Staring Down the Elevator Shaft: Postural Responses to Virtual Heights in an Indoor Environment

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Abstract

Postural control strategies for upright stance adapt when balance is threatened. We investigate behavioral indicators for control strategy change in Virtual Reality (VR). Previous VR research has shown increased postural sway during virtual height exposure, but most studies focus on outdoor-like environments with extensive visual cues that may influence balance. In contrast to these outdoor studies, our indoor VR results indicate that virtual height exposure increases the mean power frequency (MPF) of sway while reducing anterior-posterior (AP) sway range. We also find an anterior shift of the Center of Pressure (CoP) when there are vertical drops both on the front and back. These findings suggest a strong context-dependence of the strategy humans employ to counteract perceived threat and heightened neuromotor control for balance stabilization.

Keywords: Fear of Heights; Balance Control; Postural Sway; Virtual Reality

Introduction

The study of Fear of Heights (FoH) has increasingly leveraged Virtual Reality (VR) to simulate height exposure under controlled and safe conditions. VR environments enable researchers to replicate various height-related scenarios, such as standing on elevated platforms (Wuehr et al., 2019; Bzdúšková, Marko, Hirjaková, Riečanskỳ, & Kimijanová, 2023; Raffegeau et al., 2020) and roof edges (Jian, Hwang, & Liang, 2024) or walking on planks atop skyscrapers (Krupić, Žuro, & Corr, 2021; Zhu, Chen, & Lin, 2021) and cliffs (Dietz et al., 2022). Simulations can range in height from a few meters to over 100 meters, creating a flexible platform for eliciting fear responses comparable to those observed in real-world settings.

Key findings from these studies emphasize the significant physiological and postural effects of simulated height exposure, particularly changes in center of pressure (CoP) dynamics. Across various setups, participants exposed to virtual heights consistently exhibit increased general CoP sway amplitude and frequency, indicating reduced postural stability. These effects are especially pronounced in individuals with pre-existing FoH, who exhibit heightened body sway and exaggerated physiological responses such as elevated heart rate. Directional CoP changes also reveal distinct patterns. In the medial-lateral (ML) direction, exposure to virtual heights leads to increased sway amplitude, reflecting heightened lateral instability as participants attempt to maintain balance on visually intimidating platforms. Conversely, in the anterior-posterior (AP) direction, studies show mixed findings: some show decreased sway amplitudes, likely due to a stiffening strategy aimed at limiting forward and backward movement (Cleworth, Horslen, & Carpenter, 2012), while others observe increased sway amplitude at more extreme virtual heights, possibly driven by fear-induced overcompensation (Wuehr et al., 2019).

Postural adjustments in these scenarios often involve increased muscle co-contraction and greater reliance on visual inputs for balance. These adaptive strategies, while intended to stabilize posture, can sometimes exacerbate instability, as observed in studies investigating visual exploration and postural responses to virtual heights (Horslen, Murnaghan, Inglis, Chua, & Carpenter, 2013; Kugler, Huppert, Schneider, & Brandt, 2014). The interplay between fear, sensory input, and motor strategies highlights the complex nature of postural control under height-induced threat. VR environments have demonstrated a capacity to elicit fear and postural responses comparable to real-world height exposure. (Cleworth et al., 2012) found that participants in virtual height scenarios displayed physiological and balance responses similar to those induced by actual heights, underscoring the ecological validity of VR-based research for studying FoH.

Most VR-based experiments examining the effects of height exposure focus on outdoor-like environments in their simulations. These settings, such as an open-air elevator (Bzdúšková et al., 2023) or wooden platforms attached to the exterior of tall buildings (Wuehr et al., 2019) and roof edges (Jian et al., 2024), often feature urban scenery with numerous visual cues. As posture control is influenced not only by height exposure but also by these complex visual environments, findings from these studies may not directly translate to indoor environments.

To address this gap, our study investigates how exposure to heights influences human posture control in an indoor virtual environment, as shown in Fig. 1. Specifically, we aim to determine whether increased sway in fearful individuals results from excessive control efforts, leading to increased motor noise, or whether it reflects an adaptive strategy to enhance visual feedback regarding body posture. Another key limitation of prior studies is their sole reliance on pressure-sensitive posturographic platforms, which capture overall sway but fail to track joint-level oscillations that could reveal distinct control strategies. Our experiment addresses this gap by simultaneously measuring body-joint positions using an external RGB-D camera and postural control via a balance board, allowing for a more detailed analysis of the strategies individuals employ to maintain balance under fear-inducing conditions.

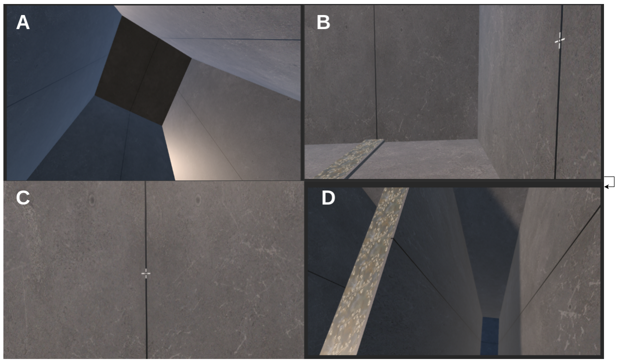

Figure 1: Different views of the virtual reality environment from the user's perspective. The environment consisted of a room with a high ceiling (A), up view. During the ground condition, the participants stood on a plank inside the room (B), side view (GC). During the height condition, the floor beneath the participants disappeared, leaving them standing on an elevated plank with vertical drops of 20 meters in both the front and back. (D), down view (HC). During the fixation phase of each experiment round, participants were required to focus on the cross displayed on the wall in front of them (C), front view.

Materials and Methods

This section describes our experimental setup, including the VR environment, sensors, and data collection tools, used to investigate the effects of virtual height exposure on postural control. Participants performed experimental tasks and completed self-report questionnaires. We collected synchronized data from multiple sensor streams for postural and physiological analysis.

Experimental Design

Participants A total of 39 participants were recruited for this study. However, the first 5 participants were excluded as they were part of a pilot session conducted before the experimental setup was finalized and another 5 participants were excluded due to missing data. This left 29 participants (mean age = 21.79 years, SD = 1.49).

Experimental Procedure All participants provided informed written consent and received standardized instructions. They first completed a battery of questionnaires (see Section Questionnaires). Subsequently, the participants were equipped with physiological and motion-tracking devices: a Polar H10 sensor for electrocardiography (ECG) (Polar Electro, 2017), a Nintendo Wii Balance Board for postural sway measurement (Nintendo, 2008), and an HTC Vive Pro head-mounted display (HMD) (HTC Corporation, 2018) fitted with the Pupil Labs HTC Vive Add-On for eye-tracking (Pupil Labs GmbH, 2016). Gaze calibration and data capture were conducted using Pupil Core software (v3.5.1) (Pupil Labs GmbH, 2021). The experimental setup is illustrated in Fig. 2.

Motion and Physiological Data Acquisition Postural sway data were captured simultaneously using the Nintendo Wii Balance Board (Nintendo, 2008) and a Microsoft Kinect v2 sensor (Microsoft, 2014). The Kinect sensor was positioned 2.5 m from participants at a 37° angle relative to their body orientation, providing complementary full-body motion tracking. ECG signals were continuously recorded via the Polar H10 sensor paired with a Polar Pro Strap (Polar Electro, 2017).

Data Collection and Synchronization All data streams were time-synchronized using the Lab Streaming Layer (LSL) (Kothe, 2014) and consolidated with LabRecorder software (v1.16.4)[1]. The following tools facilitated real-time data streaming from each device:

- LSL Kinect (v1.2.0rc)[2] for Kinect data (Microsoft, 2014),
- WiiBalanceWalker(v0.4)[3] and Wiimote (v0.2.0)[4] for Wii Balance Board data (Nintendo, 2008),
- PolarBand2lsl (v1.0.0)[5] for ECG data from the Polar H10 sensor (Polar Electro, 2017).

The virtual environment was developed in Unity (v2021.3.10f1; Unity Technologies, 2021) and executed on a Lenovo Legion 5 Pro 16ARX8 (Lenovo, 2023). The full experiment code and data processing scripts will be published upon acceptance.

Experimental Task Each trial consisted of three phases: (1) a 20-second exploration phase where participants freely observed the virtual environment, (2) an anxiety rating on an 11-point Likert scale (0 = not at all, 10 = greatest possible), and (3) a 60-second fixation phase in which participants stood still, keeping their arms relaxed while fixating on a cross at eye level.

The experiment consisted of two conditions: a Ground Condition (GC), where participants experienced a flat virtual environment, and a Height Condition (HC), where they stood on a virtual platform approximately 20 meters high. The experiment consisted of seven trials. The first trial was always a GC trial. This was followed by two randomized blocks, each containing one GC trial and one HC trial. The final part of the task consisted of a HC trial first, followed by a GC trial.

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[1] https://github.com/labstreaminglayer/App-LabRecorder

[2] https://github.com/KarimaBak/LSL-KinectV2

[3] https://github.com/lshachar/WiiBalanceWalker/releases/tag/v0.4

[4] https://github.com/labstreaminglayer/App-Wiimote

[5] https://github.com/markspan/PolarBand2lsl

Figure 2: Experimental setup showing the VR and data acquisition devices. Participants stood on the Wii Balance Board while wearing the HTC Vive Pro head-mounted display equipped with the Pupil Labs eye-tracker. Postural sway data were collected using the Wii Balance Board and Microsoft Kinect v2 sensor, placed 2.5 m away at a 37° angle with the anterior direction. Electrocardiography (ECG) was measured using the Polar H10 sensor. The setup was synchronized using the Lab Streaming Layer for accurate multimodal data integration.

Questionnaires Participants completed self-report measures before and after the VR task. Prior to the task, participants completed the STICSA (21-item state scale) (Ree, French, MacLeod, & Locke, 2008), the ASI-3 (Anxiety Sensitivity Index) (Taylor et al., 2011), the short-form STAI (10 items) (Grimm, 2009), and the PANAS State (Time Point 1) (Watson et al., 2012). Additionally, they responded to individual items assessing prior VR experience and fear of heights (0-6 scale).

After the task, participants completed the PANAS State (Time Point 2) (Watson et al., 2012) and the GASE (Generic Assessment of Side-Effects) (Rezapour, Emmelkamp, Faramarzi, & Krijn, n.d.). Finally, they provided qualitative responses regarding their experience, including their thoughts on the study's purpose and any feedback for the experimenters. Questionnaires were administered at specific time points corresponding to the experimental phases (see Section Experimental Task).

Data Processing and Analysis

Center of Pressure (CoP) CoP data were obtained from force measurements at the four corners of a balance board (228 mm × 433 mm): Top Left (TL), Top Right (TR), Bottom Left (BL), and Bottom Right (BR).

The total force exerted on the board was calculated as:

$$F_{\text{total}} = W_{\text{TL}} + W_{\text{TR}} + W_{\text{BL}} + W_{\text{BR}}. \quad (1)$$

The mediolateral (ML) and anteroposterior (AP) CoP were computed as:

$$\text{CoP}_{\text{ML}} = \frac{\sum W_i X_i}{F_{\text{total}}}, \quad \text{CoP}_{\text{AP}} = \frac{\sum W_i Y_i}{F_{\text{total}}}. \quad (2)$$

Here, W_i is the force from the i-th sensor, with X_i and Y_i representing its coordinates relative to the board's center. The left and right sensors were positioned at $-L/2$ and $L/2$ along the ML axis, and the top and bottom sensors at $W/2$ and $-W/2$ along the AP axis, where $L = 433$ mm and $W = 228$ mm. This approach calculates CoP as the weighted average of sensor positions, reflecting postural control in both directions.

We computed the following posturographic measures for both ML and AP directions:

- Mean Position (Mean): Average CoP displacement.
- Standard Deviation (STD): Variability in CoP displacement.
- Range: The difference between the maximum and minimum CoP values.
- Mean Power Frequency (MPF): A 4th-order Butterworth low-pass filter (5 Hz) was applied to reduce noise. MPF was then computed using a Hann-windowed Fast Fourier Transform (FFT):

$$\text{MPF} = \frac{\sum f_i P_i}{\sum P_i}, \quad (3)$$

where f_i and P_i denote frequency bins and their corresponding power spectral density.

Postural Sway Characteristics: Principal Component Analysis To examine postural sway patterns, we applied Principal Component Analysis (PCA) to the CoP data, focusing on the ML and AP components. The first principal component (PC1) represented the direction with the greatest variance in sway, indicating the dominant sway direction, while the second principal component (PC2) captured orthogonal sway variability.

The angle of PC1 was computed using:

$$\text{PC1}_{\text{Angle}} = \arctan(\text{PC1}_y, \text{PC1}_x)$$

This angle was used to categorize sway into AP, ML, and Diagonal directions. The explained variance ratio of PC1 quantified the extent to which sway was focused in a single direction, reflecting control of only a subset of the available degrees of freedom, in line with the 'minimum intervention principle' (Todorov & Jordan, 2002).

Joint Oscillation Characteristics We used Kinect motion capture data to track the two-dimensional position of each joint in the ML (x coordinate) and AP (y coordinate) directions. For each joint j, we first computed its mean position $\bar{x}_j, \bar{y}_j$ across the entire trial. Then, for each frame t, we derived the absolute displacement from the mean as:

$$\text{ML amplitude} = |x_{j,t} - \bar{x}_j|, \quad \text{AP amplitude} = |y_{j,t} - \bar{y}_j|.$$

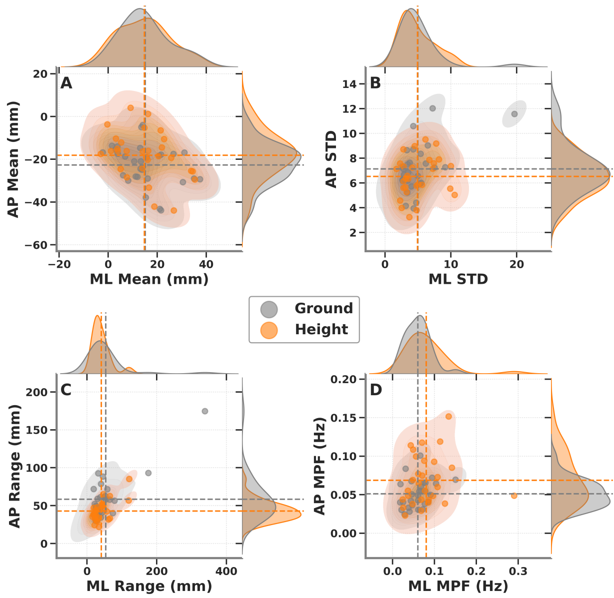

Figure 3: Comparison of center-of-pressure (CoP) metrics across Fear (orange) and No Fear (gray) conditions. (A) Mean CoP in mediolateral (ML) and anteroposterior (AP) directions, (B) Standard deviation of CoP, (C) Range of CoP displacement, (D) Mean power frequency (MPF) of CoP oscillations. Contour densities and marginal histograms indicate each condition's distribution of data points. Dashed lines mark mean values for reference.

Heart Rate Change (HRC) ECG signals were filtered using a 4th-order Butterworth bandpass filter (0.5–50 Hz). R-peaks were detected, and RR intervals were calculated to derive heart rate metrics. Heart rate change (HRC) was quantified as the difference in average heart rate between consecutive trials. HRC was analyzed across trials where participants experienced Ground and Height conditions in direct sequence. To focus on the physiological transitions between these conditions, we selected only trials where Ground and Height occurred consecutively. Trials that did not meet this criterion were excluded. A Mixed Linear Model (MLM) was applied to assess the impact of Condition (Ground vs. Height) and trial progression (Trial) on HRC, with subject-level random effects to account for repeated measures.

Psychological Measures State anxiety was measured using the **STICSA**, which includes two subscales: *Cognitive* and *Somatic* anxiety. Items were rated from 1 (*Überhaupt nicht*, "Not at all") to 4 (*Sehr stark*, "Very much"), with higher scores indicating greater anxiety levels.

Results

Mixed-Effects Modeling of CoP

We fitted a Mixed Linear Model(MLM) on each postural metric (Mean, STD, Range, MPF in ML and AP directions), for the experimental conditions (GC/HC) as a fixed effect and a random intercept for subject. Table 1 and Fig. 3 show the results.

Metrics	β	95% CI	*p*
ML Mean	-0.36	$[-1.45, 0.72]$	0.509
AP Mean	**4.55**	[2.88, 6.21]	$p < 0.001$
ML STD	-0.05	$[-1.08, 0.97]$	0.921
AP STD	-0.61	$[-1.24, 0.016]$	0.056
ML Range	-12.76	$[-36.56, 11.04]$	0.293
AP Range	**-15.54**	[-26.39, -4.70]	$p = 0.005$
ML MPF	**0.020**	[0.000, 0.040]	$p = 0.045$
AP MPF	**0.017**	[0.009, 0.026]	$p < 0.001$

Table 1: Linear mixed-effects model results comparing the Height Condition (HC) vs. Ground Condition (GC). A positive β indicates that HC is higher than GC. Bold rows indicate $p < 0.05$.

- **CoPAP Mean**: HC was significantly higher than GC ($\beta = 4.55$, $p < 0.001$), indicating participants stood more anteriorly on average in the HC condition.
- **CoPAP Range**: HC exhibited a significantly smaller AP range than GC ($\beta = -15.54$ mm, $p = 0.005$).
- **CoP MPF**: HC had a significantly higher mean power frequency in both AP and ML directions compared to GC ($p < 0.05$).
- **Other Measures** CoP ML Mean, CoP ML STD, CoP ML Range showed no significant differences ($p > 0.05$). The AP STD difference between GC and HC was borderline significant ($p = 0.056$).

These results indicate that exposure to virtual height increases the oscillatory frequency of sway (MPF), reduces the sway range in the anterior-posterior (AP) direction, and shifts the body position anteriorly (AP mean).

Principal Component Analysis of Postural Sway

Principal Component Analysis (PCA) revealed that the dominant sway direction in both the Height Condition (HC) and Ground Condition (GC) was in the AP direction. Specifically, AP sway accounted for 58% of movements in the HC and 72% in the GC (Figure 5A).

While the HC exhibited a slight increase in diagonal sway (27%) and ML sway (**14%**), these shifts were not statistically significant ($p = 0.303$). The explained variance ratio of PC1 was consistent across conditions ($M = 0.75, SD = 0.12$), suggesting similar directional consistency in sway.

Joint Oscillation Characteristics

In Figure 4, we observe that Height vs. Ground leads to visually distinguishable patterns in average joint displacement. For example, joints in the upper limbs may show slightly

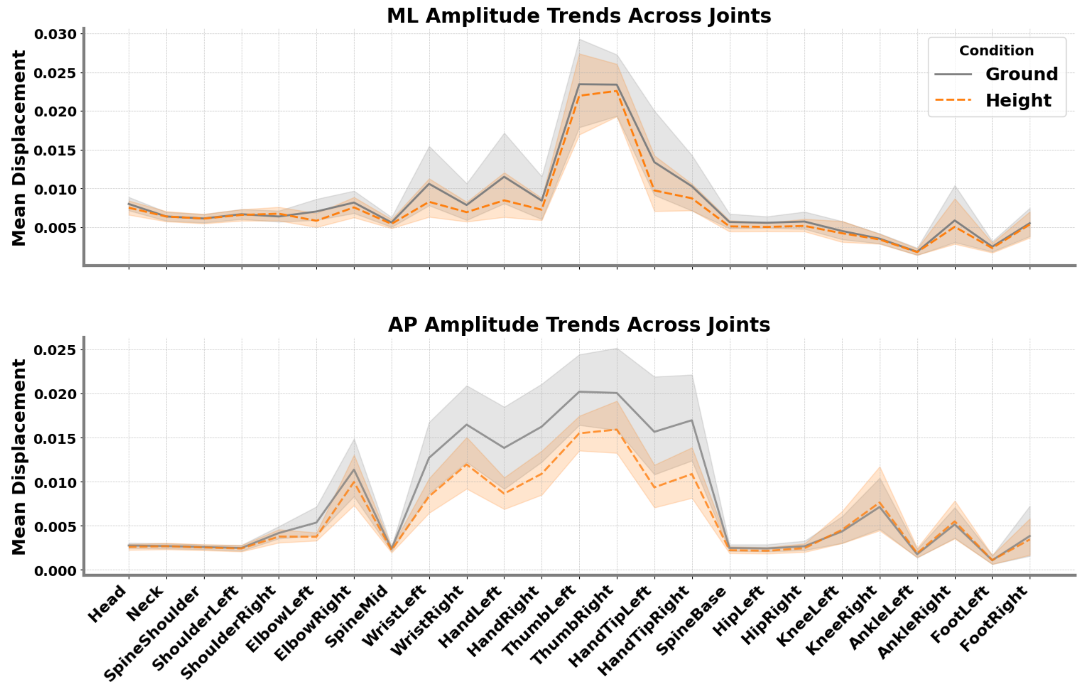

Figure 4: Mean Displacement (Amplitude) Across Joints. The top panel shows *ML amplitude* while the bottom panel shows *AP amplitude*, with joints arranged along the x-axis from head to foot in approximate anatomical order. **Orange** denotes the *Height* condition and **gray** denotes *Ground*. Shaded regions represent ±1 SD across participants. Larger amplitudes indicate greater movement relative to that joint's mean position. Notably, certain joints (e.g., trunk and arms) exhibit increased displacement in one condition compared to the other, suggesting differential postural adjustments.

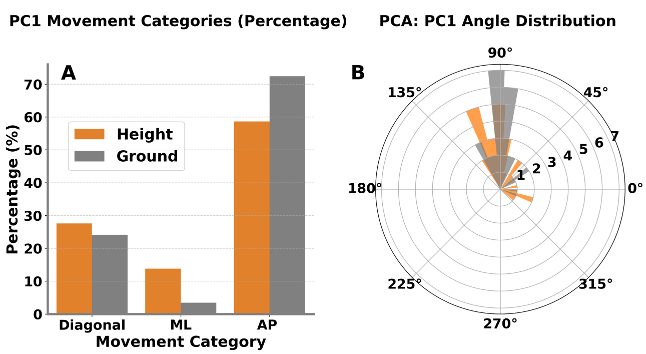

Figure 5: Principal Component Analysis (PCA) of Postural Sway. (A) Percentage of dominant sway directions categorized as Diagonal, Mediolateral (ML), and Anteroposterior (AP) for Height (orange) and Ground (gray) conditions. (B) Polar histogram showing the distribution of PC1 angles. Both conditions predominantly show AP sway, with slight increases in diagonal and ML sway under Height. However, these differences were not statistically significant.

higher ML amplitude (top panel) under Height (orange) than Ground (gray). In contrast, specific differences in AP amplitude (bottom panel) were observed around the wrist or trunk regions. Overall, these amplitude trends can inform us about how participants restrict forward-backward sway under the Height condition, indicating a more cautious postural strategy. Lower body joints (e.g., hips, knees, ankles) show less differentiation between conditions, suggesting that postural adjustments primarily occur in the upper body.

Heart Rate Change Across Conditions

The model revealed a significant increase in heart rate change (HRC) following the Height Condition (HC) compared to the Ground Condition (GC) ($\beta = 2.994$, $SE = 1.144$, $p = 0.009$), indicating an increased autonomic response after exposure to virtual height. Trial progression also showed a significant effect at the second trial ($p = 0.017$), with a marginal effect observed at the third trial ($p \approx 0.076$), suggesting potential adaptation over time.

Correlation between Psychological and Physiological Metrics

We explored the relationship between postural sway, heart rate variability, and anxiety dimensions using the State-Trait Inventory for Cognitive and Somatic Anxiety (STICSA) (Ree et al., 2008).

Metrics	β	95% CI	p
Condition [HC]	**2.994**	[0.756, 5.231]	$p = 0.009$
Trial	**2.729**	[0.492, 4.967]	$p = 0.017$

Table 2: Mixed Linear Model results for heart rate change (HRC) across Ground Condition (GC) and Height Condition (HC). A positive β indicates higher HRC from GC to HC. Bold rows indicate $p < 0.05$.

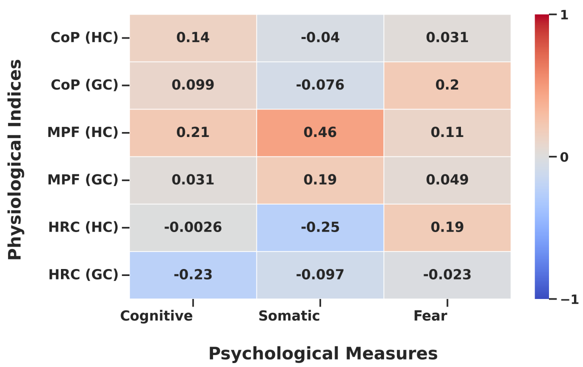

Figure 6: Correlation between Psychological Measures and Physiological Indices. This heatmap illustrates the correlations between cognitive and somatic anxiety (measured by the STICSA), fear of height, and physiological indices: Mean CoP, MPF, and Heart Rate Change (HRC) under both Height (HC) and Ground (GC) conditions. Positive correlations are shown in red and negative correlations in blue, with the strength of the correlation indicated by the color intensity.

In Figure 6, CoP represents the mean-sway magnitude (CoP-AP and CoP-ML combined), MPF reflects the postural control effort, and HRC captures the autonomic nervous system activity linked to stress responses. We find a positive correlation between somatic anxiety and MPF (HC) ($r = 0.46$), indicating a strong link between physical anxiety symptoms and postural adjustments in height conditions. Cognitive anxiety demonstrates moderate correlations with MPF (HC) and CoP (HC), while fear of height correlates positively with HRC (HC) and CoP (GC).

Discussion

The findings from our indoor VR height exposure experiment reveal distinct postural adaptations, particularly in CoP dynamics. In our study, participants exposed to virtual height exhibited a significant reduction in AP sway range (β = -15.54 mm, p = 0.005) and an anterior shift in mean AP position (β = 4.55, p $<$ 0.001) compared to the ground condition. Additionally, oscillatory frequencies in both ML and AP directions significantly increased under height exposure, as evidenced by elevated MPF values (ML MPF β = 0.020, p = 0.045; AP MPF β = 0.017, p $<$ 0.001).

These results differ from the general trends observed in studies conducted in outdoor-like VR environments, where exposure to heights typically results in increased CoP sway amplitude in both ML and AP directions (Spartakov et al., 2024). For example, (Wuehr et al., 2019) reported heightened AP sway amplitude at extreme virtual heights, likely driven by fear-induced overcompensation. Similarly, (Krupić et al., 2021) found significant increases in ML sway when participants navigated a plank suspended between skyscrapers. In contrast, the reduced AP sway range observed in our study may reflect a stiffening strategy adopted by participants to counteract the perceived threat in a confined indoor environment, where expansive visual cues typical of outdoor VR environments are absent.

The observed anterior CoP shift contrasts with findings from (Cleworth et al., 2012), who documented a posterior shift during virtual height exposure, indicating an attempt to stabilize posture by leaning backward. A potential explanation for this difference may lie in our setup, where the virtual drop was not only in front of the participant but also behind them. This dual exposure likely discouraged the typical backward-leaning strategy observed in previous studies, prompting participants to adopt a forward-leaning stance as a compensatory response to the perceived threat from multiple directions.

The increase in MPF for both ML and AP directions further supports the notion of heightened neuromotor control during height exposure. This aligns with findings from (Horslen et al., 2013), who observed increased muscle spindle sensitivity under postural threat conditions. The combination of reduced sway amplitude and increased oscillatory frequency observed in our study indicates a tightly controlled yet potentially less adaptable postural strategy in response to height-induced threat.

In summary, our results indicate that the strategy which humans employ to stabilize their posture under threat depends strongly on the context in which the threat is presented.

Building on these findings, our future research will utilize inverse optimal control to gain deeper insights into the control strategies underlying postural responses to height exposure. This approach will enable us to develop a computational model that captures the interplay between postural threat (height exposure), the context in which the threat is experienced (e.g. indoor vs. outdoor), its cognitive effects (fear), and its physical manifestations (postural sway). Additionally, we will conduct a follow-up experiment manipulating virtual indoor height conditions by comparing scenarios where the floor disappears only in front versus both in front and behind. This will help isolate the specific influence of environmental constraints on postural control, further clarifying the distinctions between indoor and outdoor height exposure settings.

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