teleporting with WriArm than Arm as indicated by asterisks (*). We observed that *Gesture Set* had significant effects on trial time where users were faster with gesture set 4 than with gesture set 1 and gesture set 3. Mean trial time for (b) distance and height (in seconds). Users' provided feedback on their preference, fatigue, speed, accuracy and easiness on a 5-point Likert scale across (c) three gesture sets and (d) two techniques. We observed that that users' ratings for WriArm was significantly higher than Arm on user preference and easiness as indicated by asterisks.

5.5.2 Participant Feedback

We collected users feedback on their preference, fatigue, speed, accuracy and easiness on a 5-point Likert scale for *Gesture Set* and *Technique*. Figure 6c shows the median ratings for the three gesture sets. A Friedman test showed no significant difference among the sets ($\chi^2(2, N = 12) = 5.91, p = 0.05$). We also received participants subjective feedback on all three gesture sets with positive comments on gesture set 3 such as, it (i.e., gesture set 3) *"...was intuitive and caused less fatigue"* [P3], *"... seemed better for selections"* [P7]. In addition, one participants commented, *"I found Gesture Set 1 to be surprisingly intuitive when using WriArm. However, Gesture Set 4 was also intuitive and caused less fatigue than Gesture Set 1"* [P4]. Participants also indicated more fatigue with Gesture Set 1 - *"The confirmation gesture of Gesture Set 1 was easy to perform at first. However, ongoing use of that gesture was causing my hands to become a little sore."* [P2]

Further, we conducted Wilcoxon Signed Ranked Tests to analyze users feedback on the *Technique*. We use Cohen's interpretation of 0.1: small, 0.3: medium, and >0.5: large effect. Figure 6d shows the median ratings for the two techniques. Results showed that WriArm, with a median rating of 5, was significantly different from Arm (median 3) on users preference ($z = -2.38, p < 0.05, r = 0.69$) and easiness ($z = -2.31, p < 0.05, r = 0.67$). There were no other pairwise statistically significant differences. However, we observed favorable mean user ratings with WriArm for all other categories – fatigue: WriArm 2.92 vs. Arm 4.17 where a lower value indicates less arm fatigue, speed: WriArm 3.92 vs. Arm 3.50 where a higher value suggests faster a technique and accuracy: WriArm 3.83 vs. Arm 3.42 where a higher value indicates a more accurate technique. In addition, participants felt that WriArm is *more natural*, *more intuitive* and thus is an *overall preferred* technique.

6 DISCUSSION

The WriArm technique, which combines both arm movement and wrist angle for pointer control, resulted in significantly faster performance than the Arm technique. Users also performed better on Gesture Set 4, which we attribute to the simplicity and ease of the pointing and confirmation gestures, as they are the most frequently performed gestures. The difference in pointing and confirmation of Gesture Set 1 and 4 are only in the orientation of the palm of the hand, which indicates that having the palm facing up is more natural and faster for mid-air pointing. The subjective feedback showed that participants preferred the WriArm technique and found it easier and more intuitive. Prior research has reported arm fatigue and 'gorilla arm'-issues related to arm-based interactions [26]. Since WriArm involves arm movements, it also causes arm fatigue. However, as the parabolic pointer can be controlled with subtle wrist movement, it helps minimise concerns related to arm fatigue. Consequently, we observed that the WriArm technique caused less fatigue than Arm, on average, even though no statistically significant difference was found.

We analyze the key insights from our results and present them as a guideline for designing future hand-detection based VR interactions and teleportation techniques.

- Techniques: Designers should consider providing users with more flexible control over the teleportation pointer. Using the flexibility of the wrist's movement to provide additional control over the parabolic pointer allowed faster, easier and more comfortable navigation to high, low and distant destinations. This establishes that even though arm input is suitable for coarse movements, incorporating wrist movement would allow fine, faster and easier control of the parabolic pointer, especially for practical environments with varying elevations and distances.

- Gesture Sets: A gesture set should be used for complex interactions such as teleportation, where users have to perform different sub-activities using separate but cohesive gestures. Our results showed that these gestures could affect the overall task performance. Therefore, users should have easy and fluent control to switch between them. In addition, we suggest designers consider explicit gestures rather than using timeout-based selection (e.g., dwell [33, 35]) to allow users more control over the confirmation and to better represent real-world usage.

- Gestures: Our study results showed that some gestures were rated higher than others. Therefore, designers should consider including the gestures which are preferred by participants. For instance, simpler gestures with small movements are better, especially when an action is to be repeated frequently. We found that the gesture sets that used simple and small movements were preferred by designers for frequent tasks (e.g., confirming the teleportation). We also observed that users performed better with these gestures and experienced less fatigue.

- Elicitation: We suggest using domain experts to find suitable gesture sets. Our experimental results showed that the top two gesture sets (i.e., gesture set 3 and 4) preferred by the designers also received higher ratings by users for speed, accuracy, ease and lower ratings for fatigue. Therefore, we recommend designers consider recruiting domain experts as participants while running any design study.

- Task Design: Realistic tasks are more suitable for evaluating locomotion techniques. Our results show that using realistic task designs that consider a combination of factors such as elevation changes, distances, and the angle of travel can all be used to evaluate the realistic performance of locomotion techniques. Additionally, we found that when using small hovering platforms, some users' fear of falling was triggered because they could see to far over the edge. Using larger platforms largely solved this issue.

7 Limitations and Future Work

In our study, we used a post-study questionnaire to gather subjective feedback from participants about arm fatigue on both of the techniques; however, a quantitative measure of arm fatigue [26] can be considered for future studies. We asked participants to stand in a location during the study while completing the teleportation tasks. Although interaction in the standing posture provides users with more immersive and engaging experiences, the sitting posture offers the user higher levels of safety, comfort and accessibility [53]. Future work could consider both standing and sitting conditions for evaluating teleportation techniques. Hand-based teleportation such as WriArm may raise privacy concerns in public places as hand tracking is done via the device's front-facing cameras, which also capture users' surroundings. For example, the device might record other people sharing the public space, thus violating their privacy without their consent. Consequently, future studies need to investigate users' and by-passers privacy concerns. In addition, a Fitts' law study could be conducted in the future to compare selection performance. This would provide a clear indication of how people trade speed for accuracy using hand-based techniques in VR compared to other devices.

We acknowledge the disproportionate ratio of male to female participants in our design session and also in our user study. Additionally, all of the participants are from the North-American region. For future studies, feedback from participants of other genders and from varying regions may be incorporated, which will improve the diversity of the participants. Our study focused solely on the parabolic pointer as it is used widely in teleportation and is more intuitive for the users [22]. However, recent studies have explored teleportation techniques that use different pointer types (e.g., Linear pointer [35]) and provide additional features (e.g., allow users to select their orientation after a teleportation [22]). Further studies are needed to evaluate the performance of our improved wrist-based technique on different types of pointers mentioned above. Finally, we created a generalized technique applicable to all users, irrespective of their physical characteristics (e.g., body height, arm length). Future studies can explore ways to create personalized teleportation techniques that optimize the technique to suit users based on their distinct characteristics.

8 Conclusion

In this paper, we designed and evaluated WriArm, a novel wrist and arm-based teleportation technique for VR. With a design study, we first explored suitable gesture sets that can be used with WriArm and arm-based pointing techniques for teleportation. We further evaluated the techniques in combination with the gestures through a user study where results showed that using the movement of both the arm and the wrist (i.e., WriArm) results in faster, easier and more preferred teleporting performance. We also report that gesture sets with natural poses and smaller movements perform faster and are preferred for frequent actions. As hand tracking becomes a common feature of commercially available headsets and grows more prominent in VR applications, our results could inspire designers to consider including natural and immersive hand-based interactions for virtual reality.

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