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The Walls Are Closing In: Postural Responses to a Virtual Reality Claustrophobic Simulation

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Abstract: Background: Changes in the visual environment and thereby, the spatial orientation, can induce postural instability leading to falls. Virtual reality (VR) has been used to expose individuals to virtual environments (VE) that increase postural threats. Claustrophobia is an anxiety disorder categorized under situational phobias and can induce such postural threats in a VE. Purpose: The purpose of the study was to investigate if VR-generated claustrophobic simulation has any impact on postural threats that might lead to postural instability. Methods: Thirty healthy men and women (age: 20.7 ± 1.2 years; height: 166.5 ± 7.3 cm; mass: 71.7 ± 16.2 kg) were tested for postural stability while standing on a force platform, upon exposure to five different testing trials, including a normal stance (NoVR), in stationary VE (VR), and three consecutive, randomly initiated, unexpected claustrophobia trials (VR CP1, VR CP2, VR CP3). The claustrophobia trials involved all four walls closing in towards the center of the room. Center of pressure (COP)-derived postural sway variables were analyzed with a one-way repeated measures analysis of variance at an alpha level of 0.05. Results: Significant main effect differences existed in all but one dependent COP-derived postural sway variables, at $p < 0.05$. Post-hoc pairwise comparisons with a Bonferroni correction revealed that, predominantly, postural sway excursions were significantly lower in claustrophobia trials compared to NoVR and VR, but only accomplished with significantly increased sway velocity. Conclusion: The VR CP trials induced lower postural sway magnitude, but with increased velocity, suggesting a bracing and co-contraction strategy when exposed to virtual claustrophobic postural threats. Additionally, postural sway decreased with subsequent claustrophobia trials, suggesting potential motor learning effects. Findings from the study offer insights to postural control behavior under virtual claustrophobic simulations and can aid in VR exposure therapy for claustrophobia.

Keywords: virtual reality; postural stability; agoraphobia; claustrophobia; anxiety



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1. Introduction

The postural control system is responsible for maintaining the body in an upright position against gravity to maintain postural stability, which is defined as the ability to maintain the body center of gravity (COG) within the base of support (BOS) [1–4]. Postural control is a complex dynamic central and peripheral sensorimotor process that helps maintain postural equilibrium, not only in static, but also during dynamic tasks [2]. The postural control system is also responsible for maintaining specific postures (both static and dynamic), allowing for efficient voluntary movement to occur, and responding to

postural perturbations to recover from postural perturbations [4]. The sensory systems responsible for maintaining postural stability include the visual, the vestibular, and the somatosensory/proprioceptive systems [2]. In any instances where there is a dysfunction of these sensory systems or problems with the availability of precise sensory feedback from these systems, such as in clinical populations, there is a reduced ability of the postural control system and its functions, leading to loss of equilibrium and failure to recover from the loss of equilibrium, resulting in falls and fall-related injuries.

Visual stimuli present in the environment alter the human body's ability to maintain upright standing [5]. Inputs into the visual system provide information regarding the environmental features with respect to the human body. The integration of environmental and intrinsic spatial cues (i.e., proprioception) facilitates the development of a bodily spatial orientation to the surrounding environment [6]. Manipulating visual environments to increase perceived postural threat increases anxiety levels [7–9]. Feelings of anxiety and associated disorders are linked to greater postural instability [10–13]. Redfern, Furman, and Jacob [14] found increased COP postural sway in persons with generalized anxiety and agoraphobia in response to changes in visual flow. The changes in postural control dynamics resulted from a bias toward visual input, in turn, leading to poor balance when the visual information was misleading [14]. Changing the visual environment, thusly spatial orientation, renders greater postural instability and increases the risk of a fall [15].

Clinical conditions, such as motion sickness and acrophobia (fear of heights), have already been reported to have postural disequilibrium, due to the sensory conflict between the visual, somatosensory, and vestibular senses [16]. While previous research on anxiety disorders, such as acrophobia and postural stability, exists [16–18], more research is warranted on other anxiety disorders that induce motion sickness and postural instability, such as Claustrophobia. Claustrophobia is an anxiety disorder categorized under situational phobias and is characterized by the fear of enclosed spaces and physically restrictive situations [19,20]. Similar to both agoraphobia and acrophobia (i.e., fear of heights), claustrophobia is described as a distortion in the relationship between the body and surrounding environment (i.e., spatial orientation) [14,20]. Two major components of claustrophobia have been suggested that include the fear of suffocating and fear of restriction or confinement [21]. Symptoms include a subjective feeling of being trapped, being suffocated, and fear of encountering such confinement and suffocation among individuals with claustrophobia [22].

Multiple methods exist to assess the influence of visual environment on postural control. A classic example is the 1974 Lee and Aronson's [23], "moving room paradigm", in which young individuals were asked to stand facing toward a wall that, unknowingly to the participant, would move toward them along the anterior-posterior axis [23]. As a result, incongruent visual information detected in relation to the body's spatial orientation results in postural instability [7,23]. More recently, visual manipulations in experimental and clinical settings use virtual reality (VR) to alter immersive virtual environments (VE) for rehabilitation [24]. VR has also been used to expose individuals to VE that can induce postural threats, such as simulated vertical heights [8,9,25–27] and rotating the visual field on the pitch, yaw, and roll principle axes [26,28], that alter center of pressure (COP) dynamics and bodily kinematics and thereby, the overall postural stability. Moreover, VR is identified as a great alternative to expose individuals to different environments they otherwise avoid due to fear [8,29].

VR has become a popular modality to assess anxiety-related changes to upright standing. For example, exposure to virtual heights increases physical anxiety levels and COP postural sway velocities [8,30]. Recent studies utilized VR to simulate claustrophobic environments to explore the potential therapeutic applications for persons with claustrophobia [29,31–33]. VR has also been used successfully as a rehabilitation and intervention tool for Acrophobia through the virtual reality exposure therapy (VERT) [34]. VR is currently even used as a treatment for phobias, including claustrophobia, which is known as VR exposure therapy [29]. However, these previous studies have not evaluated postural

control dynamics of virtual claustrophobic environments. Taking inspiration from the classical “moving room paradigm” [23] and the proposed “virtual moving room paradigm” [24], more recently, the current researchers investigated the impact of unexpected and expected moving of a front wall in a virtual room on postural control dynamics [7]. The authors reported that postural sway increased during unexpected virtual perturbations and decreased during expected virtual perturbations, due to compensatory and anticipatory postural responses, respectively [7]. However, in that study, only the front facing wall of the virtual room moved forward while the right, left, and back walls remained static. While this was sufficient to elicit significant changes in postural stability, this was not a simulation of claustrophobia. Therefore, the purpose of this study was to evaluate the changes in postural control dynamics using COP-derived postural sway variables upon exposure to virtual moving claustrophobic environments that involved unexpected closing in of the four walls of a virtual room. It was hypothesized that the participants would have greater postural decrements upon being subjected to the claustrophobic trials compared to the NoVR and VR conditions, and those decrements would be decreased over the three consecutive claustrophobic trials.

2. Materials and Methods

2.1. Participants

A total of 30 healthy collegiate students (age: 21 ± 1 years; height: 166.5 ± 7.3 cm; mass: 71.7 ± 16.2 kg; 25 women—age: 20 ± 0.8 years; height: 164.3 ± 5.3 cm; mass: 68.4 ± 14.9 kg and 5 men—age: 22 ± 2 years; height: 177.3 ± 6.8 cm; mass: 88.1 ± 13.5 kg) completed the study. Sample size was chosen based on past research assessing postural stability and using VR, with 20–22 healthy participants [7,9,35], and all participants were recruited using the University IRB-approved protocol of using flyers, word of mouth, as well as verbal and email announcements. The inclusion criteria consisted of a physically active status based on the American College of Sports Medicine (ACSM) criteria for physical activity, which included a minimum of 3–5 days of aerobic exercise per week and 2 days of resistance training per week for at least the past 3 months [36]. The exclusion criteria consisted of the presence of any claustrophobia or anxiety-related disorders as well as any recent visual, vestibular, neurological, or musculoskeletal disorders [37] or a score of >5 on the simulator sickness questionnaire (SSQ) [38] between pre- and post-VE exposure. It is well documented in the literature that postural stability is impacted by age, presence of any musculoskeletal or neurological conditions, or even fatigue in healthy individuals [2,39,40]. This experiment was proposed as a proof of concept to assess and study the postural responses due to both compensatory (feedback) and anticipatory (feedforward) mechanisms when exposed to a virtual closing-in of the walls on healthy young adults before being tested in claustrophobic individuals, to make sure the clinical populations do not have any adverse effects. Hence, a young healthy population was used for this study. All participants read and signed their own consent to participate in the study, which was approved by the Mississippi State University’s Institutional Review Board (IRB) (Protocol #21-033 with date of approval on 10 March 2021). All COVID-19 safety protocols prescribed by the Center for Disease Control (CDC) and the University were followed, including face masks, frequent hand sanitization, and social/physical distancing.

2.2. Instrumentation

Static postural stability was measured with a BTrackS™ (Balance Tracking Systems, Inc., San Diego, CA, USA). BTrackS™ balance plate was validated against the force platform, which is considered the gold standard in assessing postural stability [41]. Required VEs were developed with Unity 3D and were delivered via an HTC Vive Pro™ (HTC America, Inc., Seattle, WA, USA) HMD (Figure 1). A lobby environment and a closed-room environment were the two VEs used in the study. The BTrackS™ (Balance Tracking Systems, Inc., San Diego, CA, USA) software performed an automatic self-calibration of its sensors at the beginning of each testing session, and a sampling rate of 25 Hz was set. The

VR system was calibrated using the hand-held sensors to ensure the VEs were oriented in the correct direction and with the correct dimensions and boundaries of the room.

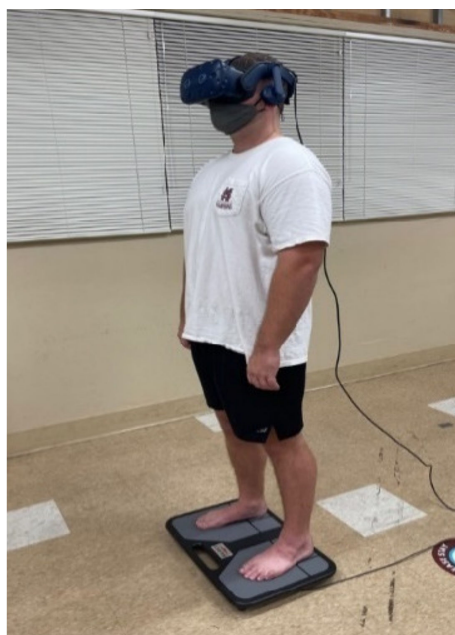


Figure 1. Participant performing the virtual reality (VR) claustrophobia trials using the HTC Vive Pro™ standing on a BTrackS™ balance force platform.

2.3. Experimental Procedures

All testing was performed in the University's Neuromechanics Laboratory. Upon arriving at the laboratory, all participants completed a physical activity readiness questionnaire (PAR-Q) [42] to detect any existing risk factors, and an SSQ [38] to detect existing simulator sickness, as the presence of any musculoskeletal or neurological complications and adverse reaction to virtual simulation can negatively impact participant involvement and findings. Any participant with risk factors detected in the PAR-Q and/or SSQ score > 5 was excluded from the study [9,43]. One participant was excluded after VE exposure due to a score of >5 on the SSQ. After collecting anthropological data (age, height, and mass), participants completed a familiarization session. Initial familiarization was done with the BTrackS™; then, participants were provided the VR headset and provided the instruction to stand as erect and as still as possible looking straight and not talking during testing. Participants were first exposed to a lobby area VE (Figure 1), which was used to familiarize them with VE as well as to practice their ability to use their gaze to complete given tasks, such as looking around the virtual room and to look at red squares until they disappeared. During each VR task, corresponding instructions appeared on the screen and additional verbal commands were given. Immediately following familiarization, the participants completed a second round of SSQ to assess their experience with VR exposure, and if the SSQ score was >5 , data collection was withheld, and the participant was excluded.

Participants were given a 10 min break between familiarization and the initiation of testing. Participants completed an SSQ before beginning any testing trials [37]. Three 20 s trials of baseline bilateral static postural stability were recorded in the eyes-open condition with quiet standing, arms by side, eyes fixed at a specific point, and without the VR headset (NoVR). Participants were then provided with the VR headset and completed three 20 s baseline trials with their eyes open with quiet standing and arms by side with the headset on in the lobby environment (VR) (Figure 2A). Testing trials with eyes open were then initiated and participants were first exposed to the lobby area VE, which was used as a transitional environment before moving onto the testing VE. Transitioning to the testing VE was accomplished by participants using their gaze to make a box disappear,

which was practiced during familiarization. Once the box in the lobby environment disappeared, participants were exposed to the new testing VE, which involved a closed-room VE (Figure 2B–D). Participants were advised to stand as erect as possible without moving and to look straight at the front wall of the room. Participants then completed three 10 s trials of an unexpected moving room in which all four walls appeared to close in on the participant (VR CP1, VR CP2, VR CP3). The walls were preset to move at 1 m/s velocity for all participants to standardize the protocol. The same investigator moved the room at a random time within a 10 s time window to minimize anticipation by participants. The initiation of the moving room was based on a random time decided by the same investigator, which resulted in all four walls closing in on the participant without any prior warning. Figure 2B demonstrates the starting position of the walls during the VR CP trials, with Figure 2C demonstrating the mid-point of the walls moving in, and Figure 2D demonstrates the final position of the closed-in walls. Thus, Figure 2B–D demonstrate the dynamic movement of the four walls closing in. Upon completion of the three trials, participants were provided with a final round of SSQ, and a Levels of Anxiety Questionnaire adapted from Bruce and Reenbrecht [31], which included two questions; (1) “on a scale of 0–10, how anxious were you, with zero being no anxiety at all and, 10 being unbearable anxiety”, and (2) “on a scale of 0–10, how claustrophobic did you feel, with zero being no claustrophobia at all, and 10 being unbearable claustrophobia”. With all participants being healthy young adults with no history of any clinical conditions including claustrophobia or anxiety disorders, and with multiple SSQ that were required to be completed, only questions specific to this study was used for anxiety-related questionnaire. Completion of these questions marked the end of the study. The entire protocol was done in the barefoot condition based on the BTrackS™ manufacturer recommendations and due to its future potential rehabilitation and disability applications.

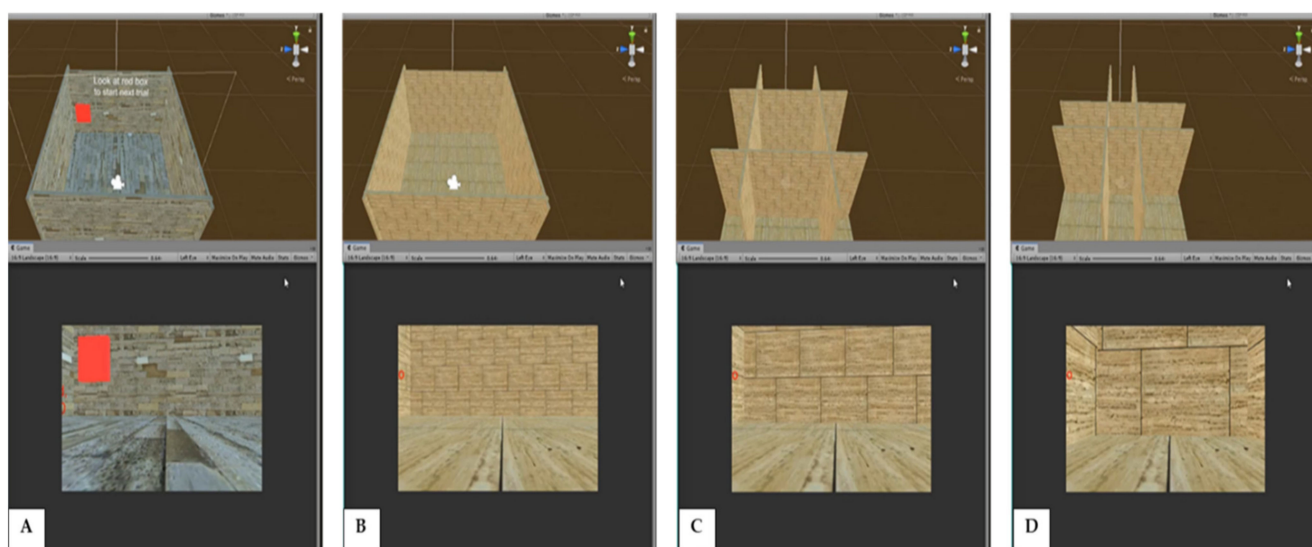


Figure 2. Top level of each figure illustrates the researcher view and bottom level illustrates the participants' point of view. (A) Lobby environment before the start of claustrophobia testing; (B) claustrophobia testing environment, start of the trial; (C) mid-point of claustrophobia testing (walls closing in); (D) completed claustrophobia testing (walls fully closed in).

2.4. Data Analyses

The BTrackS™ explore balance software was used to analyze the postural sway variables. COP excursions were used to analyze postural stability/postural control dynamics. Medial-lateral excursion, anterior-posterior excursion, 95% ellipsoid area, average sway velocity, medial-lateral root mean square (RMS-ML), and anterior-posterior root mean (RMS-AP) were calculated and considered the outcome variables of interest. Average COP sway excursions in the medial-lateral (ML) and anterior-posterior (AP) directions were

calculated from subtracting the minimum COP data from the maximum COP data in the ML and AP directions. The average COP sway velocity was calculated by dividing the total length of the COP path by the trial duration. The 95% ellipsoid area (95% EA) (cm²) represented an area of the ellipsoid based on the COP shifts, such that 95% of the data was within the ellipsoid and 5% was outside it. RMS-ML and RMS-AP were calculated by taking the square root of the mean squared ML and AP COP data. Furthermore, sway variables of higher magnitude represented decreased balance and postural stability [44]. Additionally, participants' responses to the final SSQ were calculated and an SSQ score > 5 after VE exposure would have resulted in exclusion from data analyses.

2.5. Statistical Analyses

The COP-derived postural-sway-dependent variables were analyzed with a one-way 1 × 5 (NoVR × VR × VR CP1 × VR CP2 × VR CP3) repeated measures analysis of variance (ANOVA). Significant main effects were further analyzed with post-hoc pairwise comparisons using a Bonferroni correction factor [45]. All analyses were conducted on SPSS v27 (IBM Corp.: Armonk, NY, USA) [46] at an alpha level of 0.05.

3. Results

Results for each dependent postural sway variable with F-statistic, p value, and partial eta squared effect sizes are reported in Table 1. Main effect significances were followed by pairwise comparisons reported as differences between testing conditions (Table 1 and Figures 3–6). The repeated measures ANOVA revealed significant main effect differences in all dependent COP-derived postural sway variables, except for AP RMS. Significant main effect differences existed in all but one dependent COP-derived postural sway variable, at *p* < 0.05. Post-hoc pairwise comparisons with a Bonferroni correction revealed that, predominantly, postural sway excursions were significantly lower in claustrophobia trials compared to NoVR and VR, but only accomplished with significantly increased sway velocity. Results from the levels of anxiety questionnaire revealed that 23 out of the 30 participants had anxiety greater than zero (max: 10; min: 1; average: 2.4; mean ± standard deviation: 2.4/10 ± 2.358 and standard error: 0.430) and that 22 out of the 30 participants had a sense of claustrophobia greater than zero (max: 6; min: 1; average: 2.7; mean ± standard deviation: 2.7/10 ± 2.239 and standard error: 0.409). None of the SSQ results were >5, which enabled all participants to be included in the analysis.

Table 1. Repeated measures ANOVA results for main effects and pairwise comparisons at *p* < 0.05.

Dependent Variables	Main Effects	Pairwise Comparisons
Sway Velocity (cm/s)	F (4,116) = 14.911, <i>p</i> < 0.001, η_p^2 = 0.340	NoVR & VR < CP1 & CP2; CP1 > CP3
ML RMS Sway (cm)	F (4,116) = 5.980, <i>p</i> < 0.001, η_p^2 = 0.171	NoVR > VR & CP2, CP3
AP RMS Sway (cm)	F (4,116) = 0.727, <i>p</i> = 0.576, η_p^2 = 0.024	No significant main effect
95% EA (cm.cm)	F (4,116) = 3.095, <i>p</i> = 0.018, η_p^2 = 0.094	NoVR > CP3
ML Sway Excursion (cm)	F (4,116) = 5.415, <i>p</i> < 0.001, η_p^2 = 0.157	NoVR > VR, CP2 & CP3
AP Sway Excursion (cm)	F (4,116) = 5.415, <i>p</i> < 0.001, η_p^2 = 0.157	No significant pairwise comparisons

ML—Medial lateral, AP—Anterior posterior, RMS—Root mean square, EA—Ellipsoid area, No VR—upright bilateral stance with no virtual reality, VR—with virtual reality in a virtual environment, VR CP1—first trial in virtual environment with room walls closing in, VR CP2—second trial and VR CP3—third trial in the same virtual environments.

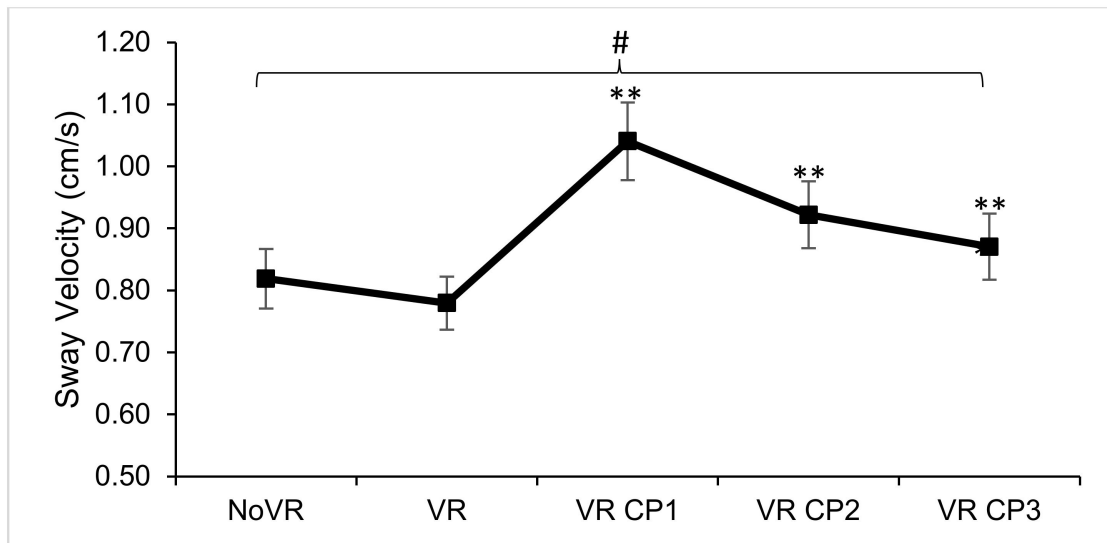


Figure 3. Sway velocity (cm/s) during upright bilateral stance with no virtual reality (NoVR), with virtual reality (VR), first trial in virtual environment with room walls closing in (VR CP1), second trial (VR CP2), and third trial (VR CP3). # represents main effect significance and * represent post-hoc pairwise comparison significance. Bars represent standard errors. ** implies significant difference from first two conditions.

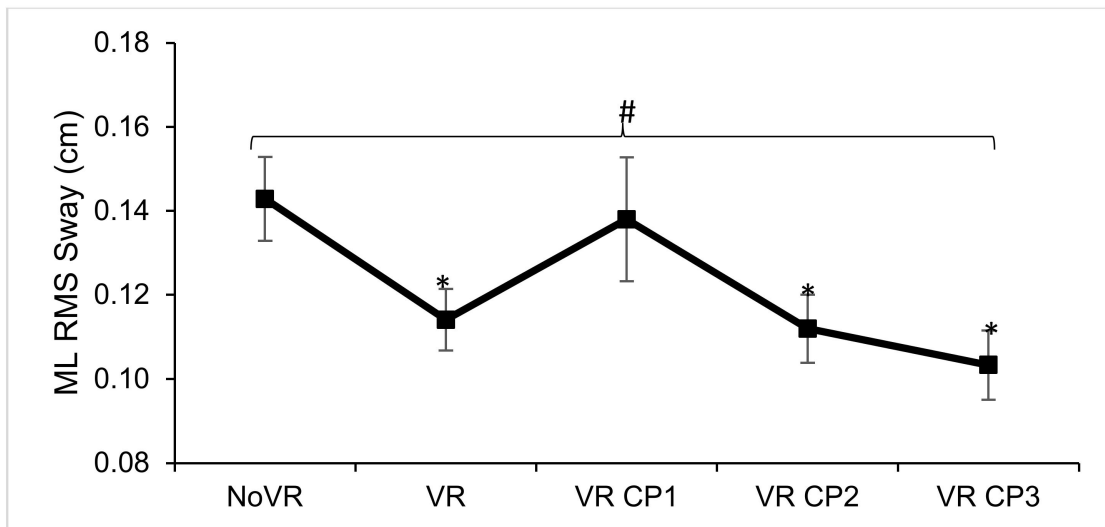


Figure 4. Medial lateral root mean square (ML RMS) sway (cm) during upright bilateral stance with no virtual reality (NoVR), with virtual reality (VR), first trial in virtual environment with room walls closing in (VR CP1), second trial (VR CP2), and third trial (VR CP3). # represents main effect significance and * represents post-hoc pairwise comparison significance. Bars represent standard errors.

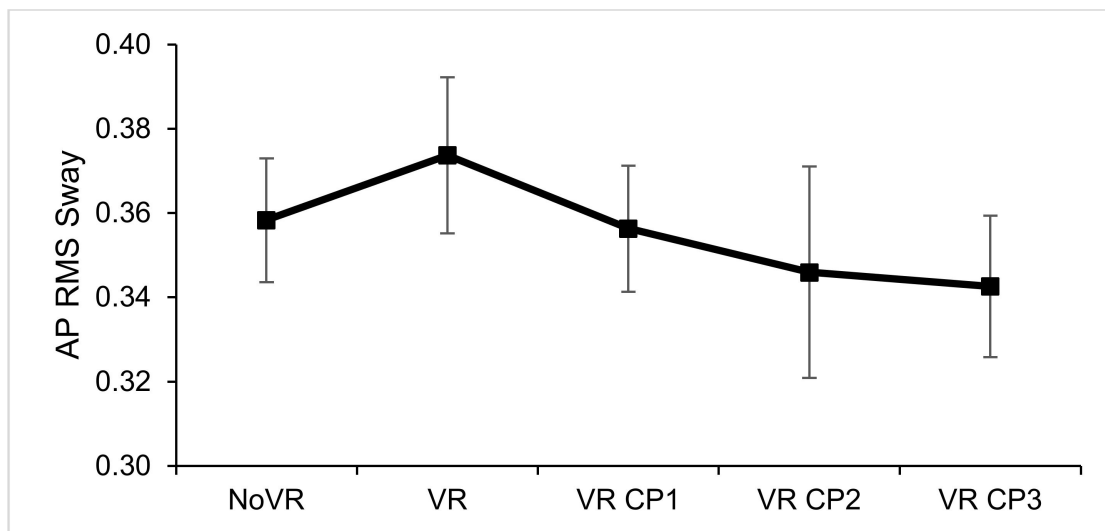


Figure 5. Anterior posterior root mean square (AP RMS) sway (cm) during upright bilateral stance with no virtual reality (NoVR), with virtual reality (VR), first trial in virtual environment with room walls closing in (VR CP1), second trial (VR CP2), and third trial (VR CP3).

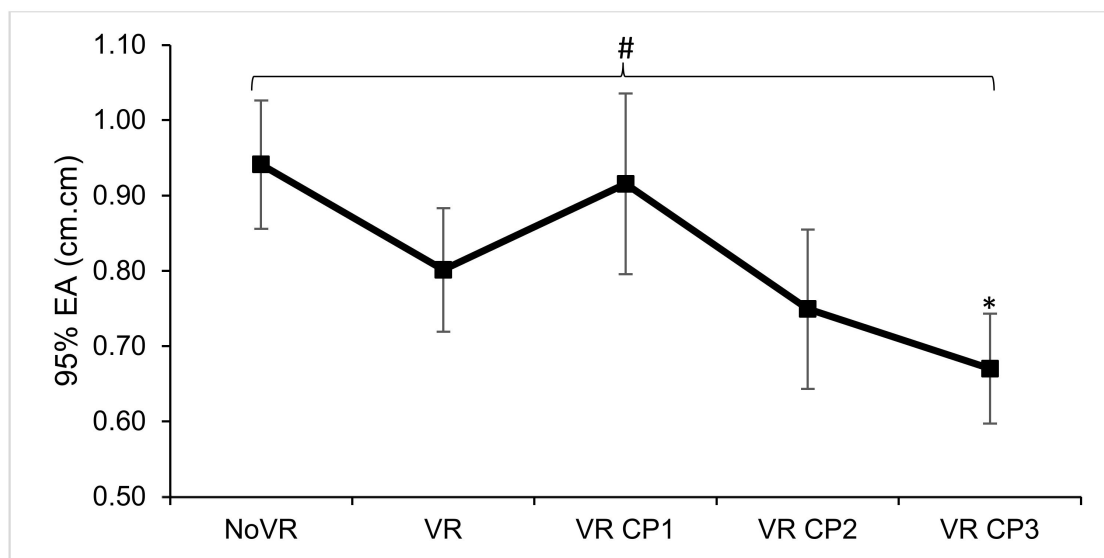


Figure 6. 95% ellipsoid area (EA) (cm²) during upright bilateral stance with no virtual reality (NoVR), with virtual reality (VR), first trial in virtual environment with room walls closing in (VR CP1), second trial (VR CP2), and third trial (VR CP3). # represents main effect significance and * represents post-hoc pairwise comparison significance. Bars represent standard errors.

4. Discussion

The purpose of this study was to evaluate postural control dynamics upon exposure to a virtual moving claustrophobic environment, “walls closing in”.

4.1. Findings

Findings revealed that exposure to a virtual claustrophobic postural perturbation (walls moving closer) altered COP postural sway variables. Specifically, medial-lateral RMS sway, medial-lateral excursion, and 95% ellipsoid sway area significantly decreased when exposed to the virtual postural perturbation due to the claustrophobic simulation, compared to static standing in a real/non-virtual environment (No VR), suggesting that the CP trials, especially when the walls were moving in without any warning, significantly

influenced the individuals to assume a braced stiff posture, minimizing the postural sway excursions. However, contrastingly, a significant increase in postural sway velocity was seen in all virtual claustrophobia trials (VR CP1, VR CP2, and VR CP3) compared to real/non-virtual (NoVR) and non-perturbed virtual environment (VR), suggesting that even if the overall COP excursion magnitude was lower in CP trials, individuals swayed faster within the lowered excursions. This finding implies a bracing strategy manifested by co-contraction of lower-extremity agonist-antagonist muscle pairs, when the walls were closing in. Finally, significant differences were evident between the three consecutive but randomly initiated CP trials, with the postural sway variables decreasing over the course of the three CP trials, thus, suggesting improved postural control dynamics due to potential motor learning effects from one trial to the next. All changes to these postural sway parameters indicate the exposure to virtual claustrophobic environments alter the postural control dynamics during quiet standing and provide a better understating of how the human body maintains postural stability under claustrophobic conditions.

Additionally, in the current findings, medial-lateral postural sway was significantly greater in NoVR compared to VR. The higher postural sway values in NoVR compared to VR were contrary to our original hypothesis and our previous study, which suggested negative impacts on postural stability or increased postural sway when exposed to VEs and the HMD, as prior research has reported such decrements in postural stability in VR-generated VEs compared to real environments due to the distorted visual feedback from the VE and changes in the visual field due to immersive VR [2,8,9]. However, this was only significant in ML RMS and ML excursion, as other variables, even though greater for sway velocity, and 95% EA, were not significant. The current study's findings in the eyes-open condition could be better understood by examining the concept of external and internal attentional focus as well as the more recent understanding of VR exposure. Although the instructions provided to the participants were the same for all tasks, which was to stand as erect as possible while looking straight at the wall in front of them, the VE was more controlled and less cluttered compared to the real lab environment. More specifically, during eyes open with VR, the participants might have externally focused on the center point of the controlled VE, which can contribute to better postural stability [47], whereas during eyes open with no VR, the participants were in an open real environment, where they may have focused not exactly on the center of the front wall. This may have contributed to the greater postural sway in the VR environment with no visual virtual perturbations of the walls closing in, as in the CP trials.

Increases in COP sway velocity are a marker of postural instability [48,49]. Exposure to the claustrophobic perturbation resulted in increased sway velocity compared to conditions with no perturbations. Pairing these results with the decrease in displacement suggests a faster postural control response was utilized to maintain upright standing. These findings are reflective of increased co-contraction of the distal muscles surrounding the ankle joint. Warnica and colleagues [50] found that as the co-contraction index of the ankle musculature increased, COP velocity increased in parallel, suggesting increased rigidity around the ankle, creating higher sway velocities in response to balance perturbations [7,50]. Postural sway differences between NoVR, VR, and CP trials were more pronounced in sway velocity, ML RMS, and 95% EA, compared to AP RMS. Findings from our previous study, which included only the front wall moving in the virtual room, demonstrated significant differences in the anterior-posterior directions compared to medial-lateral [7], suggesting that the direction of visual virtual perturbations influenced the postural sway directions. In the current study, all four walls of the room moved in together, also eliciting a medial-lateral postural response.

After the initial exposure to the virtual claustrophobic perturbation, sway parameters decreased over the course of the three CP trials. This is indicative of a learning effect after exposure to the virtual perturbations. Anticipating postural disruptions adjusts bodily responses to perturbations, thus, minimizing negative consequences associated with balance loss [51]. In this study, decreases in sway parameters indicate a shift toward a more

efficient feedforward response to counteract the claustrophobic balance perturbation. Prior to the oncoming perturbation, the COM moves in the direction of perturbation, which arranges the lower-extremity body segments in a mechanical advantageous position to maintain upright posture. Therefore, with repeated perturbations, the displacement of the COM is smaller, resulting in lower COP displacements and better body balance [51]. Moreover, this shift suggests the occurrence of sensory reweighting, with less reliance on visual input, and potentially more reliance on somatosensory/proprioceptive systems to maintain balance [52]. More recently, standing balance control and postural stability were also proposed to be reconfigured based on exposure to anxiety-inducing VEs (high-altitude) [27], thus, providing support to the changes in postural stability from the current findings when exposed to anxiety-inducing VEs.

In the current study, none of the participants experienced simulation sickness during testing, as evident from the pre- and post-VR exposure SSQ scores. However, very mild anxiety (mean \pm standard deviation: $2.4/10 \pm 2.358$ and standard error: 0.430) and very mild claustrophobia (mean \pm standard deviation: $2.7/10 \pm 2.239$ and standard error: 0.409) were experienced by participants. These subjective scores are similar to those reported by Bruce and Reenbrecht [31] under different claustrophobic VEs, therefore, suggesting that the current experiment of “walls closing in” in a virtual room can provide a VE that is capable of inducing anxiety and claustrophobia.

Finally, findings from the study need to be interpreted with caution. This study was conducted as a proof of concept on young healthy individuals with no history of claustrophobia. Hence, observed results may be different when individuals with anxiety disorders, such as claustrophobia, are enrolled. The current study had 30 participants, with an uneven split of gender (predominantly females). This was due to recruitment and participation issues that existed during the COVID-19 pandemic. However, based on previous research, there is sufficient evidence that static postural stability does not significantly differ between men and women, especially among healthy young adults, with gender differences seen only in elderly populations [53–55].

4.2. Virtual Reality Environment

The generation of highly photorealistic, real-time virtual environments is challenging. The immersiveness and realism in the VE used in the study may be interpreted as low. However, one can observe a marked increase in environment quality over the history of VE research [56,57]. Given the state of VE research and practice, the graphical quality of the scenes viewed in this study is consistent with contemporary work. Research has been conducted investigating whether graphical quality influences how observers perceive virtual spaces. Varying levels of quality, ranging from monochromatic wireframes to photographic panoramas, found negligible effects of graphical quality [56]. Jones et al. 2013 compared geometrically identical environments viewed in headsets with differing resolutions and found that spatial perception was not affected by graphical resolution [58]. Generally, it is considered that as long as conflicting graphical spatial cues are avoided, the overall graphical quality has seemingly small effects on how observers perceive a space. The current findings align with more recent literature, supporting the use of VR to safely induce mobility-related anxiety and potential habituation to anxiety-inducing VEs [13].

4.3. Limitations

Limitations in the current study include the testing of healthy college-aged individuals, the lack of other biomechanical assessments, such as the use of 3D motion capture to assess whole body and COM kinematics, the use of electromyography to assess lower-extremity postural muscle responses, the use of electroencephalography to assess cognitive measures, and the use of physiological assessments, such as heart rate responses. Finally, the sample of participants in the study included an uneven split in gender, with predominantly more females, for which the rationale was discussed earlier.

4.4. Future Work

Thus, future studies should investigate the impact of virtual claustrophobic simulations using comprehensive biomechanical, cognitive, and physiological measures and with learning and retention trials. Testing is imperative among all individuals, especially with different age groups, such as young, middle aged, and elderly, and clinical populations with specific claustrophobic or other anxiety disorders. Future studies should also attempt to create high immersiveness and realism with the VE.

5. Conclusions

In conclusion, virtual claustrophobic simulations involving “the walls closing in”, altered postural control responses in a group of young healthy adults. Specifically, these “wall moving” perturbations induced significantly decreased postural sway excursions, but significantly faster postural sway velocities, indicating a postural bracing strategy when exposed to virtual claustrophobic simulations. Additionally, these types of perturbations are susceptible to learning effects, which could serve as the basis for future interventions for those with claustrophobia. Findings from the study offer insights to postural control behavior under virtual claustrophobic simulations and can potentially aid in VR exposure therapy for individuals with claustrophobia as well as alternative postural control training through the induction of virtual-visual postural perturbations and postural threats.

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Abbreviations

VR	Virtual Reality
VE	Virtual Environment
CP	Claustrophobia
COP	Center of Pressure
COM	Center of Mass
No VR	Real Environment (not virtual)
VR CP	Virtual Reality Claustrophobia Environment
VR CP1, VR CP2, VR CP3	Virtual Reality Claustrophobia Trials 1, 2, 3
SSQ	Simulator Sickness Questionnaire
PAR-Q	Physical Activity Readiness Questionnaire
ML	Medial-lateral
AP	Anterior-posterior
RMS	Root Mean Square
95% EA	95% Ellipsoid Area
CDC	Center for Disease Control
IRB	Institutional Review Board

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