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Title: Reducing Simulator Sickness in Virtual Reality with Haptic Feedback via Walking-in-Place Locomotion

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Category	*Min*	*Max*	Chosen
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Experiment Design and Execution	*0*	*20*	20
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Quality of Paper Writing and Presentation	*10*		10
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Reducing Simulator Sickness in Virtual Reality with Haptic Feedback via Walking-in-Place Locomotion

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ABSTRACT

Simulator sickness, an illness similar to motion sickness, is a major problem in the field of virtual reality. Given the ever growing popularity and accessibility of VR, it is imperative that this problem be addressed. Thus in this paper we propose two methods of mono-directional locomotion in virtual reality both with the aim of reducing simulator sickness - a stepper and a tether, which we compare to a controller-based movement method. Both of our proposed methods are interfaced with an HTC Vive VR system using the Vives' tracker accessory. All three methods were tested in an experiment (n=27) in which subjects were exposed to the same virtual environment whilst using each locomotion method. We measured Simulator Sickness Questionnaire (SSQ) scores, heart rate, respiratory rate, skin conductance level, and usability using a System Usability Score (SUS) questionnaire. Statistical significance at $\alpha = 0.05$ was found between the controller and the stepper, and between the tether and the stepper for SSQ scores, heart rate, and respiratory rate. Furthermore, statistical significance was found between the controller and the tether, and between the controller and stepper for skin conductance level. Statistical significance was also found between the controller and the stepper for SUS scores. Ultimately we find that the stepper does not reduce simulator sickness but rather increases it. It also scores poorly on usability tests due to the extra physical effort required and the lack of stability users experience. We also found that the tether provides no significant benefit in terms of reducing simulator sickness compared to the controller, though we conclude that there is still some promise to the method given it is in its early prototype phase.

CCS CONCEPTS

• **Computing methodologies** → **Virtual reality**; • **Hardware** → *Haptic devices*.

KEYWORDS

simulator sickness, virtual reality, haptic feedback

1 INTRODUCTION

Virtual Reality (VR) has gained a boost in popularity and accessibility in large part due to advancements in hardware (such as the introduction of consumer grade VR headsets like the Oculus Rift and HTC Vive), which have greatly enhanced the user experience [2]. However, an ever present problem in VR is simulator sickness. Simulator sickness is a form of motion sickness experienced in simulators and VR. Symptoms of simulator sickness, similar to that of motion sickness but less severe, include: nausea, headache, blurred vision, and eye-strain [14, 16]. The key factor that differentiates motion sickness from simulator sickness is that simulator sickness is experienced without any physical motion.

The physiological causes of simulator sickness or motion sickness are unclear. However, there are numerous theories as to why it occurs, with the most common being the sensory mismatch theory and the postural instability theory.

Sensory conflict, or the sensory mismatch theory, is the most commonly accepted theory for the explanation of motion sickness [1]. The underlying theory is that motion sickness occurs due to a mismatch in the sensory information the brain receives. With regards to physical move and orientation, there are three sensory systems which provide different information to the brain: the vestibular (balance), visual, and somatosensory (touch) systems.

The two main components of the vestibular system are the semicircular canals and the otolith organs. The former responds to angular acceleration, while the latter responds to linear acceleration. The somatosensory system reports the position of the head relative to the body, as well as joint movements. The visual system provides information about the motion of the subject, or the environment (it cannot however distinguish between the two [1]). When the subject is experiencing normal motion, these three systems are in harmony with one another. Classical motion sickness, like sea sickness, arises when both the vestibular and visual systems provide information to the brain but they disagree. Simulator sickness occurs when the visual system provides information to the brain but the vestibular does not. This phenomenon is known as vection and occurs frequently in VR environments where the user needs to move within the environment.

Riccio and Stoffregen [21] put forth the postural instability theory in 1991 and argue that motion sickness is the result of an animal failing to maintain postural stability. They postulate that one of the main goals of any animal is to maintain postural stability as this is fundamental to performing any other action. When an animal is in an environment in which is has not learned to control its postural stability, motion sickness will occur and will get more severe over time.

Since vection is a significant contributor to simulator sickness in VR, it stands to reason that developing an efficient form of travel in a virtual environment is key to reducing simulator sickness. There are a variety of techniques of locomotion. Boletsis [2] proposes a typology to describe the four types of locomotion: real-walking, walking-in-place, controller-based, and teleportation. Figure 11 in Appendix A is a summary of the typology reproduced from Boletsis.

With real-walking, users physically walk within some confined space and this motion is translated into movement within the virtual environment. The major limiting factor of this technique is the physical size of the room in relation to the virtual environment's size. Solutions to this problem include: algorithmically directing the user so that they do not move out of the tracked area (also known as redirected walking) or making the tracked area the same size or bigger than the virtual environment [2, 3].

Walking-in-place is a technique in which the user travels within the virtual environment by performing step-like actions on the same spot. Although walking-in-place cannot match real-walking in terms of intuitiveness, it has been described as the closest thing to real walking [7]. It also has the benefits of being cost effective and convenient.

Controller based techniques are very common in VR applications. They make use of typical controllers, like joysticks or touchpads, and are low cost, have a simple implementation and are familiar to users [2]. In their 2016 study of Locomotion techniques for users with Autism Spectrum Disorder [3], Bozgeyikli *et al.* found that users responded well to joystick-based controls. It had low levels of simulator sickness, though lower levels of presence. However, overall, it ranked the highest in terms of preference.

With teleportation the user points to where they want to go and they are instantly transported there. This can be done via a controller or a gesture. Although the motion is not continuous, breaking immersion, it does not induce simulator sickness as the user does not experience any vection. A disadvantage of teleportation is that it can be disorientating.

This project is focused on the design and implementation of two systems with the aim of reducing simulator sickness when compared to controller-based movement. The first of these systems is a stepper. The stepper, which can be seen in Figure 3, is a walking-in-place form of locomotion, and builds upon existing research by Matthies [17] and Bozgeyikli [3]. The second is a tether device, shown in Figure 4, which is a combination of walking-in-place and gesture-based control and is, to the best of our knowledge, an unexplored method. Both these systems aim to reduce simulator sickness by providing additional sensory information in the form of haptic feedback. Thus our assumption is that the sensory mismatch theory is correct. The main research questions for this project are:

(1) By how much does our sports stepper implementation, interfaced with a VR headset, reduce simulator sickness when compared to a controller based solution?
(2) By how much does our tether implementation, being a tether attached to the user's waist, reduce simulator sickness when compared to the a controller based solution?
(3) How does the tether device compare to the stepper machine in terms of simulator sickness measures?

Furthermore, we will also look at the usability rating of our implementations as this is an important aspect if we want the systems to have real-world use.

Reducing simulator sickness in virtual environments is important due to the effects it has on users, which leads to lower levels of immersion and an unpleasant experience overall. Although the VR industry has grown significantly in recent years, if it wants to grow further simulator sickness is one of the major issues that needs to be tackled.

2 RELATED WORK

2.1 Triggers for Simulator Sickness

The various triggers that contribute towards simulator sickness can be grouped into three factors - technical, application design, and individual. These factors have been summarised in Table 1.

Table 1: The various triggers of simulator sickness grouped into three factors.

Technical	Application Design	Individual
Latency	Vection	Experience
Field of View	Frame Rate	Gender
Inter-Optical Distance	Sitting vs. Standing	Age

2.1.1 Technical Factors. Technical factors describe the limitations of the hardware. These factors can be solved, or at least minimized, as technology progresses.

Input latency is the major technical factor that induces simulator sickness. Due to the distortion between the users input and what is rendered on screen, it creates a sensory conflict and leads to simulator sickness symptoms [11].

An increase in the field of view (FOV) is highly linked with an increase in simulator sickness, though at the same time it is also linked with an increase in presence [20].

Another technical factor is the distance between the headsets' lenses known as the Inter-Optical Distance (IOD). Howarth [10] describes the phenomenon known as Accommodation reflex, or Accommodation-Convergence conflict, which can occur if there is continual conflict between the IOD and the inter-pupilary distance. The accommodation reflex is the eyes' reflex when changes in focal distance occur. This can lead to eye-strain, visual fatigue, heterophoria (when the resting position of the eyes are not parallel to each other) and more.

2.1.2 Application Design Factors. Application design factors differ from technical factors in that even if the perfect hardware is used, certain aspects of a VR application will still affect the user.

A prominent factor is vection, which is the illusion of self-motion and is highly linked with simulator sickness. It occurs when motion is detected by the vestibular system in either the linear or rotational axes of the human body. The sensory conflict theory, as described above, is the most common explanation for the occurrence of vection [9].

Frame rate is a significant contributor to the latency experienced by a user. Increasing complexity in an application will lower the frame rate. The consistency of the frame rate is also important. A constantly changing frame rate is more likely to induce simulator sickness than a steady, low frame rate [11].

Whether a user is standing or sitting when using a VR application is another factor. Mehri et al. [18] found that simulator sickness was more common in user who stood as opposed to sitting. This also supports the postural instability theory.

2.1.3 *Individual Factors.*

Individual factors are the characteristics of a user which increase the likelihood of simulator sickness occurring. Perhaps the biggest characteristic is the amount of experience one has with VR. The more experienced a user is with VR, the less likely they are to get simulator sickness [11]. Females are more likely to experience simulator sickness than males [8], children and the elderly are more susceptible than adults [5, 19], and individuals with a history of migraines are likely to experience more intense simulator sickness [6].

2.2 Walking-in-Place with VR

As described in the introduction, walking-in-place is a technique in which the user travels within the virtual environment by performing step-like actions on the same spot. Our stepper implementation is an example of walking-in-place. We describe our tether system as a combination of walking-in-place and gesture-based control - another locomotion technique which Boletsis [2] defines as the user making gestures tracked by input devices to move in the virtual world.

Most applications of walking-in-place are done via a treadmill but there are some other interesting applications - most notably a stepping machine [2]. It is not extensively researched but is affordable (compared to the treadmill) and provides proprioceptive feedback.

Our stepper system is based off two past works. The first one is an implementation by Bozgeyikli et al. [3] in which an optical tracker and reflective markers are used to track the motion of the machine. This movement is transferred into the virtual environment. For direction they use the users head movement, but also rotate the machine if the users head turns by more than 45 degrees. They found that the stepper machine provided a similar experience compared to traditional walking-in-place methods but did not provide more comfort and some users reported that it required a lot of physical effort.

The other is by Matthies et al. [17] who designed an inexpensive and simple stepper machine that makes use of a generic sports stepper, an Arduino, and a potentiometer. When the user steps on the stepper, it turns the potentiometer which transmits its value, and the user moves forward in the virtual environment. However, they did not use a VR headset as pretests found that users kept falling off the stepper, so they used a CAVE design which is a room surrounded by displays. Although users reported better immersion when using the VR stepper, they could not find statistical significance in their results.

2.3 Simulator Sickness Measures

Measuring simulator sickness is traditionally done with the use of questionnaires. However, some studies take physiological measurements to measure simulator sickness.

The Simulator Sickness Questionnaire (SSQ) was developed by Kennedy et al. [13] to quantify simulator sickness. It covers 16 symptoms divided into three categories: nausea, oculomotor, and disorientation. Nausea describes symptoms like stomach pain and burping, oculomotor tracks symptoms related to the vision system like eyestrain and blurred vision, and disorientation covers dizziness, vertigo and other orientation related symptoms. Using the questionnaire, the subject will rate the severity for each of the 16 symptoms, which is then used to calculate a sub-score for category. Finally, using the sub-scores and a predetermined weight, a total simulator sickness score is calculated.

Initially based off the Pensacola Motion Sickness Questionnaire (MSQ) [12], the SSQ was configured to better suit the measurement of simulator sickness as opposed to the MSQ, since the SSQ took into account the discrepancies between motion sickness and simulator sickness.

Kennedy's et. al paper on the SSQ [13] is a highly cited paper in virtual reality literature, and any experiment which attempts measure simulator sickness should use the it.

Physiological measurements provide an objective measurement when testing for simulator sickness. These measurements should be made before the test as a control, and throughout the duration of the test. Kim et al. [15] measured 16 different physiological variables on 61 participants. Using a Pearson two-tailed correlation analysis they found a significant correlation between simulator sickness scores and an increased heart rate, the eye blinking rate, respiration rate, respiratory sinus arrhythmia (changes in heart rate along with breathing), and heart period (time between heart beats). They also found a significant increase in skin conductance.

3 SYSTEM DESIGN

3.1 The Environment

During the experiment the user walks through a custom-made environment. The environment was developed using the Unity game engine. The environment is intended to increase the likelihood of one experiencing simulator sickness, and needs to be monodirectional (so that it is compatible with our movement methods). Thus we place the user on a straight path in a forest (see Figure 1). The forest helps induce simulator sickness as the density of trees on the sides of the path increase peripheral vision activity. This in turn helps induce vection, which is a major contributor to simulator sickness. We use low-poly textures to ensure that the frame rate is constantly higher than 90fps, as we want to limit the amount of application design factors that affect simulator sickness.

As the user will be in the environment for an extended period of time and they will only be moving in one direction, boredom is a concern. We had to ensure that the user interacts with the environment to reduce boredom, yet they need to be continuously moving to help induce simulator sickness. Thus, we integrated obstacles into the path that can be removed with the click of a button. These obstacles are simple in nature (e.g, a gate that opens) and were scattered throughout the environment. The environment also included animals which acted as non-interactable obstacles - the animal would move when the user was within a certain proximity to it. Sound effects for all obstacles, animals, terrain elements (e.g, a river, background ambient noise), and the users footsteps were included to increase presence. Presence is the feeling of being located in one environment even if one is physically located elsewhere. Witmer and Singer [22] found that subjects who report higher levels of simulator sickness also report lower levels of presence than those who report low levels of simulator sickness.

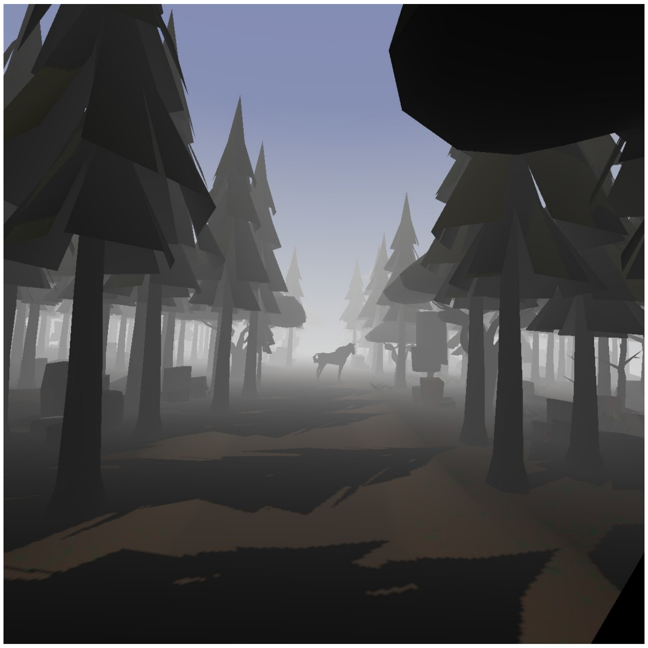

Figure 1: A screenshot of a user walking through the environment. The horse seen in the middle is an example of one of the obstacles/animals included to increase immersion and mitigate boredom.

3.2 The Stepper

The stepper is a walking-in-place implementation designed for continuous movement in one direction. The user will stand on the stepper and walk on it, and this vertical motion in translated to forward motion in the virtual environment. This translation is made possible by the HTC Vive tracker - an accessory for the Vive that constantly sends its position to the headset. The tracker is strapped just above the ankle of the user (see Figure 2). We take the y component of the trackers' velocity and apply a proportional force to the user in the z direction. Drag is also applied to the user to slow them down should they stop moving on the stepper. We use force and drag as opposed to just regular position updates as testing showed that it resulted in a more natural motion.

3.3 The Tether

The overall goal of the tether is to provide a force opposite to the motion of the user, thus providing haptic feedback in the form of inertia. The components that make up the tether system are: the tether itself which is an exercise rope with high tensile strength, two hooks, a belt, and the HTC Vive Tracker. As with the stepper, the tether uses the trackers position and transforms it to movement within the environment. The tracker is attached to the belt and thus we use the z-position of tracker to move forward in the environment. The two hooks are used to attach the tether to the belt and a nearby wall. When the user starts the virtual environment, they are standing at the origin. As they move forward in the real-world, the difference between the origin and the z-position of the tracker is used to apply a z-velocity to the user. Figure 4 shows an example of a user using the tether device.

Figure 2: A picture of how the tracker is strapped to the user when using the stepper.

Figure 3: An example of a user using the stepper.

Figure 4: An example of a user using the tether.

3.4 The Controller

Our stepper and tether implementations were compared against the HTC Vive' controller. The controller comes with the Vive and is a hand-held device with a trigger, touchpad, and multiple buttons. The user moves forward by pulling on the trigger, and interacts with obstacles by pressing the touchpad.

4 EXPERIMENTAL METHOD

4.1 Apparatus

The experiment took place in two rooms - one for subjects to put on electrodes and play a VR acclimatisation game, and the other room for using the movement methods. Two PC's were used, one for each room. The PC in the first room had an Intel i7 processor, 8GB of RAM, and an Nvidia Geforce GTX 980 graphics card. The PC in the second room had an Intel i7 processor, 8GB of RAM and an Nvidia GTX 1070 graphics card. Both rooms used an HTC Vive VR headset, with its associated controllers and light boxes. The second room contained a Biopac MP150 which is a physiological data acquisition system. We used the ECG100C, RSP100C, and GSR100C modules to record heart rate, respiratory rate, and SCL, respectively. The stepper used was a Trojan sports stepper. The tether used was a GoFit Power Tube with a weight resistance rating of 42kg.

4.2 Measures

Our main measure for simulator sickness is the Simulator Sickness Questionnaire (SSQ) developed by Kennedy et al. [13]. Each subject took a baseline SSQ and then a further 6 - one before and after each movement method. A subject took 2 SSQs instead of 1 before the controller as they would play through an acclimatisation game after their baseline SSQ and thus we had to ensure that the acclimatisation game did not affect our controllers SSQ scores. Although standard practice in literature seems to be that a subject only takes a post-experiment SSQ, we used both a pre and post-experiment SSQ to highlight the change in simulator sickness. Our results section includes both the post-experiment SSQ scores, as is done as standard practice, as well as the change in SSQ scores.

As highlighted in the related works section, we were also interested in the correlation between our SSQ scores and the relevant physiological indicators that Kim et al. [15] found to correlate with simualtor sickness in their 2005 study. The physiological measures we assessed are heart rate, respiratory rate, and skin conductance level (SCL). These measures were recorded with the Biopac device mentioned in the Apparatus section. Heart rate and respiratory rate were measured in beats per minute (BPM), whilst SCL was measured in microsiemens (μS).

Additionally, we wanted to evaluate the usability of each system. We employed the System Usability Scale developed by Brooke [4], which was developed to be a low-cost and reliable usability scale that can be used for a variety of systems in various contexts.

4.3 Experiment Design

We performed a single factor repeated measures experiment with the factor being the type of movement method. Subjects used each method on a different day and the order of the methods were fixed: a subject always used the controller, then the tether, and lastly the stepper. Subjects were recruited via the Student Research Participation Programme (SRPP) used by the psychology department of UCT. The SRPP gives a researcher access to all psychology department students. Students are rewarded with SRPP points (required to obtain DP) for participating in research. All subjects were screened during the sign-up process to ensure they did not have epilepsy or a history of severe depression, PTSD, or alcohol/drug abuse. The only demographic data recorded was the gender of the participant since we needed to know whether the participant required a female research assistant present.

Given that we were evaluating simulator sickness on human subjects, ethical issues arose. Thus we obtained ethics approval from the Faculty of Science Research Ethics Committee, who approved the use of UCT students as subjects. All participants were given a voluntary consent form which explain in detail what they would go through and that they could experience simulator sickness. All subjects were informed that they could leave at any time and still receive their SRPP points. No participant left during an experiment. All data was kept private and anonymous.

Each subject went through the following procedure during each of their sessions:

(1) The participant would enter the first room. If it was their first session they would be given the informed consent form and we would answer any questions they had.

(2) We would assist them with putting on the electrodes required for the ECG measurements (our female research assistant would assist female subjects).
(3) If it was their first day they would take a baseline SSQ and then play through a VR acclimatisation game for 3 minutes.
(4) They would then take the pre-experiment SSQ for the movement method they were using on that day.
(5) The subject would then go into the second room.
(6) We then connected the ECG leads to the electrodes, attached the respiratory belt along their diaphragm, and connected the GSR leads to their index and middle finger on their left hand. If they were using the stepper that day we would first let them use the stepper for a minute without any equipment on so that they could get comfortable with it.
(7) We then helped them attach any required accessories (belt or ankle strap)
(8) The subject then sat down and we recorded the baseline physiological data for a minute (sometimes longer if we had issues)
(9) We helped the subject put on the HTC Vive headset and a controller on their right hand.
(10) The subject then experienced our environment for 7 minutes.
(11) We took off the headset and controller, and the participant completed a post experiment SSQ.
(12) We took off all other attachments and the subject completed the SUS.

5 RESULTS

The experiment was run on 27 university students all of whom were screened for epilepsy or a history of severe depression and substance abuse. The sample consisted of 2 males and 25 females.

Each subject completed a baseline SSQ and 2 SSQ's, 1 usability questionnaire, and had a set of heart rate, respiratory rate, and skin conductance level recordings per movement method. For all measures significance was tested between each movement method. The data was tested for normality using a Shapiro-Wilks test, and if it was normal then it was tested for sphericity using a Mauchly's sphericity test.

None of the post experiment SSQ scores or SSQ deltas had a normal distribution. Heart rate had a normal distribution though it was not spherical. Skin conductance and respiratory rate did not have a normal distribution. The usability scores also did not have a normal distribution. As our data was non-parametric, a Friedman test was applied to all measures to test for significance. In the case of significance a Nemenyi post-hoc test was applied to show which methods differed. All significance tests used $\alpha = 0.05$.

Figure 5 shows a box and whisker plot displaying each movement methods' post-experiment SSQ score, as well as the various SSQ components that make up the final SSQ score. A higher SSQ score indicates that the subject feels more sick. The means and standard deviations for each movement method can be seen in Table 6 in Appendix A. Since the SSQ scores did not have a normal distribution, a Friedman test was applied and there was a statistically significant difference between the Nausea ($p = 2.05 \times 10^{-7}$, $\chi^2(2) = 30.8$) and the Ocular ($p = 0.0314$, $\chi^2(2) = 6.93$) components, as well as the total SSQ score ($p = 1.93 \times 10^{-5}$, $\chi^2(2) = 21.71$). Table 3 in Appendix A show the results of a post-hoc Nemenyi test.

The difference between a subjects pre-experiment and post-experiment SSQ was also calculated. Figure 6 shows a box and whisker plot displaying the SSQ score delta for each movement method across all SSQ components. The means and standard deviations for each movement method can be seen in Table 7 in Appendix A. None of the components had a normal distribution and so a Friedman test was applied to all of them. Significant differences were found for the Nausea ($p = 3.82 \times 10^{-7}$, $\chi^2(2) = 29.56$) and the Ocular ($p = 0.0051$, $\chi^2(2) = 10.54$) components as well as the Total SSQ ($p = 1.08 \times 10^{-5}$, $\chi^2(2) = 22.88$) scores. Table 4 in Appendix A shows the results of a post-hoc Nemenyi test for the components which had significance.

The physiological measures recorded over the 7 minutes for each subject were averaged, which follows a similar procedure to Kim et al. [15] who averaged measurements in discrete intervals. A box and whisker plot was made for each of them and these can be seen in Figure 7 for heart rate, Figure 8 for respiratory rate, and Figure 9 for skin conductance level. The means and standard deviations for each movement method can be seen in Table 8 in Appendix A. A Friedman test was applied to all three physiological measures. Heart rate ($p = 4.46 \times 10^{-8}$, $\chi^2(2) = 33.85$), respiratory rate ($p = 3.94 \times 10^{-6}$, $\chi^2(2) = 36.22$), and SCL ($p = 1.36 \times 10^{-8}$, $\chi^2(2) = 24.89$) all had statistical significant differences. Table 5 in Appendix A shows the results of a post-hoc Nemenyi test.

The average of the SUS scores were taken, which can be seen in Table 9 in Appendix A and a Friedman test was applied since the data did not have a normal distribution. Since statistical significant difference was found ($p = 9.32 \times 10^{-5}$, $\chi^2(2) = 18.56$) a Nemenyi post-hoc test was applied. The results of the test can be seen in Table 2. Figure 10 shows a box and whisker plot displaying the SUS scores for each movement method.

	Controller	Tether
Tether	0.102	
Stepper	5.40×10^{-5}	0.064

Table 2: SUS Scores: Nemenyi test results

6 DISCUSSION

After data analysis a statistical significant difference was found between the post experiment SSQ scores of the controller and stepper, and the tether and stepper. When looking at which specific components of the SSQ had statistical significant difference, it was found that the nausea component had differences between the controller and stepper, and controller and tether. Although the Friedman test for the ocular component showed statistical significant differences, a post-hoc Nemenyi test showed that there was no statistical significant difference between the individual components. A possible explanation for this is that our sample size was too small. There was no statistical significant difference for the disorientation component. Ultimately, what this shows is that tether does not perform any better or worse at reducing SSQ scores when compared to the controller. It also shows that the stepper performs worse at reducing

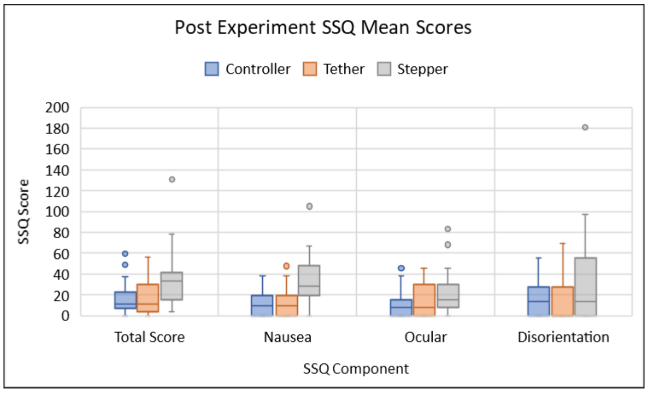

Figure 5: A box and whisker plot showing the post-experiment SSQ scores for each movement methods across each SSQ component.

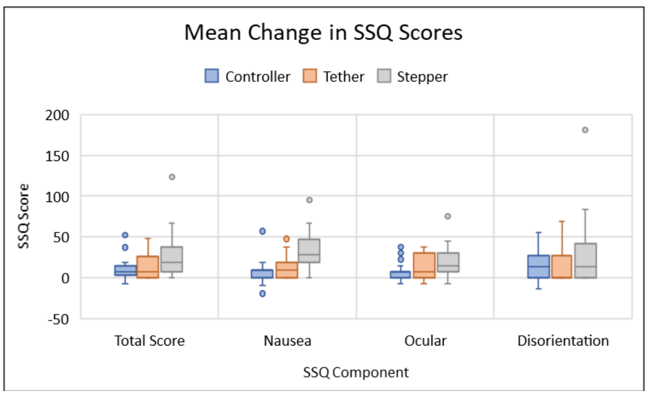

Figure 6: A box and whisker plot showing the difference in SSQ scores between a subjects pre and post experiment SSQ, divided into each SSQ component.

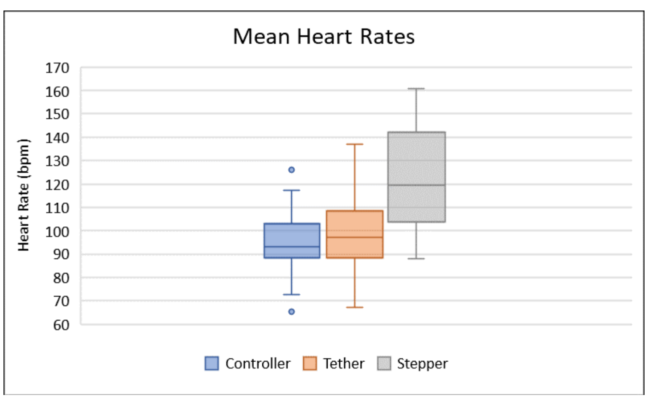

Figure 7: Box and whisker plot showing mean Heart Rates from all subjects across all movement methods.

SSQ scores than the controller, with the most significant difference found in the nausea component.

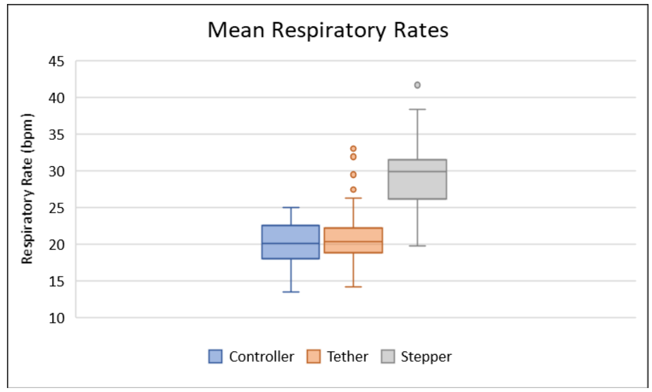

Figure 8: Box and whisker plot showing mean Respiratory Rates from all subjects across all movement methods.

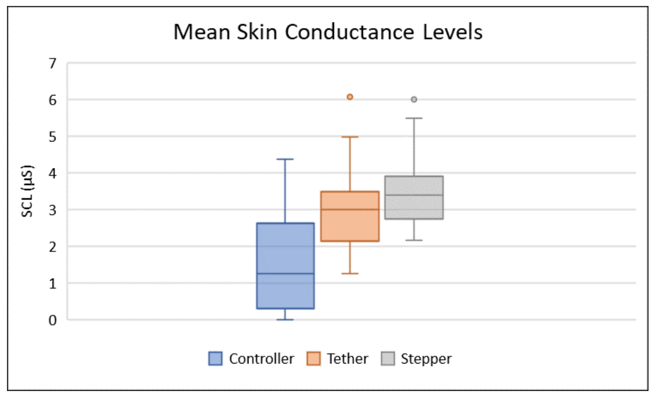

Figure 9: Box and whisker plot showing mean SCL's from all subjects across all movement methods.

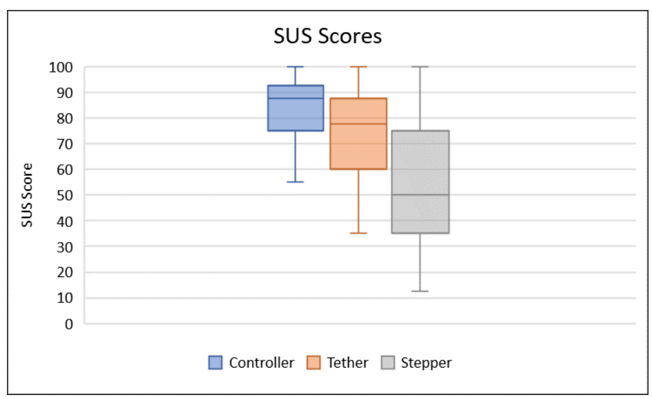

Figure 10: Box and whisker plot showing SUS scores for each movement method.

A similar comparison was done to the differences between the pre-experiment and post-experiment SSQ scores. Although most studies seem to only take the post-experiment SSQ with the assumption that all non-healthy subjects are screened out (i.e. all subjects that participate have a pre-experiment SSQ of 0), we believe that it is prudent to include the pre-experiment SSQ and find the change in the SSQ scores. A statistical significant difference was found between the SSQ deltas of the controller and stepper, and tether and stepper. Further investigation into the SSQ components show again that disorientation does not display a significant difference. Nausea displays a significant difference between the controller and stepper, and stepper and tether. A key difference between the post experiment SSQ scores and the deltas is that for the deltas the ocular component does have a statistical significant difference between the controller and stepper. A possible reason for this difference is that by using the delta between pre-experiment and post-experiment SSQs, our data takes into account whether a particular subject was experiencing ocular symptoms before the experiment began. These symptoms include fatigue, headache, eyestrain, and blurred vision, which anecdotally appear to be common among university students. In any case we see this difference as an argument to continue to look at the SSQ deltas as opposed to just the post-experiment SSQ scores.

To provide an objective measure to compare our SSQ scores against, we look at the physiological measures we recorded. We use Kim's et al. [15] paper, which showed a correlation between SSQ scores and an increase in heart rate, respiratory rate, and SCL, as a basis. Statistical significant differences were found among all three physiological measures. We find that there was a slight increase for heart rate and respiratory rate between the controller and the tether, but there was a great increase for the stepper. For SCL there was an increase between the controller and tether, and an even greater increase when using the stepper. These results appear to match Kim's et al. findings but we also note that we expect a major increase in the three measures when using the stepper as the movement method requires far more physical effort than the tether and the controller.

Although the intention of this project was to implement a system that reduces simulator sickness when traveling in VR, the system will have little real-world use unless it is easy to use for the average user. Thus an important measure for our systems is the System Usability Scale, where a rating of above 68 is considered above average. As can be seen in Figure 10, the controller scores the highest for usability ($\mu = 83.33, \sigma = 12.36$). This is expected because the HTC Vive controller is a commercial product that has been iteratively developed over the past couple years. The tether comes second ($\mu = 73.14, \sigma = 19.50$), which although is less than the controller, can still be viewed as a success as the system was developed by university students in under 6 months and is somewhat close to the controller in terms of usability. The stepper however shows its major disadvantage with a below average usability score ($\mu = 54.44, \sigma = 23.92$). In hindsight this is not surprising given the physical effort required to use the stepper. We also noted that most subjects struggled to maintain balance on the stepper at first, with some never seeming to come to grips with it. Those who struggled with the stepper also struggled to move fast enough through the environment - some would only get halfway through the environment before they ran out of time. Those who did manage to complete the path were fitter than the average student.

Ultimately, we found that the stepper does not provide any improvement, both in terms of reducing simulator sickness nor usability, over the controller. The stepper requires far more physical effort which detracts from the virtual environment experience and also induces symptoms which fall under simulator sickness - particularly the nausea related symptoms. It naturally also increases physiological readings which makes it difficult to deduce whether these increases in measures are due to simulator sickness or if they are a product of the physical effort expended by the user. Our implementation of the stepper differs from past works like Bozgeyikli et al. [3] (n=12) or Matthies et al. [17] (n=10) in that a readily-available, high quality commercial VR headset was used and accessories for the headset were used to track the position of the player. We also focused on reducing simulator sickness whereas both previous papers focused on usability and immersion. Our results seem to agree with both papers in that the stepper ranks poorly for usability, but contradicts Bozgeyikli et al. who found lower SSQ scores compared to their joystick (their equivalent to our controller albeit for a different device).

The tether provided interesting results in that although there was no statistical significant difference (for all measures) between the tether and controller, there was between the tether and the stepper. A possible explanation for this discrepancy is the underlying theory behind simulator sickness - we developed the tether under the assumption that the sensory conflict theory was correct. This meant that by providing additional sensory information to the body when moving in VR, we would reduce simulator sickness. However, the postural stability theory postulates that if an animal is in an environment in which it has not learned to control its postural stability, motion sickness will occur. By placing them in VR, which is already unfamiliar to most users, and then strapping our tether to them on top of that, one could reason that we further make the environment more unfamiliar thus increasing the likelihood of simulator sickness. This may also explain why the stepper also significantly increased simulator sickness. However, this explanation relies on the postural stability theory being the definitive explanation behind motion sickness. In any case our results for the tether could be taken as the tether being neither an improvement nor downgrade on the controller. There is no apparent past work related to the tether to compare our results to. However, our results seem to indicate that the tether is a promising alternative to a controller for mono-directional travel. The system is made up of readily available commercial components (the HTC Vive, its trackers, and the exercise rope) meaning that this study could be easily replicated. Anecdotally subjects reported that the tether was an interesting concept.

6.1 Limitations

Although effort was put into making sure the experiment was as controlled as possible there are certain limitations to our study. Our subjects solely comprised of psychology students from the University of Cape Town. Additionally, of our 27 subjects, 25 of them were female. As discussed in the Related Works section, females are more likely to experience simulator sickness. Our subjects also did not have epilepsy or have a history of severe depression, PTSD, or substance abuse. Most subjects had not used VR previously.

Experiments were run during winter meaning that it rained heavily on some days and did not rain on others. This lead to some subjects having wet hands, which although we attempted to dry, may affect SCL readings. Furthermore since the days were cold, some subjects wore multiple layers of clothing, which could affect respiratory rates.

Subjects went through the same environment for all three movement methods and thus we cannot account for any retest affect.

We only used one tether with a fixed tensile strength (42kg) yet some of our subjects were small and thus we do not know how the extra effort required to use the tether affected their results. The stepper we used was the type that had some sideways rotation which may have affected the stability of the subjects.

7 CONCLUSIONS

In this paper we conducted an experiment to show whether using VR movement methods that provide haptic feedback reduce simulator sickness when compared to the use of a controller. Two movement methods were compared against the controller. The first was a sports stepper on which a user would walk in place, and this movement is translated into forward motion within the environment. The second method is the use of a tether which is attached to the users' waist and a nearby wall. The user walks forward a few steps, and this translates to continuous forward motion in the virtual environment. Both the stepper and the tether provide additional sensory input which we hypothesised would help reduce simulator sickness as is described by the sensory conflict theory. This experiment has significance as simulator sickness is still a problem in an ever-growing VR industry.

The experiment was run with a sample size of 27 psychology students from the University of Cape Town. We measured Simulator Sickness Questionnaire scores before and after the use of each movement method. We also measured heart rate, respiratory rate, and skin conductance level for each movement method. Finally the usability of each movement method was measured using the System Usability Scale questionnaire.

A statistically significant difference was found between the SSQ scores of the controller and the stepper, as well as between the tether and the stepper. No statistically significant difference was found between the controller and the tether. These results were mirrored for heart rate and respiratory rate. A statistically significant difference was found between the SCL readings of the controller and tether, controller and stepper, and tether and stepper. Finally a statistically significant difference was found between the usability score of the controller and stepper.

This paper found that the stepper did not reduce simulator sickness in VR but rather increased it. This is likely due to the extra effort required to use the stepper and due to the instability subject experienced. This paper also found that the tether does not provide any additional benefit nor disadvantage when compared to the controller.

Ideas for potential future work involve the use of variable tensile strength for the tether, the use of two tethers for two-dimensional movement. We do not recommend the use of a stepper for future experiments as the physical effort required by the user ultimately detracts from any possible benefit.

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A ADDITIONAL FIGURES AND TABLES

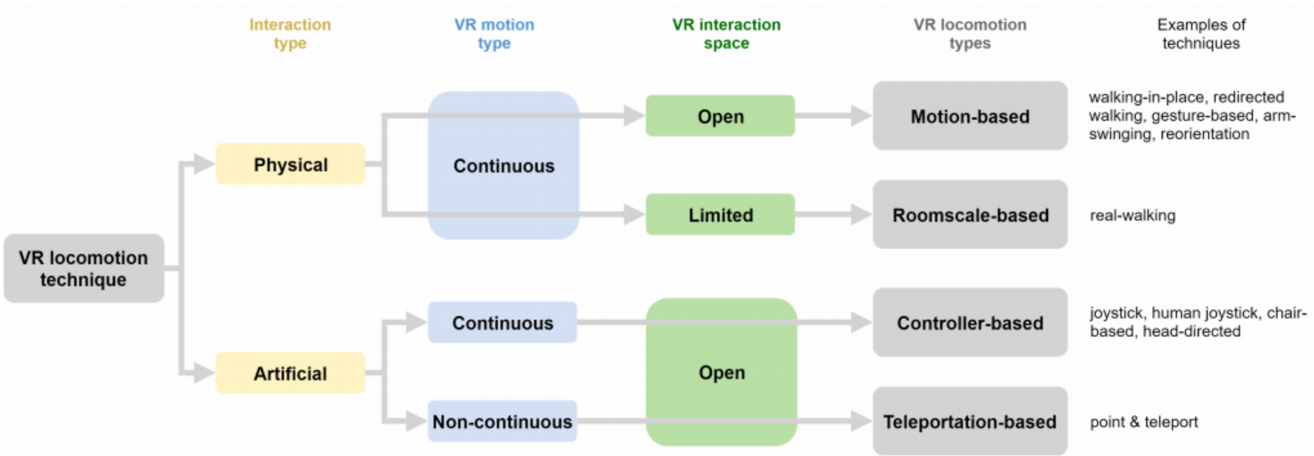

Figure 11: Boletsis [2] locomotion typology.

Nausea			Ocular			Total		
	Controller	Tether		Controller	Tether		Controller	Tether
Tether	0.73		Tether	0.938		Tether	0.43	
Stepper	5.70×10^{-6}	0.00018	Stepper	0.18	0.088	Stepper	0.0062	5.40×10^{-5}

Table 3: Post experiment SSQ: Nemenyi results

Nausea			Ocular			Total		
	Controller	Tether		Controller	Tether		Controller	Tether
Tether	0.43		Tether	0.74		Tether	0.99	
Stepper	2.90×10^{-6}	0.0007	Stepper	0.018	0.119	Stepper	0.0018	9.80×10^{-5}

Table 4: SSQ Deltas: Nemenyi results

Heart Rate			Respiratory Rate			SCL		
	Controller	Tether		Controller	Tether		Controller	Tether
Tether	0.36		Tether	0.44		Tether	0.0031	
Stepper	7.20×10^{-8}	7.30×10^{-5}	Stepper	3.30×10^{-8}	2.10×10^{-5}	Stepper	2.90×10^{-6}	0.2317

Table 5: Physiological Measures: Nemenyi results

Controller				
	Total SSQ	Nausea	Ocular	Disorientation
μ	16.20	12.01	13.19	18.56
σ	13.38	14.50	16.82	14.52
Tether				
	Total SSQ	Nausea	Ocular	Disorientation
μ	16.48	13.78	13.19	17.01
σ	14.57	13.72	23.27	15.25
Stepper				
	Total SSQ	Nausea	Ocular	Disorientation
μ	33.10	34.27	21.33	34.02
σ	22.64	19.27	41.81	27.35

Table 6: Mean post-experiment SSQ scores and standard deviations for each movement method across all SSQ components.

Controller				
	Total SSQ	Nausea	Ocular	Disorientation
μ	6.36	7.58	13.92	9.97
σ	14.25	12.08	16.38	18.03
Tether				
	Total SSQ	Nausea	Ocular	Disorientation
μ	11.66	10.67	15.47	13.99
σ	13.83	13.67	21.61	29.75
Stepper				
	Total SSQ	Nausea	Ocular	Disorientation
μ	31.8	17.41	30.42	29.23
σ	21.17	18.43	41.23	14.23

Table 7: Mean delta SSQ scores and standard deviations for each movement method across all SSQ components.

Controller			
	Heart Rate (bpm)	Respiratory Rate (bpm)	SCL (μS)
μ	94.04	19.92	1.65
σ	14.02	3.02	1.31
Tether			
	Heart Rate (bpm)	Respiratory Rate (bpm)	SCL (μS)
μ	97.23	21.29	2.96
σ	15.03	4.73	1.04
Stepper			
	Heart Rate (bpm)	Respiratory Rate (bpm)	SCL (μS)
μ	121.02	29.34	3.49
σ	21.55	4.79	0.95

Table 8: Mean physiological data and standard deviations for each movement method.

	Controller	Tether	Stepper
μ	83.33	73.14	54.44
σ	12.36	19.50	23.92

Table 9: Mean SUS score and standard deviation for each movement method.