Podoportation: Foot-Based Locomotion in Virtual Reality

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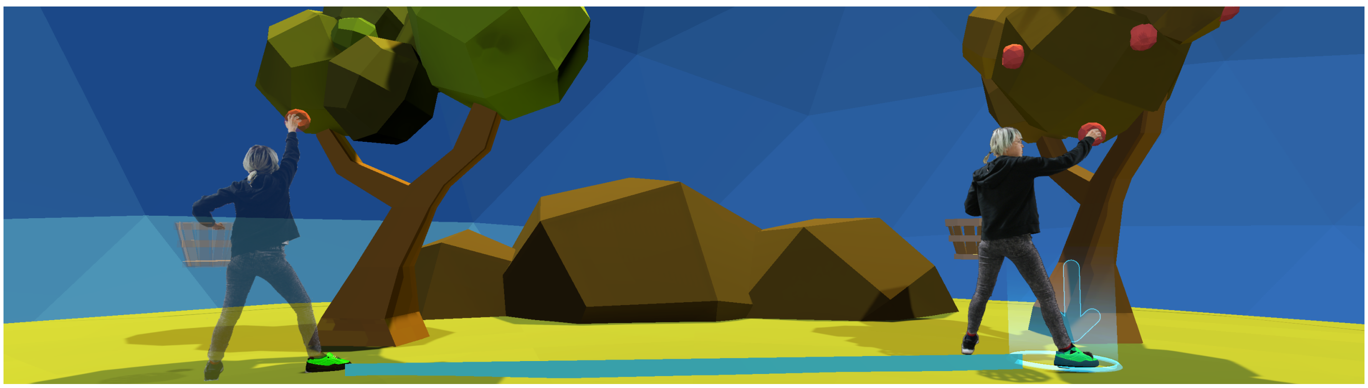

Figure 1. A person in Virtual Reality, using their feet for teleportation while simultaneously using their hands for interaction.

ABSTRACT
Virtual Reality (VR) allows for infinitely large environments. However, the physical traversable space is always limited by real-world boundaries. This discrepancy between physical and virtual dimensions renders traditional locomotion methods used in real world unfeasible. To alleviate these limitations, research proposed various artificial locomotion concepts such as teleportation, treadmills, and redirected walking. However, these concepts occupy the user's hands, require complex hardware or large physical spaces. In this paper, we contribute nine VR locomotion concepts for foot-based locomotion, relying on the 3D position of the user's feet and the pressure applied to the sole as input modalities. We evaluate our concepts and compare them to state-of-the-art point & teleport technique in a controlled experiment with 20 participants. The results confirm the viability of our approaches for foot-based and engaging locomotion. Further, based on the findings, we contribute a wireless hardware prototype implementation.

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•**Human-centered computing** → **Virtual reality;** *User studies; Interaction devices;*

INTRODUCTION
While Virtual Reality (VR) allows for infinitely large spaces, the real-world space the user's physical body resides in is usually limited. This discrepancy needs to be overcome using artificial locomotion. Current approaches in standard consumer applications rely mainly on third party controllers or the two controllers present with most VR devices on the market. Locomotion is either realized via direct motion or teleportation, both rely on button inputs and controller or head-mounted display (HMD) positions.

However, the hands are usually used for interaction, the head for exploration, and feet for locomotion. While hands and head can naturally be used for their real world purposes in VR, feet are still a neglected input modality. In this paper we explored possible input modalities relying on feet for locomotion input, to more naturally distribute task to the users' interaction habits.

An established group of approaches utilizing feet for locomotion in VR is redirected walking. Locomotion relying on redirected walking lets the user explore the world around them freely by walking around. However, the user's walking path is altered to direct them back towards the center of the tracking space, by imperceptibly altering their point of view.

Although additional hardware aiming to improve virtual locomotion is available, it is specialized[1], bulky[2], expensive [11], or any combination of these. They offer either walk in place locomotion or advanced force feedback for seated experiences.

In this paper, we present an approach aiming to tackle the task of locomotion in VRs by providing a walking inspired interaction method relying on the user's feet. Furthermore, the minimal augmentation still allows for natural walking alongside the presented teleportation based approach. By utilizing the user's foot rotation, placement or shift in weight we enable movement independent from the user's current visual focus, allowing for more natural interaction.

We evaluate multiple methods for determining the distance and direction of teleportation in VR with regards to accuracy, efficiency and usability. Additionally, we compare our approaches to the currently widespread controller-based teleportation methods.

While determining a best option is difficult due to the variety of VR applications, we provide viable combinations that can be specifically adjusted to a given application. In our study, participants took longer and the Raw NASA Task Load Index (RTLX) was higher, compared to hand-based point & teleport. We are confident that training with our proposed input modalities can improve the Task Completion Time (TCT) and task load, as participants felt confident they could improve given time to practice. For many applications, especially games, slower but intuitive foot-based locomotion could be a worthwhile trade-off. Users could also benefit from their real world experience such as using their hands while walking, to more efficiently interact with the virtual world.

RELATED WORK

A variety of different approaches aim to address the problem of limited available space in VR [6, 8].

Virtual Reality Locomotion

Utilizing **specialized hardware** to closely mimic the locomotion used in VR is a method to reduce the discrepancy between virtual and real world [58, 26]. This can, however, rarely be used in a different context.

Pressure sensors can be used directly for **Center of Pressure** based locomotion. The Center of Pressure can either be mapped directly to movement [24, 28, 26, 55] or to abstract actions [10, 12, 55]. Similar effects can be achieved by tracking the user's body and react to changes in posture [15].

An alternative is **Walking in Place** employing a similar to walking motion which does not move the user, such as arm swinging [59] or mimicking walking [52, 54, 5]. A more natural approach is countering the user's movement [41] by moving them or holding them in place [11, 51]. Such approaches leave the hands free for interaction, the indirect movements, however, can induce motion sickness [35, 30, 44]

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

[2]https://www.infinadeck.com/

Abstract actions for locomotion allow users to stand in place while moving in the virtual world. This can be achieved by simply **Pressing a Button**, **Head Tilting** [53] or **Gaze** based locomotion [29]. However, the further an action is removed from the resulting motion, the higher the risk of cyber sickness [33].

Users can also be tricked into walking in circles, known as **redirected walking**. This approach requires big, open spaces since the user's path can only be slightly altered. A recent implementation incorporating Electronic Muscle Stimulation succeeded in reducing the required area [2], however, this still requires larger than typical living room dimensions.

Scaling of natural movement is another method to deal with limited space. This can be achieved by enlarging the user [31, 1], scaling movement [25] or exaggerating specific motions such as jumping [7]. These approaches, while reducing the required space, do still rely on rather large space, usually not available in the average home.

Finally, we have **Teleportation**, allowing users to travel arbitrary virtual distances without moving in the real world. Current approaches for teleportation rely on the user's **Hands for Input** [19, 9] occupying them and hindering interaction. Set Locations for static portals [18] can also be used, this, however, is inflexible, allowing users to only teleport from one position to another. **Gaze** [34] can be used here, however, this binds the user's view to their movement, only allowing them to explore in the direction they are traveling.

Considering the insights detailed above a good VR locomotion technique should use teleportation to minimize cybersickness, disconnect the user's gaze from their direction of travel and leaves their hands free for interaction. One technique able to address all characteristics mentioned is foot-controlled teleportation. Using teleportation reduces cybersickness, employing the user's feet keeps their hands free and allows them to move independently from their gaze and hands.

Foot-based interaction

The topic of foot-based interaction is very well covered and examined [57] especially in the field of operating industry machines [3, 4, 14, 32, 45]. Foot-based interaction can be found in seated [56], standing [47, 42] and walking context [61], all with their respective use cases. Often times, foot pedals or similar hardware is used for foot-based input in such industrial applications.

For many use cases, discrete actions as opposed to continuous inputs suffice. Many models exist, mapping different foot gestures to specific actions thus forgoing the need to install foot pedals or buttons [16, 17, 37, 43, 40]. In the case of accurate teleportation in VR however, discrete actions will not work, thus rendering classification approaches moot.

Apart from foot pedals, there are many other implementations of standing, foot-based interactions. Kicking, for example, can be used either in a mobile context [21, 36] or for large displays [27] to trigger events, even if the user's hands are occupied. Due to the sudden nature of kick motions however,

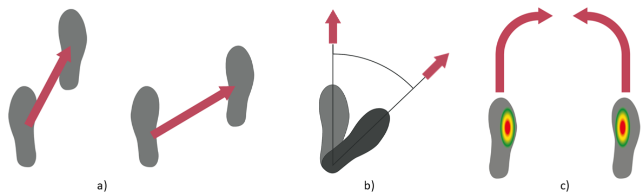


Figure 2. Illustration of the different direction input methods. a) ***inter feet direction*** **b)** ***foot direction*** **c)** ***Point and lean***

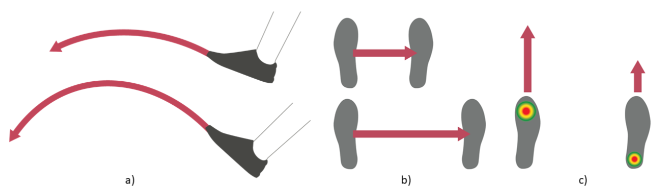


Figure 3. Illustration of the different distance input methods. a) ***forefoot lift*** **b)** ***inter feet distance*** **c)** ***intra foot pressure***

these are not well suited for accurate, continuous interaction such as steering movement in VR.

When using feet as input devices, many features can be leveraged. Relative position or movement between the user's feet, for example, [50] is an interesting feature to utilize. A single foot can also suffice for input, just the position and orientation of a single foot [36, 38] can produce the discrete input, depending on the situation. Finally, an individual foot's pressure distribution can be leveraged as input modality [39]. All approaches have their own benefits and disadvantages when it comes to our proposed interactions technique. For this reason, we included interaction methods for both in our experiment.

Foot-based interactions can also be combined with other modalities such as head movement [49] or gaze [20, 46]. As mentioned earlier, gaze-based interaction comes with its own disadvantages when it comes to VR locomotion when capturing the user's focus. For this reason, we refrained from using gaze as an input modality for our teleportation parameters.

FOOT-BASED TELEPORTATION CONCEPTS

In this section, we introduce our input modalities for distance and direction. We decided to only augment one foot with pressure sensors which we denote as *active* foot. For the sake of comparability, this was also always the right foot.

Input

Since feet are naturally mapped to movement they are a prime suspect for VR locomotion. Utilizing them also leaves the user's hands free for other interactions. Lastly, foot movement is disconnected from head movement to a degree, allowing users to move independently from their current visual focus. Therefore, we propose and evaluate foot-based locomotion techniques relying on teleportation for reducing cybersickness. We implemented multiple modes of input for the direction in which the user will teleport and for the distance of the teleport.

Taking an abstract look at teleportation, we find it can be defined by a distance and a direction. The different features that feet can produce are orientation, position and pressure distribution. We developed three distance and three direction metaphors, relying on these foot features. Since the feet are occupied performing inputs and we wanted to keep the user's hands free, a head nod detection is used to trigger the teleport.

We will now present our proposed input modalities. For directional input we devised three different methods, relying on geometric input metaphors to achieve a direct mapping.

Inter feet direction The first method incorporates the passive foot as point of reference. The teleportation direction is defined by the vector from the passive to the active foot as seen in Figure 2 a).

Foot direction This method for determining the direction of teleport is to point the foot in the desired direction as shown in Figure 2 b). For this approach the pointing direction of the active foot determines the direction of the teleport.

Point and lean The point and adjust approach uses a similar scheme to the *foot direction* approach, extending on the general idea. The direction the foot is pointing to determines the primary teleport direction. The user can fine tune this direction by shifting their weight on the active foot left and right as seen in Figure 2 c). This weight shift results in small adjustments in the corresponding direction.

The teleportation distance metaphors borrow poses found in regular walking motions and established VR input modalities.

Forefoot lift This approach aims to mimic the known hand controlled teleport method by using a similar parabola metaphor. By lifting the forefoot, the starting angle of the parabola is determined, similar to controller based teleportation. This parabola's intersection point with the floor is used to determine the teleport distance. The parabolas trajectory is driven by a simple function, aimed to emulate the baseline's parabola. Figure 3 a) shows a schematic representation of this input modality.

Inter feet distance For his approach the distance between the active foot and the passive foot is determined and scaled to input the desired teleport distance (see Figure 3 b)). This borrows from the walking metaphor by implying larger steps, which result in faster movement, for longer teleportation distances.

Intra foot pressure In this method, the distance of the teleport is determined by the ratio of pressure under the active foot. If the user applies more pressure towards their toes, the resulting teleport will span a bigger distance. This modality is loosely based on the human joystick concept [22], matching pressure in the forward direction to distance of the teleport Figure 3 c) further illustrates how this input method works.

Prototype

To realise the *point and lean* and *intra foot pressure* input modalities, the prototype needs to track the user's Center of Pressure (CoP) in 2D. For every input modality except *intra*

Figure 4. The inside of our prototype with two visible sensors (left), the top sole with the four pins (middle) and an example of how the prototype is worn (right)

foot pressure, we need to track the user's foot position and rotation. In the case of *inter feet distance* and *inter feet direction*, the position of the second foot is also required.

The pressure distribution was tracked by four pressure sensors under each foot, Figure 4 shows the internals of the prototype. For this setup, we used FSR 400 thin pressure sensors, and an ESP WROOM 32 for processing and communication. The pressure sensors were placed in four grooves in the 3D-printed sole and covered with a 3D-printed plate with matching feet which fit in those grooves. By using this slot and pin concept, distortion stemming from direct contact of the two sole parts, without any pressure sensor, was minimized.

The feet's orientations and positions were tracked using off the shelf SteamVR trackers affixed to the participants feet. On the active foot, the tracker was attached to the prototype, on the passive foot we used a simple strap since we only needed the position and not the CoP. The foot orientations were initially calibrated using know points of reference in real space.

Visualization

We decided to adapt the visualizations to the respective input modalities and metaphors. As a result, visualisations for the different teleportation techniques are combinations of individual visualizations of the different input modalities. Their look is based on the that of the default teleport (see Figure 5), with a light blue line ending in a circle with upwards fading walls and a downward pointing arrow in the center. In every case the distance inputs provide the Z (forward) and if applicable the Y (upward) portions of the resulting path to the target. The directional inputs provide the X (left/right) portion of aforementioned line.

Since *forefoot lift* uses a parabola to determine the teleportation distance, similar to hand based teleport, we decided to communicate this to the user. However, only the Z and Y coordinates of the parabola were used, since the X coordinate was governed by the direction adjustment input modality it was combined with.

For *intra foot pressure* and *inter feet distance* the teleportation distance was represented by a simple line with matching length.

The *point and lean* method provided a straight line for 90% of the total distance, stemming from the foot's directional input. The pressure adjustment, only providing a comparably small adjustment, was visualized by curving the last 10% of the line to the left or right according to the given input.

For *foot direction* and *inter feet direction* approaches provided a simple, straight line in the matching direction.

Depending on the different direction adjustment methods, the resulting visualization line starts at either the passive or the active foot. For both, the *foot direction* and *point and lean* approach, the starting point was the active foot, for *inter feet direction* it is the passive foot. These root points were chosen to closely match how the direction is determined in order to make it easier for the participants to understand the respective input method.

METHODOLOGY

To evaluate our concept, we conducted a controlled experiment with 20 participants. In particular, we assessed the accuracy, efficiency and usability of our concept. As a baseline, we used the point & teleport technique. With the experiment, we aim to answer the following research questions. First, we consider the accuracy:

RQ_1 Which combination of foot based teleportation inputs delivers the best accuracy?

- RQ_{1A} Which direction input delivers the best accuracy?
- RQ_{1B} Which distance input delivers the best accuracy?

The following research questions consider efficiency:

RQ_2 Which combination of foot based teleportation inputs delivers the best efficiency?

- RQ_{2A} Which direction input delivers the best efficiency?
- RQ_{2B} Which distance input delivers the best efficiency?

We present the research questions that consider the usability:

RQ_3 Which combination of foot based teleportation inputs is the most convenient?

- RQ_{3A} Which direction input is the most convenient?
- RQ_{3B} Which distance input is the most convenient?

Finally, we want to compare our concept to the baseline:

RQ_4 How do the foot-based teleportation input modalities compare to point & teleport?

Design

In the experiment, we compared all possible combinations of our three directional and three distance input modalities. This results in nine conditions. The baseline of point & teleport forms the tenth condition. We opted for a within-subject design to be able to compare the different conditions with the same participants. The condition order was counterbalanced using Balanced Latin Square to mitigate for sequential effects.

As task, we instructed the participants to teleport to targets spawning in front of them. We specifically told them to teleport as close as possible to the target's center. To provide a frame of reference in the Virtual Environment, we used a low

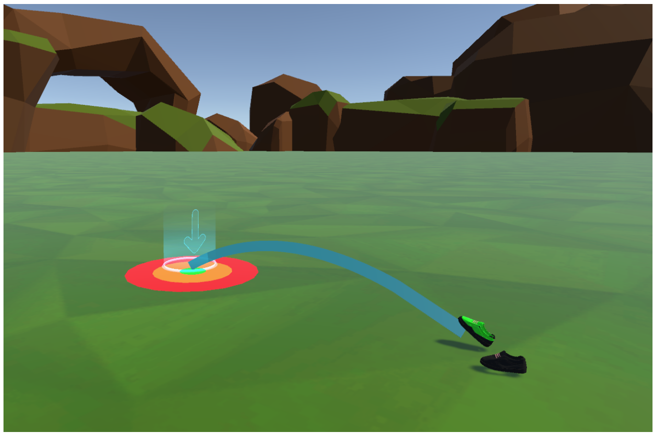


Figure 5. Screenshot of our testing environment, showing a target and a teleport being performed.

poly Virtual Environment. The teleportation targets were kept in a similar visual style, providing a visual representation of the center point (see Figure 5).

In each condition, we presented 15 targets at a distance of $2m$, $6m$ and $10m$. To evaluate the directional adjustment, we spread them out from -60° to 60° in front of the participant. The targets' positions were randomized to avoid learning effects. Participants were told that the targets could only spawn in a specific area in front of them. The study setups consisted of a $2m \times 2m$ SteamVR tracking space, using SteamVR tracking 1.0, two Vive Trackers and an HTC Vive with one standard wand controller. The test application was written in Unity3D, using the standard SteamVR plugin from the integrated asset store. Furthermore, we used an HTC Vive as VR HMD with a Deluxe Audio Headstrap.

The independent variables in our experiment are the input modalities for *distance* and *direction*, based on the concepts presented above. We logged the time participants took to confirm the teleportation movement after spawning the current target and how often participants teleported to assess the efficiency. We recorded their final offset to the current target to asses the accuracy.

We used RTLX questionnaire to access the perceived task load. To gain a deeper understanding of the participants' perceptions, we asked additional questions. In particular, we asked about their perceived convenience of the teleportation technique and how accurately they reached the targets in their view (see Figure 8). The answers could be given on a 5-point Likert scale (1: strongly disagree, 5: strongly agree).

Procedure

The procedure of the controlled experiment was as follows:

1) Welcome and Demographics. We commenced by welcoming the participants and explaining the study's purpose. Then, we detailed which data is collected during the experiment and asked them to sign a consent form. Afterward, the participant provided demographics and reported their VR experience.

2) Calibration. We proceeded by calibrating the pressure sensors for each participant by logging the minimum and maximum values while lifting the foot then placing it down, leaning left, right, forward and backward. The minimum and maximum were recorded for each sensor. We used this information to obtain a center of pressure for the foot.

3) Interaction. We asked the participants to the targets as detailed above. We furthermore allowed the participants to adjust their final position by walking. Once they were confident that they reached the target, participants could accept their current position by pressing the controller's grip button. after confirmation, the participants were reset to the starting position. This allowed them to return to a neutral stance. The spawning of a new target could be initiated by another press on the grip button. After each condition, we asked the participants to fill out the RTLX questionnaire and to give answers to the additional questions.

4) Interview. After the interaction with all conditions, we conducted semi-structured interviews. We specifically asked the participants whether they liked or disliked any aspect of the interaction. We employed open-coding for the answers given and used representative quotes when more than half of the participants agreed on a fact.

Participants

We recruited 20 participants by word-of-mouth and snowball sampling. 13 identified as male, six identified as female and one as non-binary. The age of the participants ranged from 20 to 31 ($Mean = 26$, $SD = 3.27$). Concerning their VR experience, five participants reported to be experts, two considered their experience as above average, seven as average, five as below average and one participant used VR for the first time.

Analysis

To analyse our data, we first used means for 2-factorial analysis to uncover significant effects within the levels of the two factors of our design (*direction modality* and *distance modality*). Second, to compare our methods to the baseline Point&Teleport method, we used 1-factorial tests comparing the baseline to our nine combinations.

For the 2-factorial analysis, we analyzed the recorded data using two-way repeated-measures (RM) ANOVAs. We tested the data for normality using Shapiro-Wilk's test and found no significant deviations. When Mauchly's test indicated a violation of the assumption of sphericity, we corrected the tests using the Greenhouse-Geisser method, reporting the ε. When the tests revealed significant effects, we conducted Bonferroni corrected pairwise t-tests for post-hoc analysis. For the analysis of the NASA TLX questionnaires, we applied the raw method, indicating an overall workload as described by Hart et al. [23]. For the analysis of the non-continuous data of the Likert questionnaires, we performed an Aligned Rank Transformation as proposed by Wobbrock et al. [60]. For the 1-factorial analysis, we analyzed the recorded data using one-way repeated measures ANOVAs, ensuring compliance with the assumptions as described above. Again, we used Bonferroni corrected post-hoc tests for post-hoc analysis. For the 1-factorial analysis of the Likert questionnaires, we used

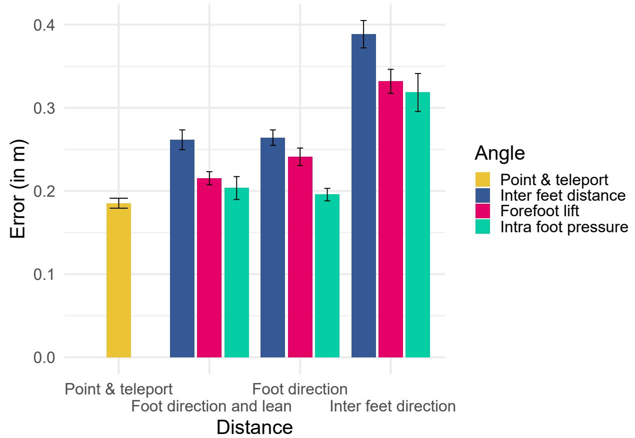


Figure 6. Error in position, measured between the target center and the participants' active foot.

Friedman's test. When significant effects were revealed, we used Nemenyi's pairwise post-hoc test.

For all results, we report eta-squared η^2 as an estimate of the effect size and use Cohen's suggestions to classify the effect size as small, medium or large [13]. As an estimate of the mean response of the individual factors, we report the Estimated Marginal Mean (EMM) as proposed by Searle et al. [48].

RESULTS

In this section, we present the results of our experiment.

Accuracy

We measured the accuracy as the distance error from the center of the presented target to the participants active foot. The analysis showed a significant ($F_{2,38} = 12.32$, $p < .001$, $\eta^2 = .056$) effect of the *direction modality* on the participants' accuracy with a small effect size. Post-hoc tests confirmed significantly higher error values for the *point and lean* conditions (EMM $\mu = 0.304\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.015\,\mathrm{m}$) compared to both, the *foot direction* (EMM $\mu = 0.263\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.015\,\mathrm{m}$, $p < .05$) and the *inter feet direction* conditions (EMM $\mu = 0.238\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.015\,\mathrm{m}$, $p < .001$). Further, the analysis revealed a significant ($F_{1.28,24.39} = 19.90$, $p < .001$, $\varepsilon = .64$, $\eta^2 = .228$) effect of the *distance modality* on the accuracy with a large effect size. Post-hoc tests showed significantly higher error rates for the *intra foot pressure* (EMM $\mu = 0.346\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.018\,\mathrm{m}$) conditions compared to both, the *forefoot lift* (EMM $\mu = 0.233\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.018\,\mathrm{m}$, $p < .001$) and *inter feet distance* (EMM $\mu = 0.226\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.018\,\mathrm{m}$, $p < .001$) conditions. We could not find any significant ($F_{2.79,53.01} = .537$, $p > .05$, $\varepsilon = .70$) interaction effects.

Comparing the conditions to point & teleport hand-base method using a one-way RM ANOVA revealed a significant ($F_{9,171} = 13.8$, $p < .001$, $\eta^2 = .318$) effect on the participants' accuracy with a large effect size. Post-hoc tests confirmed significantly lower error rates for point & teleport (EMM $\mu = 0.186\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.021\,\mathrm{m}$) compared to the *inter feet direction-intra foot pressure* (EMM $\mu = 0.317\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.021\,\mathrm{m}$), *point and lean-Forefoot lift* (EMM $\mu = 0.264\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.021\,\mathrm{m}$) and the *point and lean-intra foot pressure* (EMM $\mu = 0.388\,\mathrm{m}$, $\sigma_{\bar{x}} = 0.021\,\mathrm{m}$) conditions (all $p < .001$). Figure 6 depicts the measured mean errors for all conditions.

Task-Completion Time

As a measure for the effectiveness of the participants in our experiment, we measured the TCT as the time between spawning a new target and confirming one's final position. The analysis revealed a significant ($F_{2,38} = 46.77$, $p < .001$, $\eta^2 = .217$) effect of the *distance modality* on the TCT with a large effect size. Post-hoc tests confirmed significantly higher TCTs for the *intra foot pressure* (EMM $\mu = 10.32\,\mathrm{s}$, $\sigma_{\bar{x}} = 0.56\,\mathrm{s}$) conditions compared to both, the *inter feet distance* (EMM $\mu = 7.49\,\mathrm{s}$, $\sigma_{\bar{x}} = 0.56\,\mathrm{s}$) and the *forefoot lift* (EMM $\mu = 6.50\,\mathrm{s}$, $\sigma_{\bar{x}} = 0.56\,\mathrm{s}$) conditions (both $p < .001$). We could not find a significant ($F_{2,38} = 1.54$, $p > .05$) effect of the *direction modality* on the TCT. The analysis revealed significant ($F_{4,76} = 10.89$, $p < .001$, $\eta^2 = .055$) interaction effects between the two factors with a small effect size.

Comparing the conditions to point & teleport in a one-way ANOVA revealed a significant ($F_{9,171} = 26.2$, $p < .001$, $\eta^2 = .387$) effect on the TCT with a large effect size. Post-hoc tests revealed significantly smaller TCTs for point & teleport (EMM $\mu = 3.45\,\mathrm{s}$, $\sigma_{\bar{x}} = 0.65\,\mathrm{s}$) compared to all conditions ($p < .01$ for *foot direction-forefoot lift*, $p < .001$ otherwise). Figure 7a depicts the measured mean TCTs for all conditions.

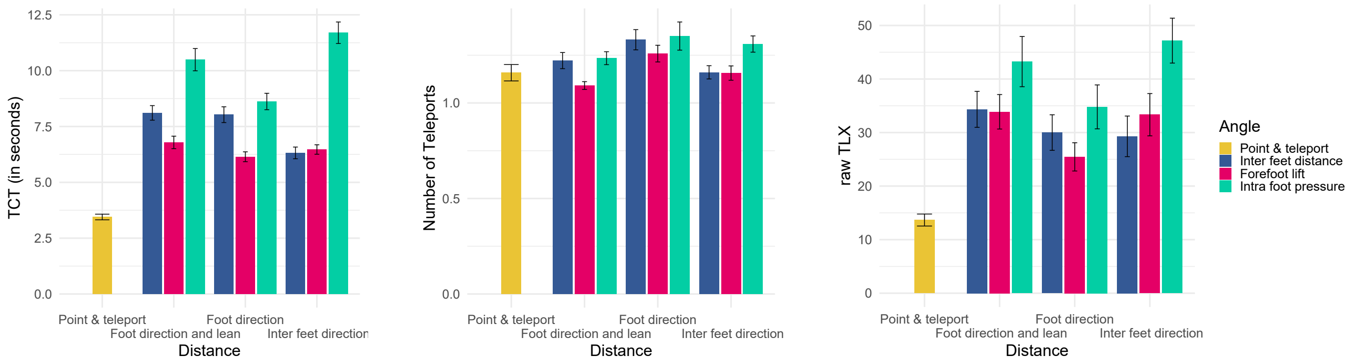
Number of Teleports

As a second measure for the effectiveness, we measured the number of teleports participants required to reach the target. The analysis revealed a significant ($F_{1.34,25.43} = 3.98$, $p < .05$, $\varepsilon = .669$, $\eta^2 = .016$) effect of the *distance modality* on the number of teleports with a small effect size. Post-hoc tests confirmed a significantly higher number of teleports for the *intra foot pressure* (EMM $\mu = 1.3$, $\sigma_{\bar{x}} = .07$) conditions compared to the *forefoot lift* (EMM $\mu = 1.17$, $\sigma_{\bar{x}} = .07$) conditions ($p < .05$). We could not find significant effects of the *direction modality* ($F_{1.18,22.33} = 1.33$, $p.588$, $\varepsilon => .05$, $\eta^2 = .021$) nor interaction effects between the factors ($F_{4,76} = .79$, $p > .05$).

Comparing the conditions to point & teleport in a one-way ANOVA did not yield any significant results ($F_{2.13,40.42} = 1.42$, $p > .05$, $\varepsilon = .236$). Figure 7b depicts the measured mean numbers of teleports for individual conditions.

NASA Task load Index

We measured the participants' mental load using the RTLX. The analysis revealed a significant ($F_{2,38} = 6.56$, $p < .01$, $\eta^2 = .034$) effect of the *direction modality* on the participants' mental load with a small effect size. Post-hoc tests unveiled a significantly lower mental load for *foot direction* (EMM $\mu = 30.1$, $\sigma_{\bar{x}} = 3.29$) compared to both, *inter feet direction* (EMM $\mu = 36.6$, $\sigma_{\bar{x}} = 3.29$, $p < .05$) and *point and lean* (EMM $\mu = 37.2$, $\sigma_{\bar{x}} = 3.29$, $p < .01$) conditions. Further, the analysis revealed a significant ($F_{2,38} = 21.84$, $p < .001$, $\eta^2 = .083$) effect for the *distance modality* on the RTLX with a medium



(a) Task-completions time (b) Number of teleports (c) Raw TLX

Figure 7. Efficiency and convenience metric of all presented input modalities including point & teleport as baseline.

effect size. Post-hoc tests confirmed a significantly higher mental load for *intra foot pressure* (EMM $\mu = 41.7$, $\sigma_{\bar{x}} = 3.23$) conditions compared to both, *inter feet distance* (EMM $\mu = 32.2$, $\sigma_{\bar{x}} = 3.23$) and *forefoot lift* (EMM $\mu = 30.9$, $\sigma_{\bar{x}} = 3.23$) conditions (both $p < .001$). Lastly, we found significant ($F_{4,76} = 2.63$, $p < .05$, $\eta^2 = .017$) interaction effects between the two factors on the RTLX with a small effect size.

Comparing the conditions to the point & teleport method using a one-way ANOVA revealed a significant ($F_{4.82,91.62} = 15.5$, $p < .001$, $\varepsilon = .536$, $\eta^2 = .240$) effect of the condition on the RTLX with a large effect size. Post-hoc tests confirmed a significantly lower mental load of the point & teleport condition (EMM $\mu = 13.7$, $\sigma_{\bar{x}} = 3.57$) compared to all *direction modality* and *distance modality* combinations ($p < .05$ *foot direction-forefoot lift*, $p < 0.001$ otherwise). Figure 7c depicts the measured mean RTLX values the individual conditions.

Questionnaire

After each condition, we asked our participants the rate their experiences in three questions on a 5-point Likert scale (1:strongly disagree, 5:strongly agree). In this section, we analyze the participants' answers.

Convenience

As a first question, the questionnaire asked the participants about the convenience using the locomotion method. The analysis revealed a significant ($F_{2,38} = 11.12$, $p < .001$) effect of the *direction modality* on the perceived convenience. Post-hoc tests confirmed significantly higher ratings for the *foot direction* conditions compared to both, the *inter feet direction* ($p < .01$) and the *point and lean* ($p < .001$) conditions. Further, the analysis unveiled a significant ($F_{2,38} = 7.16$, $p < .01$) effect of the *distance modality* on the perceived convenience. Post-hoc tests confirmed significantly higher ratings for the *Forefoot lift* and *inter feet distance* conditions compared to the *intra foot pressure* conditions (both $p < .01$). We could not find any significant ($F_{4,76} = 1.7$, $p > .05$) interaction effects between the two factors.

Friedman's test showed a significant ($\chi^2(9) = 60.52$, $p < .001$) effect of the condition on the perceived convenience. Post-hoc tests confirmed higher ratings of point & teleport for all conditions except for *inter feet direction-inter feet distance*, *foot direction-forefoot lift*, *foot direction-inter feet distance*. Figure 8 depicts all answers of the participants.

Confidence

We asked the participants about their confidence to accurately have reached the targets using the respective locomotion method. The analysis showed a significant ($F_{2,38} = 3.86$, $p < .05$) effect of the *direction modality* on the participants' confidence. Post-hoc tests confirmed significantly lower ratings for the *point and lean* conditions compared to the *inter feet direction* conditions ($p < .05$). Also, the analysis revealed a significant ($F_{2,38} = 26.33$, $p < .001$) effect of the *distance modality* on the participants' confidence. Post-hoc tests unveiled significant differences between all groups (*inter feet distance* > *forefoot lift* ($p < .05$), *inter feet distance* > *intra foot pressure* and *forefoot lift* > *intra foot pressure* (both $p < .001$)) The analysis did not show any significant interaction effects ($F_{4,76} = .98$, $p > .05$).

Friedman's test showed a significant ($\chi^2(9) = 72.06$, $p < .001$) effect of the condition on the confidence of the participants. Post-hoc tests confirmed significantly higher confidence ratings for point & teleport compared to *foot direction-intra foot pressure* ($p < .01$), *point and lean-intra foot pressure* and *inter feet direction-intra foot pressure* (both $p < .001$). Figure 8 depicts all answers of the participants.

Would like to Use

Lastly, we asked the participants if the would like to use the respective combination of *direction modality* and *distance modality* for locomotion in VR The analysis revealed a significant ($F_{2,38} = 9.20$, $p < .001$) effect of the *direction modality* on the participants' ratings. Post-hoc tests confirmed significantly lower ratings of the *point and lean* conditions compared to both, the *inter feet direction* ($p < .01$) and the *foot direction* ($p < .001$) conditions. Further, the analysis revealed a significant ($F_{2,38} = 12.13$, $p < .001$) effect of the *distance modality* on the participants' ratings. Post-hoc tests showed significantly lower ratings of the *intra foot pressure* conditions compared to both, the *forefoot lift* and the *inter feet distance* conditions (both $p < .001$). We also found significant

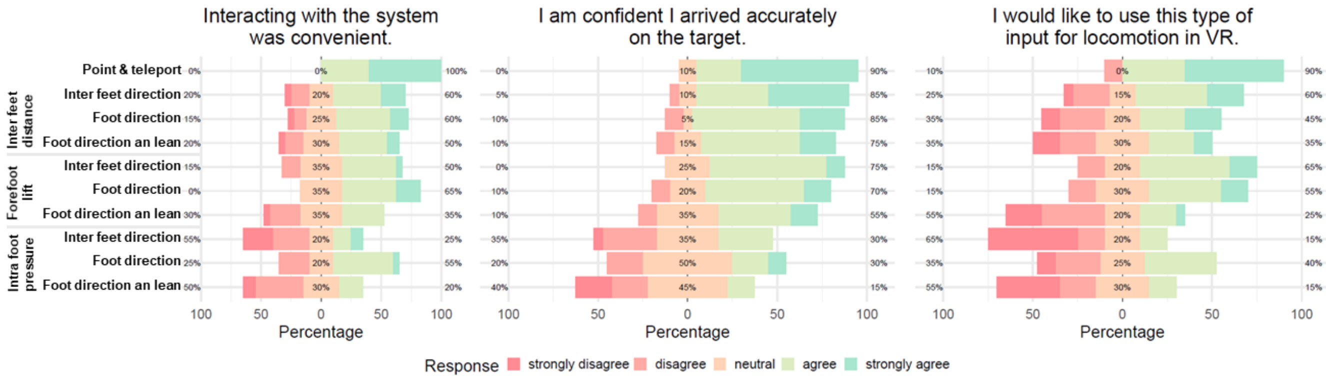


Figure 8. The results of our custom questionnaire on a 5-point Likert scale (1:fully disagree, 5:fully agree, percentage of answers)

($F_{4,76} = 4.08$, $p < 0.01$) interaction effects between the two factors.

Again, Friedman's test showed a significant ($\chi^2(9) = 50.43$, $p < .001$) effect of the condition. Post-hoc tests confirmed significantly lower approval ratings for *point and lean-forefoot lift* ($p < .01$), *inter feet direction-intra foot pressure* and *point and lean-intra foot pressure* ($p < .001$) compared to point & teleport. Figure 8 depicts all answers given.

Qualitative Feedback

We gathered qualitative feedback from every participant in a semi-structured interview after the last condition.

Most participants liked the idea of foot-based teleportation either for its novelty or practical application in VR games. Especially participants with more VR experience, knowing about the shortcomings of current point & teleport approaches, voiced interest in the adaption of some input combinations.

The pressure sensors were lacking inaccuracy, especially for short distances. Participants reported having problems getting the teleport destination onto the close targets. P16 noted that "The teleport destination for [*intra foot pressure*] felt like a dog that refuses to come closer". P3 said "There was a point for [*intra foot pressure*] when I tried to get the destination any close, it moved away again unless I was really careful.

Many participants felt that the sideways adjustment of *point and lean* was too weak. P4 mentioned, "I wish the effect of the sideways pressure was stronger, in its current form it is useless". Some input combinations did not work well together, P12 for example noted in the semi-structured interview "[*Inter feet distance-point and lean*] was really annoying, when the target was far away, it was very hard to keep my balance and the teleport target kept moving from left to right.".

Participants mostly ignored the leaning adjustment of *point and lean* when combined with *forefoot lift*, P18 noted "How should this work? I can't lift my foot and put pressure on it at the same time.".

Even though participants did not find *inter feet direction* convenient, they liked using it. P5 remarked "I like this sliding around, reminds me of my tango lessons." and P7 mentioned during *inter feet distance-inter feet direction* "My thighs will be sore tomorrow but I don't care, it's fun.".

The flat sole of our prototype in combination with the tiled floor we tested on, made it easy for participants to adjust their heading. P14 noted "I liked how I could just slide my foot around to the desired position. I think it would be annoying on carpet though.".

We could also observe the participants relaxing their arm holding the controller when using foot-based input. When asked most participants were certain that they could use their hands for a different task while teleporting. P19 said, "I can definitely imagine doing something while teleporting. Maybe shooting at enemies or something like that.". P1 remarked, "This would be nice in a game, I could move backward while shooting at zombies in front of me.".

Multiple participants expressed interest in trying specific input combination after some training. P8 said, "I think if I train using [*inter feet distance-inter feet direction*] for a week, I will get good at it.". P2 remarked, "Now I want to try this locomotion in [VR-game] at home.".

DISCUSSION

In this section, we discuss the findings of the user study and answer our research questions.

Accuracy

Direction

For RQ_{1A}, concerning the accuracy of the directional inputs, we found significant better results for *inter feet direction* over *point and lean*, as well as *foot direction* over *point and lean*. We attribute the difference between both pairs to the same effect. Participants reported, that the adjustment effect of *point and lean* was too weak in their opinion. In comparison with *foot direction*, we observed participants relying more on the foot's direction than on leaning. The second effect was the inability to adjust the pressure in combination with *forefoot lift*. We observed *forefoot lift* making it almost impossible to control for the participants, since their foot did not rest on the floor, making pressure adjustment unfeasible.

Multiple participants reported having trouble accurately aiming with the seemingly random left and right offsets. Further, we observed participants having problems maintaining accurate control over their foot's CoP when placing their feet far apart in combination with the *inter feet distance* condition.

Foot direction and *inter feet direction* did also benefit from the flat sole of our prototype. The sole slid easily over the tiled floor making it easy to adjust foot position and rotation. Participants favored adjusting their foot's direction via pressure in the *point and lean* condition. In this situation, the pressure adjustment became a nuisance to them, as it changed when turned their foot.

Distance

Regarding RQ_{1B} concerning the distance inputs, we found that *inter feet distance* and *forefoot lift* performed significantly better than *intra foot pressure*.

Inter feet distance did also benefit from the sole of our prototype, making it easy for participants to slide their foot around for adjustments. Not needing to lift their foot, participants could also see their teleportation target in real-time. In combination with the scaled direct mapping of foot distance to teleport distance, participants had no problems with accurately adjusting their teleport distance.

Concerning *forefoot lift*, many participants drew from their experience with controller-based input, making it easier to learn. Some participants even held their foot in the air, not resting their heel on the floor as originally intended.

Changing rotation or position of one foot inevitably changes the center of pressure on that foot putting *intra foot pressure* at a disadvantage. This means that participants had to either readjust their distance after adjusting their direction or accept the error. *Intra foot pressure* is also limited to the smaller input range of a foot, compared to the 1-meter range of *inter feet distance*, making it harder to perform fine adjustments.

There is no singular answer to RQ_1 (which combination is the most accurate) since we could not find significant differences between the four possible combinations of *foot direction*, *inter feet direction*, *inter feet distance* and *forefoot lift* concerning accuracy. This also matches the participants' perception which is reflected in the final questionnaire (Figure 8).

Efficiency

Direction

Answering the question RQ_{2A}, which directional input is the most efficient, we rely on the TCT and number of teleports as quantitative measures. Apart from various individual combinations exhibiting significant differences between them, as seen in Figure 7a, we found no significant differences between directional input modalities.

Point and lean in combination with *intra foot pressure* performed significantly worse compared with all other conditions except for *foot direction-intra foot pressure* and *inter feet direction-intra foot pressure*. Especially in combination with *forefoot lift*, participants found it very difficult to control their teleportation distance using *intra foot pressure* as input. Other directional input modalities required the participant to move their feet when adjusting their heading, introducing errors into their *intra foot pressure* adjustments. Participants also had trouble accurately adjusting their center of pressure in two dimensions simultaneously which explains the bad performance of *point and lean-intra foot pressure*.

The *inter feet direction* in combination with *intra foot pressure* performed significantly worse than all other combinations not involving *intra foot pressure* and also worse than the combination of *foot direction* with *intra foot pressure*. This can be explained by the same effect presented in the answer to RQ_{1B} where participants had to sacrifice accuracy in directional input for accuracy in distance input and vice versa. We could not find any significant differences in number of teleports for *directional* input.

Distance

Taking a look at the TCT for *distance* input to answer RQ_{2B} we found significant differences between the 3 input modalities. We find both, *forefoot lift* and *inter feet distance* to be significantly better than *intra foot pressure*. *Intra foot pressure* again suffered from input changes introduced when adjusting the directional component of a teleport, which had to be countered by the participants. These adjustments were further hindered by the inaccuracy of the sensors involved which made it hard for participants to find the right input, often alternating between too far and too close. Participants generally felt they had a more accurate grasp of the required input adjustments when using *forefoot lift* and *inter feet distance*.

The ability to slide their feet over the floor was also beneficial for *inter feet distance* input method, eliminating the need to lift one's foot. Balancing one's foot on its heel made it easier for participants to adjust the input direction when using *foot direction* or *point and lean*.

We could only find significant differences between *forefoot lift* and *intra foot pressure* concerning number of teleports between the *distance* modalities. Again, there is no definitive answer which input modality is most efficient, however with *forefoot lift* being significantly better concerning number of teleports we would suggest a combination including *forefoot lift* when efficiency is important. Thus to answer RQ_2, the 2 most efficient input modalities are *forefoot lift-foot direction* and *forefoot lift-inter feet direction*.

Convenience

Direction

We gathered three measures for the convenience of our input methods, RTLX and two questions from the final questionnaire. One question asked how convenient participants perceived the interaction technique, the other how much participants would like to use the given modality on a daily basis.

Concerning the directional input modalities, we found *foot direction* to be favored in all measures. Participants found it easy to simply point at the target and then adjust the required distance. *inter feet direction* scored lower in the RTLX and the direct question about convenience than *foot direction* but significantly better than *point and lean* concerning the every day use. Participants found it difficult to coordinate their feet, especially without the possibility to switch which foot had to be in front, to input a direction. However, many participants found joy in the required motions, especially in combination with *inter feet distance*. *Point and lean* scored significantly lower in all measurements, compared to *inter feet direction* and *foot direction*. This again shows the difficulty of accurately controlling one's center of pressure with the given measuring hardware.

Considering all measures equally when answering RQ_{3A}, *foot direction* is the most convenient directional input in this study.

Distance

Considering the distance input methods, we found both *forefoot lift* and *inter feet distance* to score significantly better in all 3 measures, compared to *intra foot pressure*.

Participants had trouble controlling their foot's center of pressure with, especially for close targets. *Forefoot lift* and *inter feet distance* were also perceived as more intuitive and enjoyable, compared to *intra foot pressure*, judging from the remarks in the semi-structured interview.

Overall, *forefoot lift* and *inter feet distance* both are equally well suited for convenient distance input.

Overall

Regarding all results concerning the convenience of the different input modalities, there again is no definitive answer to RQ_3. The most convenient combinations of inputs are *forefoot lift-foot direction* and *inter feet distance-foot direction*.

Baseline comparison

We will now answer RQ_4, taking a look at how foot-based input modalities hold up against established point & teleport input. Point & teleport exhibited a significantly lower TCT compared to all foot-based input combinations. As such it is still the prime choice when speed is the only consideration.

However, considering accuracy and number of teleports, *inter feet distance-foot direction*, *inter feet distance-inter feet direction*, *forefoot lift-foot direction* and *forefoot lift-inter feet direction* did not perform significantly different from point & teleport. Additionally, participants agreed they are confident that they could interact using their hands while using our foot-based interaction methods. This would be especially interesting for planable locomotion, such as moving somewhere once a task, e.g. picking an apple tree clean, is completed.

Regarding the RTLX, point & teleport performs significantly better than foot-based interaction. This might be explained by the familiarity of the participants with the point & teleport method, as most have used VR before. Pointing with the hand also is a familiar task from the real world trained in everyday life. We expect that training with our foot-based input techniques could improve the task load of using foot-based teleportation techniques.

LIMITATIONS & FUTURE WORK

In this section, we will discuss the limitation of our approach and suggest possible improvements for the future.

Improved Prototype

One limitation of the prototype used in this experiment was the need to support multiple input modalities. A specialized foot controller for an individual input method could address problems inherent to the given input combination. This could improve the control users have over their input.

Furthermore, we found that the rigid material of the prototype made some input modalities difficult to control. This problem was most apparent with the *forefoot lift* method. Utilizing more flexible material could alleviate this problem, making the critical combinations more feasible.

The sensing characteristics of the utilized pressure sensors, while enabling the required interaction for this experiment, could have been improved. Considering the error in distance to the target and the task completion time in conditions relying on pressure input, the limitations become apparent. More accurate, reactive sensors could greatly increase the accuracy with which users can input their desired teleportations, potentially marking pressure input a viable alternative.

Different Input Modalities

The presented concept did also rely on absolute input metaphors, relative input metaphors might be an interesting field to explore as well. *Intra foot pressure* forward to move the teleportation target away, backward to move it close and neutral CoP to stop is one such idea.

Incorporating pressure sensing for both feet is also promising, resulting in a pressure input modality requiring less accurate balance shift.

CONCLUSION

We presented nine novel, foot-based input methods for teleportation locomotion in VR, relying on foot-based input. We compared them to current controller-based teleportation input with regards to accuracy, efficiency, and convenience. Four approaches proved promising with regards to efficiency while performing worse concerning accuracy and convenience, compared to current, controller-based approaches. Foot based teleportation, on the other hand, allows for hands-free locomotion which is not given with controller-based methods. This trade-off between a quick locomotion, interrupting users' hand-based interactions and slightly slower locomotion allowing users to keep interacting will have to be made on a per-use case basis. Additionally, it is not yet clear whether training with our proposed interaction techniques could improve their efficiency.

The presented prototype did cater to all our proposed interaction techniques simultaneously, thus detracting from its potential for each interaction technique. Specialized hardware for every interaction type might improve their respective performance further.

After establishing their viability, the proposed locomotion techniques could be tested in scenarios exploiting their hands-free nature. Thus examining whether their predicted advantage over controller-based input holds up in reality.

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