

Auditory, Vibrotactile, or Visual? Investigating the Effective Feedback Modalities to Improve Standing Balance in Immersive Virtual Reality for People with Balance Impairments Due to Type 2 Diabetes

M. Rasel Mahmud*
Computer Science
The University of Texas at
San Antonio

Alberto Cordova†
Kinesiology
The University of Texas at
San Antonio

John Quarles‡
Computer Science
The University of Texas at
San Antonio

ABSTRACT

Immersive Virtual Reality (VR) users often experience difficulties with maintaining their balance. This issue poses a significant challenge to the widespread usability and accessibility of VR, particularly for individuals with balance impairments. Previous studies have confirmed the existence of balance problems in VR, but little attention has been given to addressing them. To investigate the impact of different feedback modalities (auditory, vibrotactile, and visual) on balance in immersive VR, we conducted a study with 50 participants, consisting of 25 individuals with balance impairments due to type 2 diabetes and 25 without balance impairments. Participants were asked to perform standing reach and grasp tasks. Our findings indicated that auditory and vibrotactile techniques improved balance significantly ($p < .001$) in immersive VR for participants with and without balance impairments, while visual techniques only improved balance significantly for participants with balance impairments. Also, auditory and vibrotactile feedback techniques improved balance significantly more than visual techniques. Spatial auditory feedback outperformed other conditions significantly for all people. This study presents implementations and comparisons of potential strategies that can be implemented in future VR environments to enhance standing balance and promote the broader adoption of VR.

Keywords: Virtual Reality, balance, postural stability, auditory feedback, vibrotactile feedback, visual feedback, VR accessibility, VR usability, Head-Mounted Display, diabetes.

1 INTRODUCTION

Immersive Virtual Reality (VR) technology, employing head-mounted displays (HMDs), has various applications, including education, physical fitness, rehabilitation, and entertainment. However, previous studies have demonstrated that HMDs had a negative impact on users' balance [9, 24, 33]. This poses a significant accessibility challenge for all, which is especially severe for individuals with balance impairments (BI) because VR exacerbates their balance issues, resulting in an increased risk of near falls and stumbling [12, 51]. Unfortunately, VR research and development have largely neglected the needs of these individuals, resulting in exclusive and inaccessible experiences. For example, HMDs are not widely utilized for visual feedback in rehabilitation programs because of balance issues, where projectors and large screens serve as the primary display medium. However, previous research suggested that HMDs offer a more immersive experience for visual feedback than projectors and give users a stronger sense of presence [1]. Theoretically, HMDs have the potential to engage participants more

effectively. Therefore, it is imperative to address the balance issues users face when wearing HMDs.

Despite these difficulties, not much study has been done to deal with these balance issues during immersion. Very few prior works investigated assistive feedback techniques (auditory, vibrotactile, and visual) to solve the problem. For example, Mahmud et al. [26] investigated the impact of several auditory techniques on balance in immersive VR for participants with multiple sclerosis (MS). They found that all auditory feedback conditions improved balance in VR for both those with and without BI, where spatial and center of pressure (CoP) auditory conditions outperformed others. However, their results found no significant difference between spatial and CoP conditions. They did not investigate any other feedback modalities in the study.

Vibrotactile feedback is a type of haptic feedback that specifically uses vibration as the mode of sensory feedback. Mahmud et al. [27] investigated the impact of several vibrotactile feedback modalities on VR balance for participants with MS. They found that all vibrotactile feedback conditions improved balance significantly for all participants. Spatial and CoP vibrotactile feedback performed significantly better for both groups of participants. However, they did not find a significant difference between spatial and CoP conditions. As a result, they were inconclusive about which one could be preferred between spatial and CoP conditions. Also, vibrotactile feedback was reported to lack immersion and interaction in many cases [8]. Nevertheless, they did not investigate and compare other feedback modalities in the study.

Based on the prior studies, we had three research questions: 1) Which feedback modality performs better for standing balance improvement in immersive VR: auditory, vibrotactile, or visual? 2) Which feedback type is better between spatial auditory and CoP auditory, and between spatial vibrotactile and CoP vibrotactile? 3) Can we apply the feedback modalities to people with different profiles (e.g., people with BI due to type 2 diabetes instead of MS)?

To fill the research gaps, our study explores the impact of different feedback modalities (auditory, vibrotactile, and visual) on balance in VR for participants with and without BI. Through empirical studies, participants attempted to maintain balance while standing in virtual environments (VEs) with various feedback modalities. Our study aimed to enhance the accessibility of HMD-based immersive VR by employing diverse types of feedback and assessing their effects on balance in immersive VR. Our major contributions include the following:

- We investigated the impact of three feedback modalities (auditory, vibrotactile, and visual) on balance in immersive VR and compared the modalities. Each of the feedback modalities had six study conditions. Thus, we investigated and compared 18 different feedback conditions. A few studies investigated only one kind of feedback modality during standing balance [11, 26, 27]. To our knowledge, no study has compared three different feedback modalities for standing balance improvement in immersive VR.

*e-mail: m.raselmahmud1@gmail.com, mrasel.mahmud@my.utsa.edu

†e-mail: Alberto.Cordova@utsa.edu

‡e-mail: John.Quarles@utsa.edu

- We found significant differences between spatial and CoP conditions for standing balance improvement for both auditory and vibrotactile feedback, which were not found before.
- We recruited participants with balance impairments due to type 2 diabetes, who were rarely considered in VR, and participants without balance impairments. We had 50 people in our study (25 with BI due to type 2 diabetes and 25 without BI).

2 BACKGROUND STUDY

2.1 Imbalance in Virtual Reality

Previous research reported that participants exhibited less balance control in VEs compared to real environments [21]. HMDs also provided inadequate stabilization of balance in VEs compared to real environments [20]. Wearing HMDs hindered participants' visual feedback from the real world, resulting in balance loss due to end-to-end latency and illusory sensation of body movement induced by VEs [28,46]. Prolonged immersion in VR environments further contributed to postural instability [31]. Some studies also explored the effects of imbalance on walking patterns [47]. Thus, balance issues are well-documented problems experienced by users in HMD-based VR. However, there has been limited effort to address this problem.

2.2 Assistive Feedback Technology for Balance Improvement

2.2.1 Auditory Feedback

The utilization of auditory cues based on the user's body tilt proved effective in rectifying posture for individuals without BI [4] in non-VR environment. In the case of participants with BI, the employment of spatial audio, which allows users to discern sound sources in three-dimensional space, demonstrated efficacy in maintaining stability in non-VR environment [48]. Ross et al. [37] reported that auditory white noise decreased swaying in the posture of individuals aged 65 and above in non-VR environment. Hasegawa et al. [16] reported center of pressure (CoP) based auditory feedback improved balance for participants with BI in the real world. Furthermore, rhythmic audio, characterized by a steady beat, exhibited the potential to enhance gait for individuals grappling with neurological issues (such as multiple sclerosis and Parkinson's) and the elderly [14] in non-VR environments.

However, limited prior research has examined the use of auditory techniques in VR environments to improve balance. For instance, Gandemer et al. [13] investigated the postural sway of blindfolded individuals and found that spatial audio in an immersive VE enhanced postural stability. Spatial audio is generally favored in VR due to its ability to enhance immersion [32,52]. Mahmud et al. [26] studied the impact of various auditory techniques on balance in immersive VR for participants with MS. However, their results did not reveal a significant difference between spatial and CoP conditions.

2.2.2 Vibrotactile Feedback

Kingma et al. enrolled 39 individuals who had an imbalance due to severe bilateral vestibular loss in a study to examine the impact of vibrotactile feedback on balance and mobility in real-world scenarios [23]. The participants were instructed to wear a tactor belt equipped with 12 vibrators around their waist for two hours daily over the course of a month. The vibrators were controlled by a microprocessor and activated as needed. The participants were asked to rate their balance and mobility on a scale of 0 to 10 both before and after the one-month period. The study demonstrated a significant increase ($p < .00001$) in average mobility and balance scores when comparing usage with the vibrotactile feedback. Rust et al. investigated how vibrotactile feedback influenced trunk sway in 15 individuals with MS under real-world [40]. The participants wore a headband fitted with eight 150 Hz vibrators positioned at

45-degree intervals. The vibrators were triggered when a predefined sway threshold was exceeded in the corresponding direction. The participants engaged in a series of training, gait, and balance tasks over a four-week span. The authors utilized the SwayStar system to measure trunk sway with the vibrotactile feedback. The findings indicated a significant reduction in trunk sway ($p < .02$) compared to the baseline after one and two weeks of training with vibrotactile feedback. In a study conducted by Ballardini et al. [2], 24 participants were recruited to explore the influence of vibrotactile feedback on standing balance in a non-VR environment. The researchers utilized two vibration motors positioned on the front and back of the body to administer vibrotactile feedback. Two encoding methods were compared: continuous vibration and vibration with a "dead zone" where no vibration occurred when the signal was below a certain threshold. Additionally, the impact of the informational quality of the feedback was assessed using sham vibrations unrelated to actual postural oscillations. Nine participants were exposed to continuous vibration, sham feedback, and fifteen experienced dead zone feedback. The results revealed that synchronized vibrotactile feedback led to a significant reduction in sway in both the anterior-posterior and medial-lateral directions. The presence of sham vibrations actually increased postural sway, highlighting the importance of the encoded information.

However, Most studies involving vibrotactile feedback did not take place in VR environments. Among the very few, Mahmud et al. [27] investigated the impact of various vibrotactile feedback techniques on VR balance for participants with MS. However, they found no significant difference between spatial and CoP conditions, making it inconclusive to determine the preferred option. Additionally, vibrotactile feedback has been reported to lack immersion and interaction in many cases [8].

2.2.3 Visual Feedback

Although most previous research was focused on users without disabilities, Ferdous et al. [44] conducted a study with 14 participants (7 with BI due to MS and 7 without BI) to investigate the effect of a Static Rest Frame (SRF) on postural stability in VR and augmented reality (AR). Participants used a Wii balance board and played a balancing game in which they had to dodge virtual tennis balls. The study employed a Vive HMD for VR and HoloLens for AR experiences. Results showed that the SRF significantly improved postural stability for participants with MS in both VR and AR environments.

Ferdous et al. [12] also studied how different visual components (frame rate, field of view, display resolution) affected balance in VR for both persons with and without BI. They reported that postural instability increases significantly with the decrease of frame rate and field of view for the participants with BI, but no effect of display resolution on balance was found. On the other hand, they did not find any effect of any visual components on balance for the participants without BI.

Mohebbi et al. [29] examined the impact of visual field amplitude and velocity on the dynamic body sway of healthy adults. Participants stood on a balance board and researchers manipulated the amplitude and velocity of the visual field to investigate their effects on postural stability. They found that increasing visual input amplitude contributed to imbalance, while velocity had a nonlinear effect. However, these studies did not compare other feedback modalities which we did in our study. Also, we included people with BI due to type 2 diabetes which was not the case for the prior studies. Balance problems are more likely to be a result of vascular diseases, which can be a potential complication of type 2 diabetes and it was reported that diabetes is related to peripheral neuropathy for which technology can be used as an alternative treatment [34].

3 METHODS

3.1 System Description

Balance Measurement: To assess participants' balance in each scenario, the BTrackS Balance Plate was employed. The balance plate had a sampling frequency of 25 Hz.

Safety Equipment: To prevent unexpected falls, participants were equipped with a harness connected to a weight-bearing suspension system. The suspension system and harness were provided by Kaye Products Inc.

Computers, VR Equipment, and Software: The VEs were developed using Unity3D. The VR setup included an HTC Vive headset with a 110-degree field of view, 2160 x 1200 pixel resolution, and a 90 Hz refresh rate. To ensure an optimal audio experience and minimize external noises, noise-canceling headphones were used. The VE rendering and data recording were performed on a computer with the following specifications: Windows 10 operating system, 4.20 GHz Intel Core i7 processor, 32 GB DDR3 RAM, and an NVIDIA GeForce RTX 2080 graphics card. Data from the BTrackS Balance Plate were collected using NI LabView software (version 2020) and streamed to Unity3D via sockets.

Vibrotactile Equipment: We used three types of vibrotactile equipment from bHaptics (<https://www.bhaptics.com>): 1) Vest: participants wore a wireless vest equipped with 40 vibrotactile motors. The vest featured 20 motors on the front side and 20 on the backside, adjustable with shoulder snap buttons. It weighed 3.7 lbs. 2) Arm Sleeves: participants wore adjustable arm sleeves on both forearms, positioned between the wrist and elbow. Each arm sleeve contained six vibrotactile motors. The weight of each arm sleeve was 0.66 lbs. 3) Forehead: the device had six vibrotactile motors attached to the HMD, covering the area around the forehead. Its weight was 0.18 lbs. The vibrotactile motor positions have been shown in Figure 1 (a).

Environment: The research was conducted in a temperature-controlled laboratory with ample open space (over 600 sq ft). Throughout the study, only the participant and the experimenter had access to the lab. We used the same settings and environments for three studies.

3.2 Study Conditions: Auditory Feedback

To investigate the impact of auditory feedback on balance in VR, we examined four VR-based techniques for auditory feedback (static, rhythmic, CoP, spatial) and a condition with no audio. White noise was used as the auditory feedback instead of music or user-selected audio tones as it improves performance through stochastic resonance phenomena [17]. Previous non-VR studies have also reported the effectiveness of white noise in reducing postural sway [15,38,41,54]. We followed [26] to implement the auditory feedback conditions. **Static** condition involved playing white noise in headphones, unrelated to the listener's position. It has been reported to improve balance in elderly individuals in previous non-VR studies [37]. For **rhythmic** condition, white noise with a rhythmic beat at a 1-second interval was played. Previous research has suggested that hearing a steady beat can improve balance in individuals with neurological problems and the elderly in non-VR environments [14]. For **CoP** condition, white noise was played in headphones, similar to the static condition, but the pitch and stereo pan changed based on the CoP path obtained from the balance board. The pitch was mapped to the x-coordinate of the balance plate's CoP, and the stereo pan was mapped to the y-coordinate [16]. For **spatial** condition, simulated 3D audio using spatialized white noise was played in headphones. The sound's volume varied in each ear based on the user's head movements. When the user's head moved from the center position to any other direction, the audio volume was increased. The spatial audio was created using the Google Resonance Audio SDK in Unity

which uses head-related transfer functions (HRTFs) to model 3D sound effectively [5,35]. The coordinates of the 3D audio source and the participant in the VE were 0,1,0 and 0,0,0, respectively. The effectiveness of spatial audio on balance in the real world has been established in previous studies [13,48]. The **VR-baseline** condition served as a baseline to measure participants' balance in VR without auditory feedback. Participants wore headphones but did not receive any auditory feedback.

3.3 Study Conditions: Vibrotactile Feedback

To investigate the impact of vibrotactile feedback on balance in VR, we explored four categories of VR-based vibrotactile feedback conditions (static, rhythmic, CoP, and spatial) and a condition with no vibrotactile feedback. Audio-to-vibrotactile technology was used to translate the auditory feedback from the previous study conditions (section 3.2) into equivalent vibrotactile feedback for each vibrotactile condition. Eccentric Rotating Mass (ERM) actuators were used for all vibrotactile equipment and vibrotactile feedback was perceived in a similar way by all participants. We followed [27] to implement the vibrotactile feedback conditions. First, we attached the audio input to the Unity scenes. Then we provided the same static, rhythmic, CoP, and spatial audio from the auditory conditions as input to the Audio-to-vibrotactile technology from bHaptics ([bhaptics.com](https://www.bhaptics.com)) which generated static, rhythmic, CoP, and spatial vibrotactile feedback respectively. For the Audio-to-vibrotactile technology, we set the intensity level at 50% for both audio and vibration. However, we allowed participants to set the intensity level based on their comfort level during the study. For **static** condition, the vest, arm sleeves, and forehead vibration motors vibrated continually. The location of the user had no effect on the feedback. For **rhythmic** condition, the vest, arm sleeves, and forehead vibration motors vibrated at every 1-second interval. For **CoP** condition, when the participant moved from his center position on the balance board to any other side (e.g., left, right, front, or back), the participants felt greater vibration in the corresponding direction as we designed the vibration intensity to increase with the increase of CoP and vice versa. For **spatial** condition, the forehead bHaptics device vibrated based on head tilts, the vest vibration varied with its position detected by the Vive tracker, and the arm sleeves' vibration changed according to the Vive controllers' location. For the **VR-baseline** condition, participants still wore the HMD, bHaptics suit, arm sleeves, and forehead component, but no vibrotactile feedback was provided.

3.4 Study Conditions: Visual Feedback

For **static** condition, a virtual static frame ('+' sign within four boundaries) was displayed on the front wall, fixed to the users' view in VR (see figure 1(b)). The frame moved with the head-movement of the participants. This heads-up display was implemented based on prior work by Shahnewaz et al. [44]. **Rhythmic** condition was similar to the static condition, but the virtual static frame appeared at a 1-second interval instead of being continuously displayed. For the **CoP** condition, when participants stood at the center position on the balance board, a fixed texture appeared on the front wall. As participants moved away from the center position in any direction (left, right, front, back) texture boundaries shifted outward in a corresponding direction to indicate increased deviation of the CoP. This allowed participants to correct their posture by observing the texture boundaries. For the **spatial** condition, similar to the static condition, a virtual frame texture was used, but this time it was affixed to the wall and did not move with head movement. The coordinates of the texture and the participant in the VE were 0,3,0 and 0,0,0, respectively. For the **VR-baseline** condition, participants performed the task without any additional visual feedback but could still see the VR environment throughout the study.

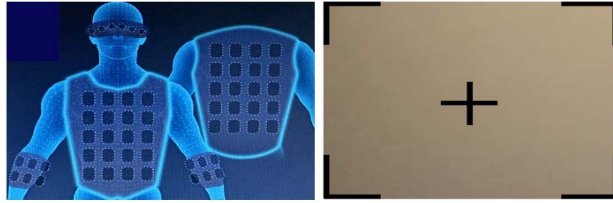


Figure 1: (a) Vibrotactile motor positions (left), (b) Texture for visual conditions (right)

Table 1: Descriptive statistics for participants

Participant Group	Participants		Age (years)		Height (cm)		Weight (kg)	
	Male	Female	Mean	SD	Mean	SD	Mean	SD
BI	12	13	46.5	13.0	164.84	12.62	82.79	22.18
Without BI	12	13	43.2	12.6	164.33	12.7	85.25	17.96

3.5 Hypotheses

Based on the prior works (described in sections 1 and 2), we had the following hypotheses:

H1: Compared to the non-VR baseline condition, balance will deteriorate without any additional feedback in the VR environment.

H2: Compared to the VR baseline condition, balance will be greatly improved in each of the VR-based feedback conditions (static, rhythmic, CoP, and spatial) for auditory, vibrotactile, and visual techniques.

H3: Auditory and vibrotactile feedback techniques will perform better than visual feedback techniques.

H4: Spatial auditory condition will outperform all other feedback conditions.

3.6 Participants, Selection Criteria, and Screening

Based on the study design and correlations identified in previous research [26, 27], a power analysis was conducted for the current study. The analysis was performed with a significance level (a) of 0.05, a power of 80%, and an expected medium effect size of 0.5. We did the power analysis considering the three different user studies. The results indicated that a sample size of 44 participants would be necessary. To account for potential dropouts, we recruited a total of 50 participants from the local area. 25 participants (12 males and 13 females) had experienced BI due to type 2 diabetes, while the remaining 25 participants (12 males and 13 females) did not have BI, type 2 diabetes, or any other physical conditions. However, the two groups were comparable in terms of age, weight, and height, with an age range of 40-50 years. Table 1 provides the mean and standard deviation (SD) values for age, height, weight, and gender information for both the BI and without BI groups. To recruit participants, we contacted various local rehabilitation institutions, hospitals, and community organizations.

3.7 Study Procedure

The study received approval from the Institutional Review Board (IRB). Prior to each user study, participants read and signed a consent form and provided information regarding their handedness to determine their dominant and non-dominant hands [7]. Then we described the whole study procedure. Next, the participants were attached to the harness and the suspension system. The participants were supported by the harness, stood on a balance board, and were barefoot for the entire study session.

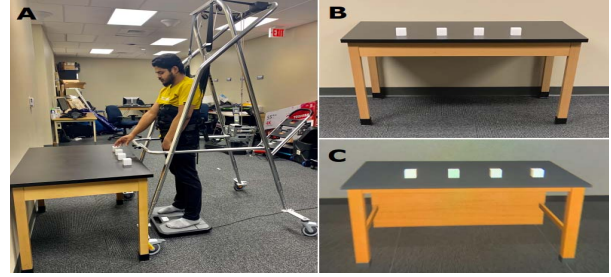


Figure 2: Standing reach and grasp task: (A) Workspace (B) Real environment (C) Virtual environment

3.7.1 Pre-Session Questionnaires

Participants completed the Activities-specific Balance Confidence (ABC) questionnaire [43] and the Simulator Sickness Questionnaire (SSQ) [22] at the beginning of the study.

3.7.2 Tasks

Participants performed standing reach and grasp tasks in both a VR environment and a non-VR environment. The VE was the replica of the real environment.

Standing Reach and Grasp Task (Non-VR) Participants reached for and grasped real objects within their reach on a table. The table had four objects (cubes with a width of 5.08 cm) placed at marked positions, with a distance of 24 cm between each pair of objects. The balance board was aligned with the middle of the table, positioned on the ground, and placed 12 cm away from the table. Participants stood barefoot and positioned each foot in marked places on the balance board. Participants rested their non-dominant hands on their upper thighs and used their dominant hand to reach and grasp the objects. They were instructed to lean forward to a comfortable distance without lifting their heels off the balance board and to stand straight while grasping the objects. The participants randomly grasped the four objects, lifted them to chest level, and returned them to the same positions. This task was implemented based on a previous study in non-VR environments by Cordova et al. [6]. Figure 2 shows a participant performing standing reach and grasp task and a comparison between the real environment and VE. This motor task was chosen because reaching is essential in everyday activities, and serves as a measure of balance in non-VR environments [3, 19, 49].

3.7.3 Baseline Measurements without VR

Participants stood on a BTrackS Balance Plate while supported by a harness to prevent falls. Balance measurements for the standing reach and grasp task were recorded for three trials, each lasting one minute.

3.7.4 VR Task

The VR task replicated the baseline task, with subtle differences due to the virtual environment. Participants used the HMD to view the VE for the virtual task. The VR task was repeated for each of the five auditory, vibrotactile, and visual feedback conditions, with three trials for each session. We counterbalanced the feedback conditions Latin square design to reduce learning effects. Each feedback condition (auditory, vibrotactile, and visual) took around 15 minutes to complete.

Standing Reach and Grasp Task (VR) Participants reached for and grasped virtual objects within their reach using the controllers. When the participants' controllers touched the virtual objects, the object's color changed to red. Participants then pulled the

trigger on the controller to grasp the objects in random order, lifted them to chest level, and released the trigger to return the objects to their original positions. The virtual environment and measurements were consistent with the baseline task.

3.7.5 Post-Session Questionnaires

At the end of the study, participants completed an SSQ and a demographic questionnaire.

Each of the study lasted approximately one hour per participant. Participants received a payment of 30 US dollars per hour and reimbursement for parking fees upon completion of the study.

4 METRICS

In our study, the measurement of balance primarily relies on the center of pressure (CoP) velocity [42]. CoP velocity is a widely accepted and valid indicator for assessing balance [25]. To calculate CoP, we utilized the formula developed by Young et al. [53], which takes into account the readings from the four pressure sensors of the BTrackS Balance Plate.

$$CoP(X, Y) = \frac{\sum_{i=1}^4 Weight_i * (x_i, y_i)}{\sum_{i=1}^4 Weight_i} \quad (1)$$

Where (x_i, y_i) = coordinates of the pressure sensor i , $Weight_i$ = weight or pressure data on the i th sensor, and $CoP(X, Y)$ = coordinates of the CoP.

Then, we computed the CoP path for all samples using the following formula.

$$CoP Path = \sum_{i=1}^{n-1} \sqrt{(CoP_{i+1}X - CoP_iX)^2 + (CoP_{i+1}Y - CoP_iY)^2} \quad (2)$$

Here, CoP_iX = X coordinate of CoP at i th second, and CoP_iY = Y coordinate of CoP at i th second.

Finally, we calculated CoP velocity by dividing the CoP path for all samples by the total data recording time for all samples (T).

$$CoP Velocity = \frac{CoP Path}{T} \quad (3)$$

4.1 Activities-specific Balance Confidence (ABC) Scale

To evaluate participants' confidence in performing specific daily activities, we administered ABC Scale [36]. This scale consists of 16 items that inquire about the individual's level of confidence in each activity. The ABC score is determined by summing the percentages assigned to each question (1-16), resulting in a maximum total of 1600. To obtain the ABC%, this sum is divided by 16. The scale's interpretation is as follows: 80% corresponds to a high level of physical functioning, 50-80% indicates a moderate level of physical functioning, and less than 50% indicates a low level of physical functioning.

4.2 Simulator Sickness Questionnaire (SSQ)

In order to identify participants who may be susceptible to severe cybersickness and explore its correlation with postural instability, we utilized the SSQ [22]. This questionnaire comprises 16 items that assess the physiological discomfort experienced by the participants.

5 STATISTICAL ANALYSIS

We assessed the normality of the data using the Shapiro-Wilk test, histograms, normal Q-Q plots, and box plots. We observed that the data exhibited a normal distribution for three feedback modalities among participants with and without BI. To examine potential variations in CoP velocities, we conducted a mixed-model ANOVA with

a 2x6 design, incorporating two between-subject factors (participants with BI and participants without BI) and six within-subject factors (six study conditions: Non-VR baseline, VR baseline, static, rhythmic, CoP, and spatial) for three modalities separately (section 6.1) and finally a combined analysis of the modalities to compare them (section 6.2). Whenever a significant difference was found, we conducted paired two-tailed t-tests for within-group and independent two-tailed t-tests for between-group comparisons as post-hoc analyses. To evaluate cybersickness, we performed two-tailed t-tests separately for each participant group, comparing pre-session SSQ scores with post-session SSQ scores. Additionally, we employed two-tailed t-tests to compare the ABC scores between the two participant groups, aiming to assess differences in physical ability. We applied Bonferroni correction to account for multiple comparisons in all statistical tests.

6 RESULTS

We first investigated the effect of auditory feedback on balance in immersive VR followed by vibrotactile, and visual feedback. Thus, we conducted three different studies with the same 50 participants. However, to compare between modalities, we have represented the results in Figure 3.

6.1 Within Modalities Comparisons on CoP Velocity

6.1.1 Auditory Feedback

After conducting ANOVA tests, we discovered a significant difference for participants with BI, $F(5,120) = 38.17, p < .001$, effect size $\eta^2 = 0.09$. We also found a significant difference for participants without BI, $F(5,120) = 37.94, p < .001, \eta^2 = 0.08$. Then, to identify differences between specific study conditions, we conducted pair-wise comparisons using two-tailed t-tests for both groups.

Non-VR Baseline vs. VR Baseline: We found a significant increase in CoP velocity in the VR baseline condition compared to the non-VR baseline condition for participants with BI; $t(24) = 25.19, p < .001, d = 1.5$ and for participants without BI; $t(24) = 23.88, p < .001, d = 1.1$. As balance decreases with the increase of CoP velocity [39,50], these results indicated that balance decreased significantly for participants with and without BI in the VR baseline condition compared to the non-VR baseline condition.

VR Baseline vs. VR-Based Auditory Conditions: For all VR-based auditory conditions, CoP velocity decreased significantly for participants with and without BI. Such as, in the static condition, for participants with BI; $t(24) = 7.19, p < .001, d = 0.3$ and for participants without BI; $t(24) = 6.99, p < .001, d = 0.2$. In rhythmic auditory feedback, for participants with BI; $t(24) = 8.01, p < .001, d = 0.3$ and for participants without BI; $t(24) = 7.66, p < .001, d = 0.3$. In CoP condition, for participants with BI; $t(24) = 11.89, p < .001, d = 0.7$ and for participants without BI; $t(24) = 11.33, p < .001, d = 0.5$. Furthermore, in spatial condition, for participants with BI; $t(24) = 14.77, p < .001, d = 0.9$ and for participants without BI; $t(24) = 14.03, p < .001, d = 0.9$. Results from ANOVA and post-hoc two-tailed t-tests also showed that there was a significant difference in CoP velocities for baseline conditions between the two groups (participants with and without BI); $t(24) = 8.97, p < .001, d = 0.6$. However, we did not notice any significant difference between other study conditions.

Comparisons Between VR-Based Auditory Conditions: We found that CoP velocity decreased significantly ($p < .01$) in spatial auditory feedback compared to other VR-based auditory feedback conditions (static, rhythmic, and CoP). CoP velocity also decreased significantly ($p < .01$) in CoP auditory feedback compared to static and rhythmic auditory feedback conditions. However, we did not observe any significant difference between static and rhythmic auditory feedback conditions.

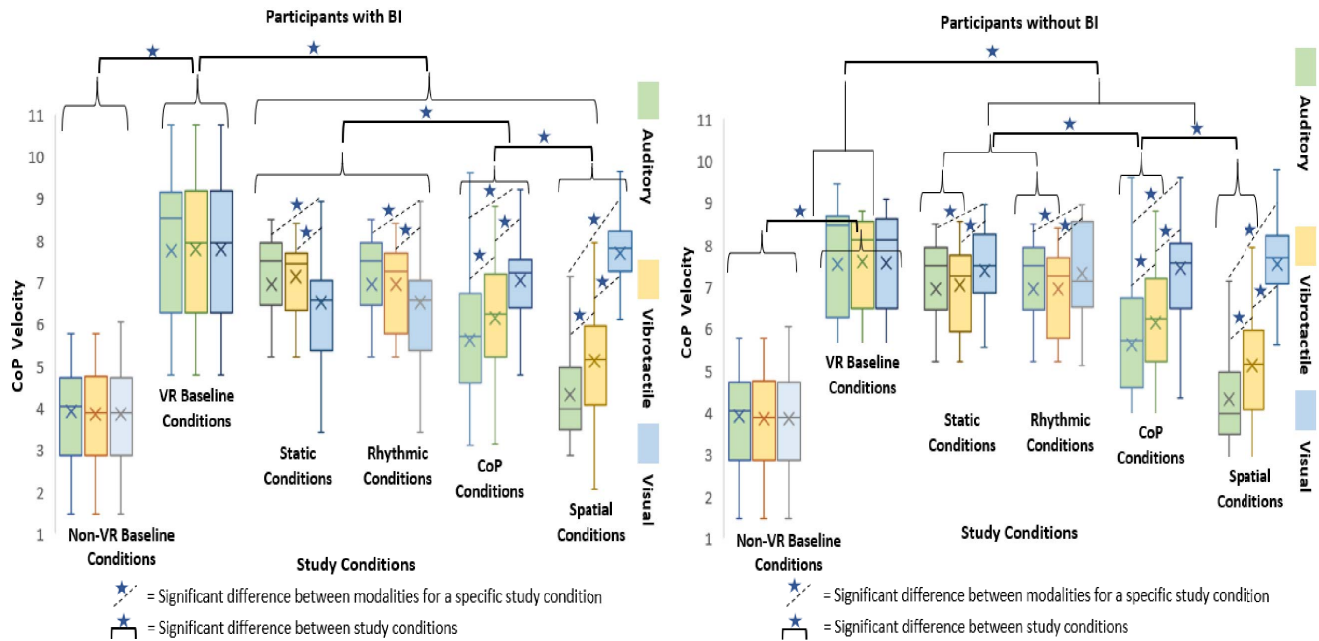


Figure 3: CoP velocity comparisons of different feedback modalities (auditory, vibrotactile, and visual) for all study conditions for standing reach and grasp task.

6.1.2 Vibrotactile Feedback

After running ANOVA tests, we observed a significant difference for participants with BI, $F(5,120) = 35.47$, $p < .001$, $\eta^2 = 0.08$. We also found a significant difference for participants without BI, $F(5,120) = 35.12$, $p < .001$, $\eta^2 = 0.07$. Next, to find differences between specific study conditions, we performed pair-wise comparisons using two-tailed t-tests for both groups.

Non-VR Baseline vs. VR Baseline We observed a significant increase in CoP velocity in VR baseline condition compared to non-VR baseline condition for participants with BI; $t(24) = 21.04$, $p < .001$, $d = 0.7$ and for participants without BI; $t(24) = 18.19$, $p < .001$, $d = 0.6$. Thus, the results also indicated that balance decreased significantly for participants with and without BI in the VR baseline condition compared to the non-VR baseline condition.

VR Baseline vs. VR-Based Vibrotactile Conditions For all VR-based vibrotactile conditions, CoP velocity decreased significantly for participants with and without BI. Such as, in static condition, for participants with BI, $t(24) = 6.98$, $p < .001$, $d = 0.3$ and for participants without BI; $t(24) = 6.55$, $p < .001$, $d = 0.2$. In rhythmic feedback, for participants with BI; $t(24) = 7.86$, $p < .001$, $d = 0.3$ and for participants without BI; $t(24) = 7.72$, $p < .001$, $d = 0.3$. In CoP feedback, for participants with BI; $t(24) = 10.09$, $p < .001$, $d = 0.5$ and for participants without BI; $t(24) = 10.02$, $p < .001$, $d = 0.5$. In spatial feedback, for participants with BI; $t(24) = 13.92$, $p < .001$, $d = 0.8$ and for participants without BI; $t(24) = 13.88$, $p < .001$, $d = 0.8$. Results from ANOVA and post-hoc two-tailed t-tests also showed that there was a significant difference in CoP velocities for baseline conditions between the two groups; $t(24) = 7.15$, $p < .001$, $d = 0.5$. However, we did not obtain any significant difference between other study conditions.

Comparisons Between VR-Based Vibrotactile Conditions: We found that CoP velocity decreased significantly ($p < .01$) in spatial vibrotactile feedback compared to other VR-based vibrotactile feedback conditions (static, rhythmic, and CoP). CoP velocity also decreased significantly ($p < .01$) in CoP vibrotactile feedback

compared to static and rhythmic vibrotactile feedback conditions. However, we did not observe any significant difference between static and rhythmic vibrotactile feedback conditions.

6.1.3 Visual Feedback

From the ANOVA tests, we found a significant difference for individuals with BI, $F(5,120) = 15.03$, $p < .001$, $\eta^2 = 0.04$. However, we did not find any significant effect for participants without BI for any tasks except for the baseline conditions. Next, we conducted the following pairwise comparisons by applying two-tailed t-tests to identify differences between specific study conditions.

Non-VR Baseline vs. VR Baseline We obtained a significant increase in CoP velocity in the VR baseline condition compared to the non-VR baseline condition for participants with BI; $t(24) = 17.22$, $p < .001$, $d = 0.6$ and for participants without BI; $t(24) = 15.31$, $p < .001$, $d = 0.4$. Thus, the results also indicated that balance decreased significantly for participants with and without BI in the VR baseline condition compared to the non-VR baseline condition.

VR Baseline vs. VR-Based Visual Conditions For static, rhythmic, and CoP visual conditions, CoP velocity decreased significantly for participants with BI. We obtained $t(24) = 7.11$, $p = .03$, $d = 0.4$ for static; $t(24) = 7.15$, $p = .02$, $d = 0.4$ for rhythmic; and $t(24) = 5.06$, $p = .04$, $d = 0.2$ for CoP condition. However, for spatial visual feedback, we did not find a significant difference in CoP velocity for participants with BI; $t(24) = 1.34$, $p = .09$, $d = 0.06$. Also, VR-based visual feedback techniques had no significant effect on participants without BI. Results from ANOVA and post-hoc two-tailed t-tests also showed that there was a significant difference in CoP velocities for baseline conditions between the two groups; $t(24) = 6.23$, $p = .03$, $d = 0.2$. However, we did not obtain any significant difference between other study conditions.

Comparisons Between VR-Based Visual Conditions: We found that CoP velocity decreased significantly ($p < .04$) in static and rhythmic visual feedback compared to CoP visual feedback condition for participants with BI. However, we did not observe any

significant difference between static and rhythmic visual feedback conditions. Also, there was no significant difference among the VR-based visual feedback conditions for participants without BI.

6.2 Between Feedback Modalities Comparisons

Effect size comparisons of different feedback modalities have been shown in Figure 4.

6.2.1 Auditory vs. Vibrotactile Feedback Conditions

We observed a significant decrease in CoP velocity in spatial auditory condition compared to spatial vibrotactile condition for participants with BI; $t(24) = 7.89, p = .03, d = 0.3$ and for participants without BI; $t(24) = 6.77, p = .02, d = 0.2$. Experimental results also revealed a significant decrease in CoP velocity in CoP auditory condition than CoP vibrotactile condition for participants with BI; $t(24) = 7.08, p = .03, d = 0.3$ and for participants without BI; $t(24) = 6.93, p = .03, d = 0.2$. However, we did not find any significant difference in static and rhythmic conditions between auditory and vibrotactile feedback.

6.2.2 Auditory vs. Visual Feedback Conditions

We found a significant decrease in CoP velocity in spatial auditory condition compared to spatial visual condition for participants with BI; $t(24) = 15.07, p < .001, d = 0.9$ and for participants without BI; $t(24) = 14.99, p < .001, d = 0.8$. We also obtained a significant decrease in CoP velocity in CoP auditory condition compared to CoP visual condition for participants with BI; $t(24) = 11.37, p < .001, d = 0.6$ and for participants without BI; $t(24) = 11.06, p < .001, d = 0.5$. However, we noticed that CoP velocity was significantly decreased in rhythmic visual than the rhythmic auditory condition for participants with BI; $t(24) = 7.43, p < .01, d = 0.3$. However, rhythmic auditory again outperformed rhythmic visual for participants without BI; $t(24) = 6.87, p < .01, d = 0.2$. Furthermore, we found that CoP velocity was significantly decreased in static visual than the static auditory condition for participants with BI; $t(24) = 6.35, p < .01, d = 0.2$. However, static auditory provided better feedback than static visual for participants without BI; $t(24) = 6.01, p < .01, d = 0.2$.

6.2.3 Vibrotactile vs. Visual Feedback Conditions

While we compared the effects of vibrotactile feedback with the effects of visual feedback techniques, we found similar results as we found when comparing auditory feedback with visual techniques. For both groups of participants, we found that spatial vibrotactile had a greater effect than spatial visual ($d = 0.8$), and CoP vibrotactile had a greater effect than CoP Visual ($d = 0.5$). However, static and rhythmic visuals had a greater effect than static and rhythmic vibrotactile feedback techniques ($d = 0.2$) for participants with BI. For participants without BI, static and rhythmic vibrotactile feedback had a greater effect than static and rhythmic visual feedback techniques ($d = 0.2$).

6.3 Activities-specific Balance Confidence (ABC) Scale

There was a significant difference between the ABC scores of participants with and without BI; $t(24) = 9.14, p < .001$. The mean ABC score for participants with BI was 69.18%, indicating a moderate level of physical functioning. In contrast, participants without BI had a mean ABC score of 88.45%, indicating a high level of physical functioning.

6.4 Simulator Sickness Questionnaire (SSQ)

No significant difference was found between the pre-session and post-session SSQ scores for any of the three feedback modalities in either group. For the auditory study, $t(24) = 1.72, p = .08, d = 0.03$ for participants with BI, and $t(24) = 1.78, p = .09, d = 0.02$ for participants without BI. In the vibrotactile study, $t(24) = 2.34, p = .07, d = 0.05$ for participants with BI, and $t(24) = 2.11, p = .07, d = 0.04$ for participants without BI. In the visual study, $t(24) = 1.48, p$

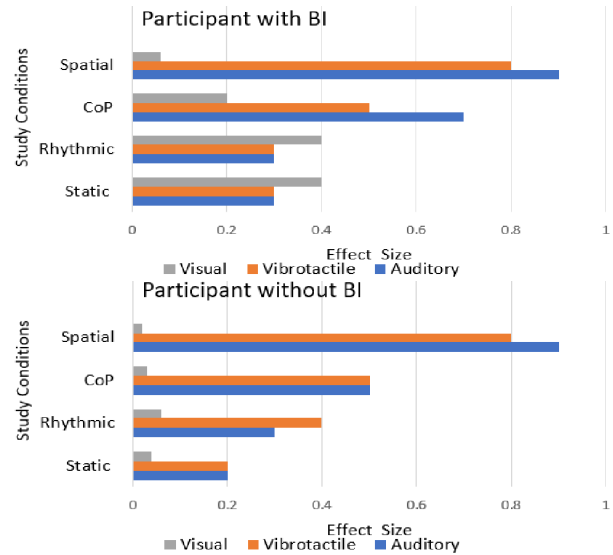


Figure 4: Effect size comparisons between feedback modalities

$= .09, d = 0.02$ for participants with BI, and $t(24) = 1.39, p = .09, d = 0.02$ for participants without BI.

7 DISCUSSION

7.1 Impact of Virtual Environment

In the VR-baseline conditions, CoP was significantly higher compared to the non-VR baseline conditions, regardless of the feedback modality (auditory, vibrotactile, or visual) and participant group. This finding supported our hypothesis **H1** that balance diminished in the VR environment without assistive feedback techniques. Previous studies have also reported increased postural instability in VR, leading to higher CoP velocity compared to the real world [10, 45].

7.2 Effect of Auditory Feedback on Balance in VR

The experimental results demonstrated that static, rhythmic, CoP, and spatial auditory conditions significantly improved balance in both participant groups, supporting our hypothesis **H2**. These findings were consistent with prior studies that reported the positive effects of auditory white noise [15, 38, 41, 54], spatial [13, 48], CoP [16], static [37], and rhythmic audio [14] on balance in real-world environments. The results indicated that spatial and CoP audio conditions outperformed rhythmic and static conditions, with no significant difference between static and rhythmic conditions, which aligns with a previous study by Mahmud et al. [26]. However, our study found that spatial auditory feedback significantly outperformed CoP auditory feedback, contradicting Mahmud et al.'s findings [26], where no significant difference was observed between spatial and CoP conditions. Spatial audio induced better immersion in VR for prior studies [32, 52] which might have a positive impact on its performance. It is also worth noting that Mahmud et al. [26] investigated participants with BI due to MS, while our study focused on participants with BI due to type 2 diabetes who might have been affected differently. Almost all of the previous work had been with people with MS. If the imbalance was caused by a different disease, it was unclear if the techniques would still work. Therefore, we wanted to demonstrate more generalizability, and type 2 diabetes is another disease that has imbalance as a symptom. BI due to MS is basically because of the impaired nervous system, whereas BI due to type 2 diabetes is basically because of the impaired vascular system. Thus, the two groups might have been affected differently.

7.3 Effect of Vibrotactile Feedback on Balance in VR

Results from the vibrotactile study indicated that static, rhythmic, CoP, and spatial conditions effectively improved balance in both participant groups, supporting our hypothesis **H2**. The outcomes were similar to the prior study by [27]. We also found that spatial and CoP vibrotactile feedback performed significantly ($p < .001$) better than rhythmic and static conditions for individuals with and without BI with no significant difference between static and rhythmic conditions which are also similar results as the prior study by [27]. However, we found spatial vibrotactile outperformed significantly CoP vibrotactile condition which was not found in prior studies and supported our hypothesis **H4**. This result contradicts the results of Mahmud et al. [26] as they found no significant difference between spatial and CoP conditions for participants with BI due to MS and participants without BI.

7.4 Effect of Visual Feedback on Balance in VR

Balance was significantly improved in static, rhythmic, and CoP visual feedback conditions compared to the no visual feedback condition in VR for participants with BI. However, there was no significant difference in balance for the spatial visual feedback condition. These findings partially supported our hypothesis **H2**. However, experimental results did not indicate any significant improvement in balance for any visual feedback condition in participants without BI, which contradicts prior studies by Mahmud et al. [26, 27], where significant improvement was observed for both people with and without BI. These results supported prior studies [12, 44] where they also found visual feedback was more effective for participants with BI than those without BI. Based on the experimental results, we hypothesized that spatial feedback, represented by a fixed '+' sign within four frames in front of the participants, did not provide significant feedback. In contrast, the static and rhythmic feedback conditions involved visual elements that moved with the participants' head movements, while the CoP condition adjusted the boundaries of the frame based on the participants' CoP directions. As a result, static, rhythmic, and CoP feedback provided significantly better feedback compared to spatial feedback. Moreover, static and rhythmic visual feedback conditions showed significantly better balance improvement compared to CoP and spatial visual feedback conditions for people with BI. CoP visual feedback also improved balance significantly more than the spatial condition. However, no significant difference was found between static and rhythmic feedback conditions.

7.5 Comparison of Feedback Modalities

The effect sizes of auditory and vibrotactile feedback techniques were greater than those of visual feedback techniques. Auditory and vibrotactile techniques significantly improved balance for both participant groups, whereas visual techniques were only effective for participants with BI. These supported our hypothesis **H3** that auditory and vibrotactile feedback techniques outperformed visual feedback techniques. One possible reason for the reduced effectiveness of visual techniques is that participants might have been more focused on completing the VR tasks, resulting in less continuous attention to visual feedback. In contrast, auditory and vibrotactile feedback techniques provided continuous feedback. Additionally, prior studies reported that participants with BI relied more on visual cues [12, 44], which might explain why visual feedback was effective for participants with BI but not for those without BI. For both participant groups, spatial auditory significantly outperformed spatial vibrotactile and spatial visual feedback. Spatial vibrotactile feedback also significantly improved balance compared to spatial visual feedback. Similarly, CoP auditory feedback significantly outperformed CoP vibrotactile and CoP visual feedback. CoP vibrotactile feedback also significantly improved balance compared to CoP visual feedback. Thus, spatial auditory outperformed all other feedback

conditions which supported our hypothesis **H4**. Prior studies reported that spatial audio provided greater immersion in VR [32, 52], which might help spatial auditory feedback to perform better than other feedback conditions. For participants with BI, static and rhythmic visual feedback conditions significantly outperformed static and rhythmic conditions for both auditory and vibrotactile feedback. However, the results were the opposite for participants without BI, where static and rhythmic auditory and vibrotactile conditions significantly outperformed static and rhythmic visual conditions. These results again supported prior studies [12, 44] where they reported visual feedback was more effective for participants with BI than those without BI.

7.6 Limitations

Although the conditions within the studies were counterbalanced, we conducted the three studies in order using the same 50 participants in each in different sessions. Thus, there could have been ordering effects. Because the studies were run at least a month apart, the ordering effects were likely minimal. However, more research will be needed to understand ordering effects.

The height of the table was not adjusted according to the participants' height, which might have influenced the findings. Nevertheless, there were no statistically significant differences in the heights of the participants (Table 1), and thus we expected minimal impact.

Participants wore harnesses during the experiment to prevent falls, which might have slightly improved their balance. However, to ensure consistency and safety, all participants were asked to wear harnesses, regardless of their balance difficulties. Therefore, the findings might vary slightly when examining balance without a harness.

The mean CoP velocity was measured as a standard metric for balance assessment [25]. However, whole-body movement was not quantified in this study.

We did not add a virtual avatar to our study. However, adding a virtual avatar could affect participants' depth perception [18, 30].

Participants performed real and virtual tasks while standing on the balance board for an extended period. This often required participants to rest between trials by removing the HMD. This rest period might have allowed participants to regain spatial awareness and balance, which might have slightly influenced the results.

8 CONCLUSION

This research paper examines the impact of various feedback modalities involving auditory, vibrotactile, and visual on balance in immersive virtual reality for individuals with balance impairments caused by type 2 diabetes and individuals without balance impairments. The findings revealed that all auditory and vibrotactile conditions (static, rhythmic, CoP, and spatial) significantly improved balance for both participant groups. Notably, static, rhythmic, and CoP visual feedback also showed significant improvement in balance for participants with balance impairments. Among the feedback conditions, spatial auditory feedback demonstrated superior performance. These results contribute to a deeper understanding of the efficacy of different assistive feedback methods for maintaining balance in a virtual environment based on HMDs. Furthermore, this research has practical implications for developers aiming to design more accessible VR experiences for individuals with and without balance impairments. Future investigations will incorporate locomotion tasks to further examine the effectiveness of the feedback modalities in immersive virtual reality.

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