Jogging-in-Place: Exploring Body-Steering Methods for Jogging in Virtual Environments

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ABSTRACT

Walk-in-Place is an established locomotion technique for walking in virtual environments, as it incorporates body motion similar to regular walking. Although there is extensive research on the performance and experience of walking in virtual reality spaces, it typically requires minimal-to-moderate physical movement, e.g., stepping forward and turning around, to explore virtual spaces. Therefore, the question we ask ourselves in this work is how user experience and performance are affected when the user is actively moving in place. In this paper, we explored three body-steering methods for jogging-in-place in virtual environments: (1) head-, (2) hand-, and (3) torso-based. To investigate the performance of the proposed body-steering methods for jogging in virtual reality, we conducted a controlled lab experiment (N = 12) to assess task completion time, number of steps, and VR sickness. We discovered that hand- and torso-based methods require fewer steps than the head-based method, and the torso-based is slower than the other two. Moreover, the number of collisions and virtual reality sickness were comparable among the methods.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **User studies**; **Empirical studies in HCI**.

KEYWORDS

virtual reality, jogging, steering, physical movement

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1 INTRODUCTION

Locomotion is the self-propelled movement in virtual environments (VE) [21] and is considered one of the most important elements of Virtual Reality experiences. Moving freely through virtual spaces has been for decades a central appealing feature of many applications, such as video games [36, 42]. However, virtual movement can only partially be mapped to physical movements because virtual reality environments allow for infinitely large spaces and physical movement is limited by the boundaries of the tracking space in the real world. Searching for a better mapping is part of current research. To accommodate differences between the virtual and physical space, researchers have introduced artificial locomotion techniques [1, 14, 22, 24, 70] with "Walk-in-Place" being a common locomotion technique that incorporates body motion similar to regular walking [56]. This technique is similar to normal bipedal walking but without requiring much space and has been found to reduce motion sickness [12, 51]. Although there is extensive research on the performance and experience of walking in virtual reality spaces, it typically requires minimal-to-moderate physical movement, e.g., step forward and turn around, to explore virtual spaces. Therefore, the question we ask ourselves in this work is how user experience and performance are affected when users are actively moving in place while jogging, given additional impact due to vigorous-intensity physical movement. We explore this question using the example of jogging in place, which requires constant lifting of the feet to move forward and body control to maneuver.

In this paper, we explore the body-based locomotion methods for jogging in place in virtual reality environments. For this, we implemented three body-steering techniques while physically mimicking jogging in place based on different body parts: (1) head-, (2) hand-, and (3) torso-based. The hand-based method requires holding a smartphone in the direction of jogging; with the head-based method, participants run in the direction indicated by their head, and the torso-based implies body-steering using the upper body. To investigate the efficiency of these methods while jogging in place in virtual reality, we conducted a controlled lab experiment (N = 12) to assess the task completion time of jogging, number of steps, number of collisions with virtual objects, the usability of the body-steering methods, and the virtual reality sickness induced the jogging experience. Our results show that participants were faster with hand- and head-based methods than with the torso-based method. Moreover, they made more steps with the torso-based method than the other two. The usability of the torso-based method was rated lower than the other two. Lastly, the number of collisions and virtual reality sickness were comparable among the methods. We outline these results in detail in the following subsections.

Our main research contributions include:

- Three body-steering locomotion methods for jogging-in-place in virtual environments.
- An empirical evaluation of three proposed body-steering locomotion methods for jogging in virtual environments focused on quick and precise movement without increasing virtual reality sickness.

2 RELATED WORK

In this section, we provide an overview of (1) locomotion methods in Virtual Reality and (2) controller- and body-based steering in virtual environments as a basis for jogging experience.

2.1 Locomotion Methods in Virtual Reality

There is a multitude of locomotion techniques in virtual reality (VR), ranging from walking in place [60], moving tiles [24] and shoes [25], leaning in chairs [31, 67], using fingers [29, 74] and controllers to simulated walking [55]. They typically fall under the categories of *discrete* and *continuous* movement through virtual space. The discrete methods, often referred to as teleportation [9], facilitate covering virtual distances in "jumps" without moving in the real world, using controllers [9, 17], feet [11, 66], gates [26], or static portals [16]. The continuous locomotion techniques [7], such as redirected [2, 34, 43, 49, 57], scaled [1, 71], or in-place [5, 24, 44, 55, 60, 63] walking, facilitate continuous movement in virtual environments by walking on one spot or in circles. Although there is extensive research on the performance and experience of using discrete and continuous techniques, they typically require minimal to moderate physical movement to explore virtual spaces. Therefore, the question we ask ourselves within the scope of this paper is how user experience and performance are influenced when users are actively moving in place. We explore this question with the example of jogging-in-place, which requires constant lifting of feet to move forward and body-steering to maneuver. In the following subsection, we outline existing controller- and body-based steering methods, which our work builds on.

2.2 Controller- and Body-based Steering in Virtual Environments

In locomotion, steering plays an essential role in indicating the direction of movement in virtual environments. Previous work has introduced many steering methods in virtual reality, including controller- and body-based methods. Controller-based methods are predominantly used for teleportation [10, 17, 39] that utilizes a form of hand-directed steering in which the user points in the desired direction and subsequently teleports there instantaneously or continuously. Such systems facilitate travel in virtual spaces in "jumps", if used for discrete teleportation, or continuously for continuous locomotion [10, 17, 39, 55]. Although these methods are commonly used in many VR applications [10, 46], reduce motion sickness [39] and enhance the user sense of control [10], they occupy one hand with holding a controller while moving, which disables two-handed interaction and leads to lower realism of the VR experiences [10, 35, 53]. To overcome this limitation, previous research has introduced and evaluated locomotion methods that do not require holding a controller in one hand and alternatively employ other parts of the body to facilitate implicit and natural locomotion in virtual spaces [56, 62, 65], e.g., using feet [11, 66], head, or torso [69]. For example, when comparing torso-directed to head-directed steering, Williams et al. [69] found the torso-directed steering to decrease spatial awareness. Usoh et al. [65]) found that users experienced easier navigation of a virtual space using head-direction over hand-direction. However, hand-directed steering has outperformed head-directed steering in a relative motion task, i.e., users could move easier in relation to an object when they could look at the object and move in another direction [7]. As for the torso-based steering, Razzaque et al. [50] used torso-directed steering when implementing redirected walk-in-place, in which they attached a tracker to the back instead of the torso, which they found was a better representation of the user's body orientation [45]. They also found that perceived presence increased compared to using a joystick. Another recent study by Kitson et al. [32] compared torso- and head-directed methods but found no significant differences.

Our work is closely related to walk-in-place methods that mimic normal walking without much need for physical space [12, 13, 27, 41, 58, 69, 72]. Since users have to walk in place, i.e., imitate walking without not taking forward steps, researchers have explored step detection methods to map the user walk-in-place steps to virtual locomotion speed. This requires the user step detection and an algorithm to convert it to an appropriate speed. In general, these methods can be split into two categories: (1) systems that detect foot-ground contact and (2) systems that track continuous movement [45]. Foot-ground systems track the user's stepping speed based on load sensors embedded in the platform, for example, physical walking platforms or Wii Balance Boards [3, 6, 69]. Continuous movement systems use Inertial measurement units (IMUs) that include accelerometers and gyroscopes or computer vision tracking to determine steps, e.g., by tracking the user's head movement [37, 62, 64], heel velocity [15, 30, 68], or full body [33, 73, 76]. Step detection methods based on IMU sensors are more reliable than computer vision-based methods. The head-based step detection has high tracking accuracy and only requires sensor data from the VR headset as input [37]. In our work, we explore body-steering methods to facilitate a close-to-reality jogging experience in which build on the success of using body parts for steering continuous movement in virtual spaces. These methods include hand-, head-, and torso-steering. However, since jogging-in-place introduces additional impact due to the vigorous-intensity physical movement, we need a better understanding of how body-steering methods affect user experience and how effective these methods are regarding task completion time, accuracy, and virtual reality sickness. In the following, we outline the body-steering methods and the experiment for jogging-in-place.

3 EVALUATION

In this work, we aim to extend the advantages of existing locomotion methods for jogging in virtual reality. This will require a

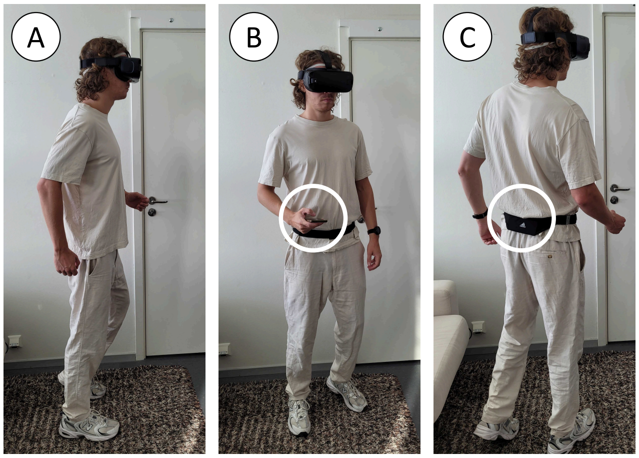

Figure 1: We explored three body-steering methods for jogging in virtual environments based on: (A) head (left), (B) hand (center), and (C) torso (right) movements. The HMD (Head-Mounted Display) method allows steering by turnings the user head left and right, the hand – by turning the smartphone in the hand in the direction of movement, and the torso – by turning the whole body in the direction of movement measured by smartphone sensors placed the back.

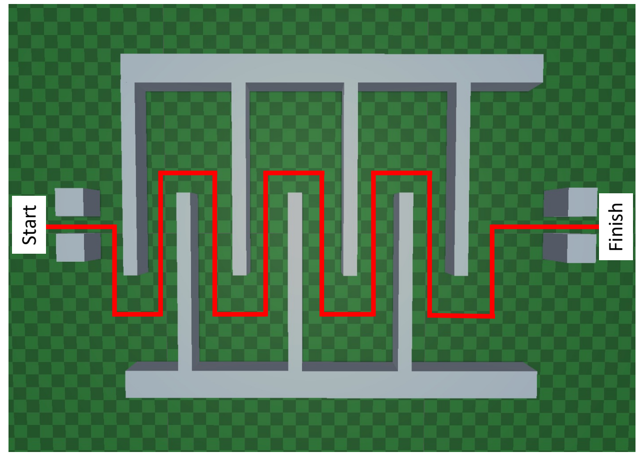

Figure 2: Participants had to follow a predefined route (bird's eye view above), where each route consisted of eight left and right turns.

re-assessment of the most common implementation and reevaluation of continuous movement in VR, given that users will physically step on the same place, imitating jogging-in-place, and therefore, experience additional shaking of the body and the headset. This leads us to the following research question: *"How can we facilitate jogging-in-place the most efficiently in terms of speed and accuracy without increasing VR sickness?"* To answer this research questions and investigate the efficiency of the proposed methods in virtual environments, we conducted a controlled lab experiment in the virtual reality space.

3.1 Participants

We recruited twelve participants (9 male, 3 female) aged between 20 and 29 ($M = 23.8, SD = 2.6$). Eight participants had never, or only once, experienced VR before, two tried VR approximately 2-5 times and two participants had tried VR more than five times before. Only one participant had tried a walk-in-place application before. The participants were recruited through the advertising channels of our institution and no compensation was provided for their participation.

3.2 Study design

The study was designed to be within-subject with one independent variable: *body-steering method*. The body-steering method consisted of three levels which included (1) head-, (2) hand-, and (3) torso-based locomotion methods (Figure 1). All three methods are based on the work of Tregillus et al. [64] and require participants' movement in place, i.e., jogging-in-place, to move forward in a virtual space. The *head-based steering* facilitates continuous movement in the direction indicated by a head. We base this method on the previous work and its success for walking [37, 62, 64], driving [54], and cycling [40]. The speed of movement is controlled by head movements up and down measured by the accelerometer in a VR headset. Such movements reflect natural implicit movement while jogging. The *hand-based steering* method utilizes hand-directed steering in which the user points in the desired direction and is continuously moving in that direction in the presence of physical jogging-like movement. We based this method on the previous work, which typically used for controller-based continuous locomotion methods [8, 10, 17, 39]. The speed of movement is controlled by hand movements up and down and measured by the accelerometer in a smartphone placed in a hand to decouple the movement from the VR headset and facilitate better exploration of the virtual environment, similar to jogging in real world when runners hold their smartphones in hands. The *torso-based steering* tracks the direction of the user's upper body and leave both hands free and detached from the user's gaze-direction. We based this method on the previous work used for walking [8, 69] that indicated advantages of spatial awareness and space orientation [32, 45]. With this method, we also aimed to replicate a "natural" jogging experience from the real world. The speed of movement is controlled by torso movements up and down and measured by the accelerometer in a smartphone placed behind the belt in the back of user body. Each body-steering method reflects one experimental condition, i.e., the participant experienced all three steering methods as three separate conditions. The order of the steering methods was counterbalanced using a balanced Latin square. The task assigned to participants was to follow a predefined curved route (Figure 2 and 3) using each of the locomotion methods, and to reach the target point as fast as possible while avoiding collisions with virtual walls in the environments. The route consisted of eight turns left and eight turns right and was 52 meters long.

3.3 Apparatus

We used the Samsung GearVR (a wireless headset) to avoid inconveniences with wires. The physical experimental area was calibrated to a size of 1 x 1 (WxL) meters with a carpet underneath, for users to feel the boundaries with their feet and chaperone bounds turned on for participant safety. In the head-method, both steering and step detection is determined by the VR-headset. For the torso- and hand-methods, we used an external smartphone (Google Nexus 5) as IMD sensor (gyroscope for rotation, accelerometer for step detection). We used a smartphone as external device for two reasons. First, smartphones are ubiquitous and can easily be used with headsets that don't use VR-controllers, e.g., Apple Vision Pro. Secondly, the smartphone multi-touch screen and other capabilities could be used as inputs in VR for other contexts than locomotion. To attach the smartphone for the torso-method, we used a sport wrist bag. The wrist bag was positioned on the back of the user, close to the hips, as suggested by Nilsson et al. [45] (Figure 1 c). The gyroscope data from the external smartphone was sent every frame over Bluetooth, and step detection on each event trigger. For the head-based method, the gyroscope and accelerometer data was accessible from the smartphone in the headset. An application containing the virtual experimental track was created with Unity.

3.4 Measures

To compare the locomotion methods in VR, we measured the following dependent variables:

- *Task Completion Time (in sec)*: the time necessary to go from a start to the end point of the predefined route.
- *Number of steps*: we counted a number of physical steps made by participants while using the locomotion methods. For this, we used the algorithm with a low overhead for step detection that accounts for consistent frame-rate in VR created by Zhao et al. [75]. The algorithm takes accelerometer data as input, which we feed from the smartphone used as VR headset (head) or external smartphone (torso, hand).
- *Number of collisions*: we counted the number of collisions into the walls along the track.
- *Virtual Reality Sickness*: for each locomotion method, participants filled in the questions from the Simulation Sickness Questionnaire (SSQ) to assess their general state of motion sickness. To calculate the SSQ score [28], we used the formula from [4].
- *Usability*: for each locomotion method, participants filled in the questions from the System Usability Scale (SUS) to assess their general level of usability.

3.5 Procedure

After obtaining informed consent, we collected demographic data from the participants. We then provided a brief overview of the locomotion methods and the participants familiarized themselves with the three methods in a test task. Once the participants felt comfortable, we started the experiment, in which they had to go from a starting to an end point of a predefined route as fast as possible without colliding with the track walls along the route. At the end of the study, we interviewed the participants about their general preferences for the explored body-steering methods, their ease of use, and realism. The entire study lasted approximately one hour per participant.

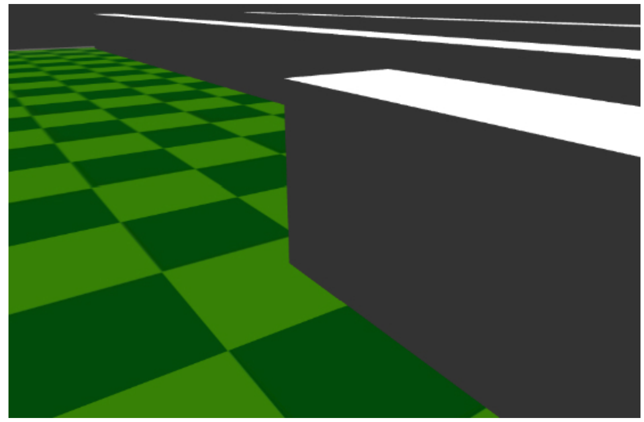

Figure 3: The predefined route as seen from inside the VR headset.

3.6 Data analysis

We used the one-way ANOVA as an omnibus test, and t-tests for post-hoc analysis for the parametric data. For non-parametric data, we use a Friedmann test as an omnibus test, and a Wilcoxon signed-rank test for post-hoc analysis. We used a Bonferroni correction for post-hoc analysis.

4 RESULTS

Our results show that participants were faster with hand- and head-based methods than with a torso-based one. Moreover, they made more steps with the head-based method than with the other two. The usability of torso-based method was rated lower than the other two. Lastly, the number of collisions and virtual reality sickness was comparable among the methods. We outline these results in detail in the following subsections.

4.1 Task completion time

We discovered that participants finished the track faster with head- ($M = 22.6sec, SD = 7.9$) and hand-based ($M = 24.2sec, SD = 4.6$) methods than with a torso-based ($M = 29.6sec, SD = 9.6$). This finding was shown to be statistically significant as indicated by a Friedmann test ($\chi^2(2) = 3.2, p < 0.05, \eta^2 = 0.13$). The post-hoc analysis has shown that participants were slower with the torso-based method than with hand- ($p = 0.026$) and head-based ($p = 0.01$) ones. However, there was no statistically significant differences between the hand- and head-based methods ($p > 0.05$).

4.2 Number of steps

We found that participants made more steps using the head-based method ($M = 93.1, SD = 12$), followed by hand- ($M = 62.6sec, SD = 7.6$) and torso-based ($M = 62.6, SD = 8.8$) methods. This finding was shown to be statistically significant as indicated by a Friedmann test ($\chi^2(2) = 18.7, p < 0.001, \eta^2 = 0.78$). The post-hoc analysis has shown that participants made more steps with the head-based

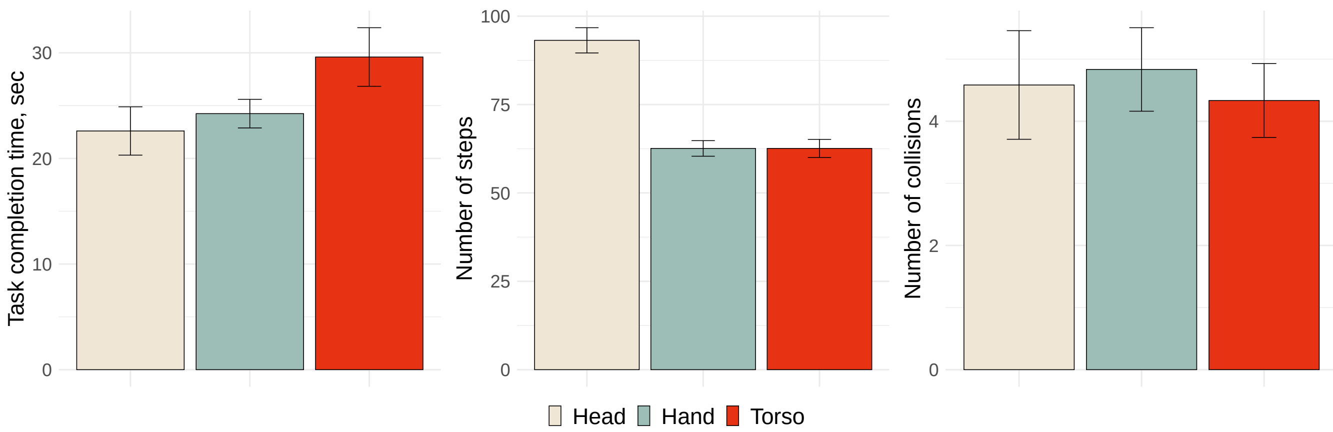

Figure 4: Overview of results: means and standard errors for the task completion time, number of steps, and number of collisions.

method than with hand- ($p < 0.001$) and torso-based ($p < 0.001$) ones. However, there was no statistically significant differences between the hand- and torso-based methods ($p > 0.05$).

4.3 Number of collisions

The number of collisions with the track walls was shown to be comparable among the three methods: head- ($M = 4.5, SD = 3$), hand- ($M = 4.8, SD = 2.3$), and torso-based ($M = 4.3, SD = 2$). This finding was shown to be statistically non-significant as indicated by one-way ANOVA ($F(2, 33) = 0.12, p > 0.05$).

4.4 Virtual Reality Sickness

We found that all methods induce comparable level of virtual reality sickness based on the total SSQ score: head-($M = 23.3, SD = 22.3$), hand-($M = 25.2, SD = 22.5$), and torso-based ($M = 28.9, SD = 24$). This finding was shown to be statistically non-significant as indicated by a Friedmann test ($\chi^2(2) = 0.97, p > 0.05$). Furthermore, we did not observe statistically significant differences between methods for each subcategory of questionnaire using a Friedmann test: nausea ($\chi^2(2) = 1.6, p > 0.05$), disorientation ($\chi^2(2) = 2, p > 0.05$), and oculomotor ($\chi^2(2) = 1.58, p > 0.05$).

4.5 Usability

We found the head-($M = 83.3, SD = 12.5$) and hand-based ($M = 83.3, SD = 13.6$) methods had higher usability score than the torso-based ($M = 73.3, SD = 21$) one. This finding was shown to be statistically significant as indicated by a Friedmann test ($\chi^2(2) = 1.76, p < 0.05, \eta^2 = 0.07$). The post-hoc analysis has shown that the usability of the hand-based method was higher than torso-based ($p = 0.048$). However, there was no statistically significant differences between the head- and torso-based methods ($p > 0.05$) and between the head- and hand-based method ($p > 0.05$).

4.6 Qualitative Feedback

Participants preferred the hand-steering method the most (N = 6), followed by torso- (N = 3) and head-based (N = 3) ones. Regarding realism, participants found the head-steering method (N = 6) the most realistic, followed by torso- (N = 5) and hand-based (N = 1). However, participants found the head-steering method the easiest to use (N =8), followed by the hand-(N = 4) and torso-based (N = 0) ones. Participants reported that the head-based method was the easiest to use, but it also created nausea and lockiness. As some of them mentioned: *"bobbing my head made me feel nauseous"*, *"It is easier to just nod your head instead of jogging"*, *"it was less 'Gizmos' to think about"*. Participants reported that the torso-steering method was the most difficult to learn but felt more realistic. As some noted: *"Back takes a few seconds longer to learn than just the head but is preferred since it's more realistic. It was nice to run one way and look the other. I tried it in the end in the open field."*, *"No real need to look around since it was not that much to see, but I would have benefited from it more in a game like Amnesia (First-person horror game)"*, *"I liked back the most, it's best for games like shoot'em ups (sub-genre of shooting games)"* Finally, another participant mentioned that the torso-steering method can complement head- and hand-based ones: *"The head and hand methods are probably best used to complement the torso-steering method. The back method would be great if the delay were smaller"*. As for the hand method, participants mentioned that it easy to use and was intuitive. As one participant mentioned: *"The Hand-method can be the easiest because it's user friendly"*.

5 DISCUSSION AND FUTURE WORK

5.1 Torso-steering takes longer and head-steering leads to a higher step count

To our surprise, the torso-based method was slower than using a hand or a head since we expected that turning around corners should be easier when the locomotion direction is detached from the viewing direction [58, 59]. As some participants commented, one potential explanation could be that many of them did not use their entire body while using the head- and hand-based methods. Thus, they did not jog in place as they would normally do when using a walk-in-place method. Instead, many stood still to trigger the step detection and only moved their head or hands. Using smaller motions could have made it easier to keep up the speed, since the step detection algorithm outputs a higher speed if the time intervals

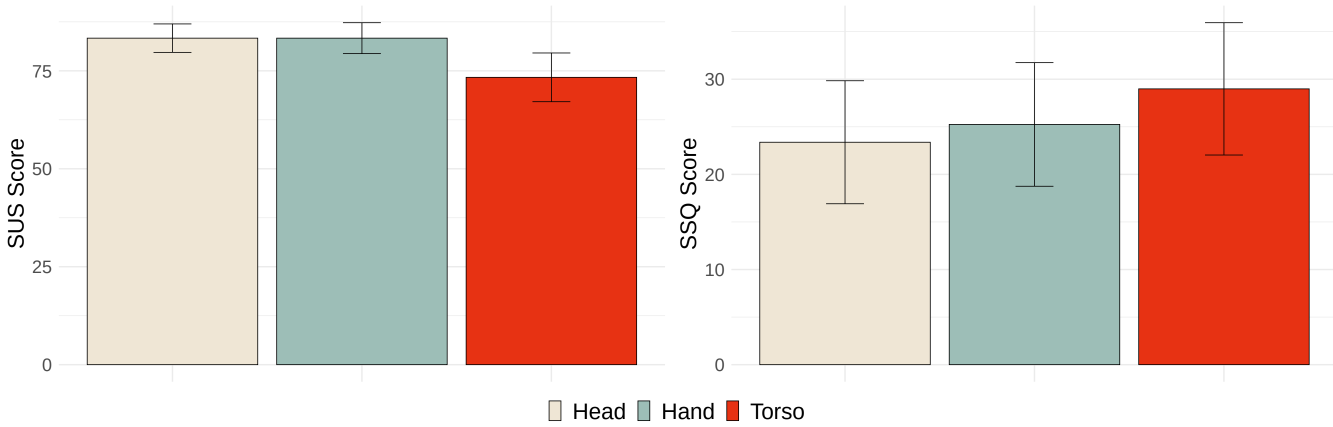

Figure 5: Overview of results: means and standard errors for the SUS and SSQ scores.

between steps are smaller. The torso-based method required the participants to move their body for step detection, thus making it more cumbersome and slow compared to the "cheating" possibility afforded by the other methods. A second explanation could be that the torso-based method was more difficult to learn, as shown by the participants' preferences in the after-study questionnaire since none thought that the torso-based method was easiest to learn. Instead, eight participants found the Head-based method the easiest to learn. Similar findings have also been reported that non-head-directed steering can increase cognitive load, making such a method more difficult to learn [8]. Since we did not find statistically significant differences in the completion time between the hand- and head-based methods, we believe that it has more to do with the combination of torso-steering and full-body movement than detaching steering and step detection from the head.

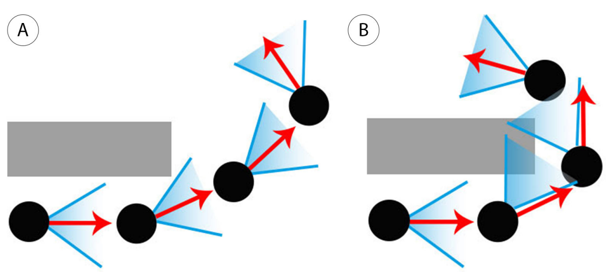

Figure 6: Difference in travel path: (a) head-based and (b) detached (hand & torso) body-steering methods. The blue triangle represents field-of-view, the red arrow represents walking direction.

As for the number of steps, participants made more steps using the head-based method. Participants found it easier to trigger steps with the head-based method since it does not require full body movement and needs the user to move their head up and down slightly. This could have led to steps being triggered more quickly and easily, thus leading to better maneuverability. At the same time, it could also have led to unintended step detection. However, based on the participants' comments and observations made during the experiment, the hand-based method resembled the head-based method in how easily step detection was triggered, i.e., it was easy for users to trigger steps by moving their hand slightly up and down. If unnecessary step-triggering is the only explanation for more steps, the head- and hand-based methods would show similar results regarding the number of steps. Therefore, it seems likely that torso-directed and hand-directed steering gave participants an advantage for moving in relation to another object (the track walls in our experiment) [7]. For instance, participants could better optimize their path around obstacles (a wall in our experiment) by focusing their gaze on the wall ending while moving forward simultaneously. We illustrate this explanation of navigational path difference in Figure 6. Additionally, exploring a combination of the proposed methods might be interesting future work. For example, head-directed steering in combination with a hand control can provide a good control over locomotion speed, as was previously shown for walking [52].

5.2 Head-steering is the most realistic and easiest to use

Our results indicate that participants preferred the hand-steering method as much as head-steering, but the head-steering method was the most realistic and easiest to use. This is surprising since head-directed steering is less similar to normal walking compared to the other methods [61]. However, it is in line with previous work of head-based steering for cycling that showed a high usability [40]. Our observation during the experiment revealed that many participants moved their head or hand for step detection despite full-body walk-in-place movement being more akin to normal walking. This tendency towards minimizing movement can also be observed within other application areas and platforms. For instance, the Nintendo Wii was introduced to increase movement and more bodily engaging games, but many users learn to play the games sitting on their couch with minimal movements instead [20]. Perhaps this is a general human evolutionary tendency in which we strive to perform tasks in as energy-efficient manners as possible [47]. As for the virtual reality sickness, although we did not observe a statistically significant difference in SSQ scores, two participants said that they got dizzy and nauseous from too much head movement, which is in line with previous work [50]. Individual differences could have affected the results since the sample size was limited. Also, each participant only spends roughly a minute in the VE per method. Longer exposure time may have given a different outcome. Additionally, we observed that many participants did not jog or even walk in place. Instead, they only moved their hand or head enough to trigger the step detection, which implies that participants should have picked the torso method to be more realistic than the head method since it required more movement akin to real jogging. Since head-based steering was experienced as more realistic compared to torso-directed steering, other factors than the steering method affected participants' perception of realism. Since most participants did not think the torso method was the easiest to use, the simplicity of the other methods likely impacted perceived realism.

6 LIMITATIONS

The investigated body-steering methods for jogging in virtual reality have several limitations. For instance, neither supports strafing, i.e., jogging sideways or backward. These are common maneuvering capabilities in many first-person games [36, 45], and a logical expansion for future implementation is to incorporate these capabilities, for example, by extending them to the gaze-based methods [19]. Users typically use their eye gaze when navigating [18], which could be used to slightly rotate the rendered screen image instead of slightly rotating the head. Detaching step detection from the head would also be necessary to minimize the HMD from bumping.

We have also experienced drifting problems using the proposed methods. Thus, a more stable gyroscope may be necessary in future implementations. The new GearVR controller [23] has a better gyroscope sampling rate than the Nexus 5 [38] and can be used. Additionally, we only explored the maneuverability of the proposed methods on one jogging task, and more different task scenarios should be evaluated in future work, such as information gathering and free exploration. Our work is exploratory, and we tested with only twelve participants, and a bigger sample size is necessary in future studies. While the frame rate of smartphone-based VR can induce VR sickness [48], longer experiment durations can also be tested in future studies. However, our results provide an initial understanding of how physical body movement, head, hands, and torso, can influence the jogging experience in virtual environments.

7 CONCLUSION

In this paper, we explored three body-steering methods for jogging-in-place in virtual environments. To investigate the performance of the proposed body-steering methods, we conducted a controlled lab experiment to assess speed, accuracy, and VR sickness. We found that participants were faster with hand- and head-based methods than with a torso-based one, which might be explained by the increased demand for a new form of head and torso coordination and a need for more practice to master. Moreover, they took more steps with the torso-based method than the other two. The usability of the torso-based method was rated lower than the other two. Lastly, the number of collisions and virtual reality sickness was comparable among the methods.

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