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A baropodometric analysis of postural therapy supported by immersive virtual reality

Ígor Andrade Moraes [**Minas Gerais State University** | ***igorandradesystem@hotmail.com***]
Eduardo Gabriel Queiroz Palmeira [**University of Brasília** | ***eduardo.palmeira@unb.br***]
Raul Matsushita [**University of Brasília** | ***raulmta@unb.br***]
Alexandre Gomes de Siqueira [**University of Florida** | ***agomesdesiqueira@ufl.edu***]
Dean A. Rodrigues de Oliveira [**Federal University of Uberlândia** | ***deanazevedo@yahoo.com.br***]
Alexandre Cardoso [**Federal University of Uberlândia** | ***alexandre@ufu.br***]
Edgard Afonso Lamounier Júnior [**Federal University of Uberlândia** | ***lamounier@ufu.br***]

Ituiutaba Unit, Minas Gerais State University, Rua Ver. Geraldo Moisés da Silva, s/n, Universitário, Ituiutaba, MG, 38302-192, Brazil.

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Abstract Virtual Reality (VR) can support postural therapies through proprioceptive assistance and engaging interactive features. Plantar pressure measurements are critical for accurate and individualized diagnosis of gait and posture. In a previous work, we developed an immersive VR environment to support postural therapy and conducted a user study. This study expands on previous research and aims to investigate the impact of postural therapy supported by immersive VR technology, compared to a traditional method. Our analysis utilizes unexplored baropodometric data collected during supervised therapy sessions in our prior work. Based on our current understanding, this study represents the pioneering exploration of combining baropodometric analysis with immersive VR technology to support postural therapy. In the experiment, healthy students ($n = 22$) with an average age of 12 years were randomly assigned to either an experimental or a control group. The experimental group underwent the therapeutic intervention using immersive VR, while the control group followed the same protocol without VR assistance. Baropodometric data were collected before and after the sessions and analyzed using the Wilcoxon test. Both groups showed postural improvements after the intervention, particularly in reducing foot pressure imbalances between the left and right feet; however, a statistical analysis indicated that VR-assisted therapy demonstrated more noticeable improvements in baropodometric parameters regarding weight and rearfoot weight distributions, as well as maximum foot pressure. Our findings reinforce the potential of integrating VR technology and baropodometric parameters to enhance therapeutic outcomes. This combination can serve as a complementary tool in clinical and research contexts, with the aim of improving diagnosis and treatment in postural therapy.

Keywords: Virtual Reality, Baropodometry, Scoliosis, Postural Control, Postural Assessment

1 Introduction

Postural imbalances affect a significant portion of the population. Scoliosis is a condition characterized by a lateral deviation in the normal vertical alignment of the spine. It affects around 2-3% of school-age children globally, causing discomfort and pain [Janicki and Alman, 2007; Weinstein, 1999]. The curvature of scoliosis tends to worsen with time, leading to increased complications proportional to the angle of the spine and muscle strain. It can also cause complications such as deformations of the thoracic cage, which can impact lung and heart function. Moreover, even in mild cases, exercise capacity can be reduced [Koumbourlis, 2006]. Those affected by scoliosis may undergo psychological effects, leading to issues such as low self-esteem and suicidal tendencies [Payne III *et al.*, 1997].

Although there are no definitive solutions for this condition [Lau, 2011], different approaches to the treatment of scoliosis have been tested [Janicki and Alman, 2007]. In young people, corrective postural improvement and muscle strengthening interventions can influence bone development and reduce spinal curvature. However, for adults, treatment primarily aims to reduce pain and stop or slow the progression of abnormal curvature [Lau, 2011]; in some cases, these interventions may even reduce the progression of severe curvature [Negrini *et al.*, 2015]. Therefore, early diagnosis is crucial, given that surgical interventions for severe cases have high risks and can limit the patient's quality of life [Lau, 2011; Wilk *et al.*, 2006].

Activation-targeted exercises to strengthen affected muscles are one of the most effective preventive and corrective strategies for the treatment of scoliosis [Janicki and Alman, 2007]. Physiotherapeutic approaches such as Global Postural Reeducation (GPR) are often preferred, as they are considered non-invasive and can improve overall outcomes [Dupuis *et al.*, 2018]. However, physical therapies that aim to improve posture and rehabilitation require the guidance of experienced professionals and often come with challenges, such as pain and discomfort due to muscle activation. Factors like unsatisfactory results, anxiety in the patient or lack of self-confidence, and insufficient therapist attention can lead to abandonment of treatment [Jack *et al.*, 2010; Williams *et al.*, 2015]. Notably, the effectiveness of these therapies is directly associated with consistent muscle development; the more diligently a patient adheres to the prescribed exercise routine, the better the chances of achieving a postural improvement [Mendrin *et al.*, 2016].

Immersive Virtual Reality (VR) systems are increasingly recognized as a valuable complementary tool in rehabilitation scenarios [Howard, 2017], offering high levels of immersion and participation through natural interactions within controlled virtual environments (VE) [Jerald, 2015; LaViola Jr. *et al.*, 2017]. This technology has shown promise in supporting motor and cognitive activities [Saposnik *et al.*, 2010] and pain management [Hoffman *et al.*, 2011; Li *et al.*, 2011]. Although VR has demonstrated its utility in several healthcare settings—such as post-stroke rehabilitation [San Luis *et al.*, 2016]—and despite the encouraging technological landscape, its application in supporting the treatment of scoliosis remains little explored [Moraes *et al.*, 2020].

This study hypothesizes that the integration of VR with baropodometry equipment can improve postural diagnosis techniques [Costa *et al.*, 2019]. Specifically, baropodometric parameters, which are closely related to posture maintenance, can provide deeper insights when analyzed in combination with VR experiences—the existing literature already acknowledges a strong link between baropodometric parameters and posture [Souza *et al.*, 2014; Rosário, 2014; Ma *et al.*, 2020; Tadeus, 2018; Alves *et al.*, 2018]. A baropodometer is a device that is used to measure plantar pressure while a patient is standing or moving [Baumfeld *et al.*, 2017]. The device's accuracy can vary depending on the specifications of the equipment used; some models are capable of detailing plantar pressure across distinct regions of the feet [Baumfeld *et al.*, 2017, 2018]. This allows for a comprehensive and efficient individualized diagnosis of gait and posture [Costa *et al.*, 2019; Ma *et al.*, 2020].

Expanding on our previous work [Moraes *et al.*, 2022], where we developed an immersive VR environment to support postural therapy and carried out an experiment, we now aim to delve into baropodometric analysis. Our prior work focused primarily on the technological features of the proposed VR solution and data on its potential advantages for the therapeutic process, but did not analyze baropodometric parameters. Here, our objective is to investigate the effects of immersive VR-supported postural therapy using baropodometric data collected during the same supervised therapy sessions from prior work—our new findings were not included in the previous publication.

The remainder of this paper is organized as follows. Section 2 examines related work, subdivided into two subsections focusing on VR and postural control, and baropodometry and postural evaluation. Section 3 describes the methods used in our research. Section 4 presents the results of this work, followed by Section 5, which delves into discussions, including the limitations of our study. Finally, Section 6 concludes the paper and offers directions for future work.

2 Related Work

This work is grounded in the literature that examines the use of VR in rehabilitation and the use of baropodometry in postural evaluation. In this section, we outline the application of VR in postural control and the role of baropodometric analysis in postural therapy, summarizing how the association of the findings serves as the foundation for this investigation.

2.1 Virtual Reality and Postural Control

Considerable preventive and corrective approaches have been shown to effectively reduce abnormal spinal curvature, thus improving the quality of life of patients undergoing targeted therapeutic processes [Janicki and Alman, 2007]. Physiotherapeutic approaches vary widely, depending on factors such as age, curvature, and risk of progression. An effective method involves performing specialized exercises to strengthen and compensate for weak muscles, thereby preventing the progression of abnormal curvature [Mendrin *et al.*, 2016]. Early intervention, especially during the bone development phase, has been proven to lead to better long-term results [Lau, 2011]. Current technology trends encourage the use of immersive VR systems to improve these physical therapy routines [Moraes *et al.*, 2020], especially given the complexity of human postural control. The purpose of using this technology is to support patient adherence and overall treatment outcomes, which can be challenging due to factors such as anxiety, pain, and low self-esteem that often cause patients to abandon treatment [Jack *et al.*, 2010; Williams *et al.*, 2015].

The immersive nature of VR allows for visual manipulation of controlled VE that can influence patient sensory and motor perception and distract them from physical discomfort [Wright, 2013; Hoffman *et al.*, 2011; Li *et al.*, 2011]; this makes VR particularly useful in physiotherapeutic settings for postural control. This visual immersion can be a powerful tool in postural rehabilitation, where maintaining specific postures or manipulations often causes physical and emotional discomfort, factors that contribute to withdrawal from treatment [Jack *et al.*, 2010]. In this sense, virtual simulated scenarios enable patients to make adaptations to postural control [Virk and McConville, 2006; Wright, 2013]. Moreover, VR's interactive elements contribute not only to motor competencies but also cognitive abilities [Saposnik *et al.*, 2010], offering real-time visual feedback on body balance and positioning. This improves proprioceptive perception and enriches assisted therapeutic protocols [Czerwosz *et al.*, 2009; Postolache *et al.*, 2016].

For postural therapies that involve VR, it is highly recommended to incorporate three-dimensional body tracking (six degrees of freedom), since this intervention requires spine movements in multiple orientations [Wibmer *et al.*, 2016]. Moreover, high-precision tracking devices are essential to effectively assess posture [Postolache *et al.*, 2016]. Design efforts should prioritize creating an environment that is immersive and comfortable, using tracking technology with sufficient precision. This can not only improve treatment outcomes, but also improve postural control management—which is beneficial to both patients and therapists.

2.2 Baropodometry and Postural Evaluation

Baropodometric devices offer various functionalities and evaluation criteria; the apparatus used determines the available assessment parameters [Giacomozzi *et al*., 2012; Valentini *et al*., 2011]. Key hardware specifications such as precision, resolution, accuracy, and sampling rate characterize the quality of a baropodometer [Giacomozzi, 2010]. Computerized baropodometry allows professionals to assess plantar pressure and identify pathologies directly or indirectly related to weight-bearing distribution [Baumfeld *et al*., 2017, 2018; Bacha *et al*., 2015]. This technology has demonstrated its ability to validate associations between plantar pressure distribution and foot-related symptoms such as deformities, callosities, and frequent pain [Fernández-Seguín *et al*., 2014; Costa *et al*., 2019]. In addition, it has contributed to understanding other aspects of body physiology and has been instrumental in recommending suitable treatments based on gait analysis [Costa *et al*., 2019; Ma *et al*., 2020].

Among the key parameters identified in baropodometric studies for posture, stability and balance evaluations, the center of pressure [Zhang and Li, 2013; Martins *et al*., 2019; Tadeus, 2018], the average and maximum plantar pressure [Feka *et al*., 2019; Alves *et al*., 2018], and the distribution of anteroposterior or laterolateral plantar weight [Feka *et al*., 2019; Azevedo *et al*., 2016; Bacha *et al*., 2015; Souza *et al*., 2014; Martins *et al*., 2019] are often used to describe changes in foot morphology after therapeutic interventions. Center of pressure displacement can indicate postural behaviors [Souza *et al*., 2014; Tadeus, 2018] and stability control conditions [Menezes *et al*., 2012]. Plantar pressure is particularly sensitive to the plantar weight distribution, revealing differences between healthy individuals and those with specific symptoms reflected by postural quality [Zhang and Li, 2013]. Peaks of pressure can imply instability and difficulty in maintaining posture [Valentini *et al*., 2011], while reduced plantar pressure indicates better weight distribution [Bacha *et al*., 2015]. Furthermore, studies reveal a strong correlation between postural symmetry and weight distribution along anteroposterior and laterolateral axes [Azevedo *et al*., 2016; Martins *et al*., 2019; Ma *et al*., 2020].

Plantar pressure measurement is performed using a baropodometer, a force platform that can be adapted to standing and moving patients [Baumfeld *et al*., 2017]. The essential parameter for a baropodometric evaluation is the plantar pressure. Plantar pressure data can be subdivided into foot segments according to the precision and resolution of the plantar pressure measurement device used [Giacomozzi *et al*., 2012]. Aligning the available parameters with the evaluation goals is essential for effective baropodometric analysis. The significance of tactile feedback from the feet to the nervous system and its role in maintaining posture has provoked multiple studies examining the effects of physical activities on plantar pressure [Zhang and Li, 2013]. Given the accuracy of the equipment, researchers can pinpoint relationships between plantar pressure distribution and specific sports [Feka *et al*., 2019], as well as subtle posture changes triggered by auditory stimuli [Azevedo *et al*., 2016].

To the best of our knowledge, no studies have been found investigating the use of baropodometric analysis combined with immersive VR technology to support postural therapy. As examined in this section, the existing literature supports the potential of VR to enhance postural control [Virk and McConville, 2006; Wright, 2013; Postolache *et al*., 2016; Wibmer *et al*., 2016; Moraes *et al*., 2020]. It also establishes a connection between posture and plantar distribution [Bacha *et al*., 2015; Souza *et al*., 2014; Ma *et al*., 2020; Cano-Mañas *et al*., 2020; Yi *et al*., 2021; Alves *et al*., 2018], noting changes in weight distribution on the foot surface after practicing various physical activities or targeted exercises for postural improvement [Feka *et al*., 2019; Martins *et al*., 2019; Ciccarelli *et al*., 2015; Janin and Dupui, 2009]. Specifically concerning baropodometric analysis, plantar pressure measurement devices have been shown to be sufficiently accurate for detecting delicate body oscillations [Azevedo *et al*., 2016; Rosário, 2014; Alves *et al*., 2018]. This precision has allowed researchers to confirm relationships between different human body systems [Azevedo *et al*., 2016; Souza *et al*., 2014; Morlino *et al*., 2017] and observe postural improvements after physical trauma or pathologies [Bacha *et al*., 2015; Valentini *et al*., 2011; Cano-Mañas *et al*., 2020; Giardini *et al*., 2018; Iunes *et al*., 2014; Kelekis *et al*., 2014]. Based on these related works, we hypothesize that baropodometric analysis can provide valuable information on the effectiveness of different postural therapy approaches and that immersive VR can improve treatment adherence and overall prognosis by providing proprioceptive assistance and engaging interactive features focused on plantar pressure.

3 Method

This section outlines the method of our study. Initially, the experimental protocol is introduced. Subsequently, the study design and participant details are provided. We then explain the experimental apparatus and detail the specifics of the VE, interaction metaphor, and experimental procedures. Lastly, statistical analysis methods are discussed.

3.1 The Protocol

The protocol used incorporates two postures from the GPR (Figure 1): (a) erect with anterior slope and (b) seated posture. These postures focus on strengthening the thoracic and lumbar regions, improving muscle balance, reducing lumbar pain, and stimulating better muscular force distribution through isometric contractions [Souchard, 2003]. Although GPR alone might not significantly change the curvature of scoliosis, it provides numerous advantages. These include a reduction in Cobb angle [Tavares *et al*., 2015], an increase in maximal respiratory pressures, better thoracic and abdominal mobility [Moreno *et al*., 2007], a decrease in nonstructural thoracic scoliosis and associated pain [Toledo *et al*., 2011], and improved postural stability in orthopedic alterations in the lower limbs [Teodori *et al*., 2011]. Considering that physiotherapeutic approaches such as GPR can be enriched with other strategies for more effective scoliosis treatment [Dupuis *et al*., 2018], we seized this opportunity to incorporate VR technology and its capabilities into the therapeutic context.

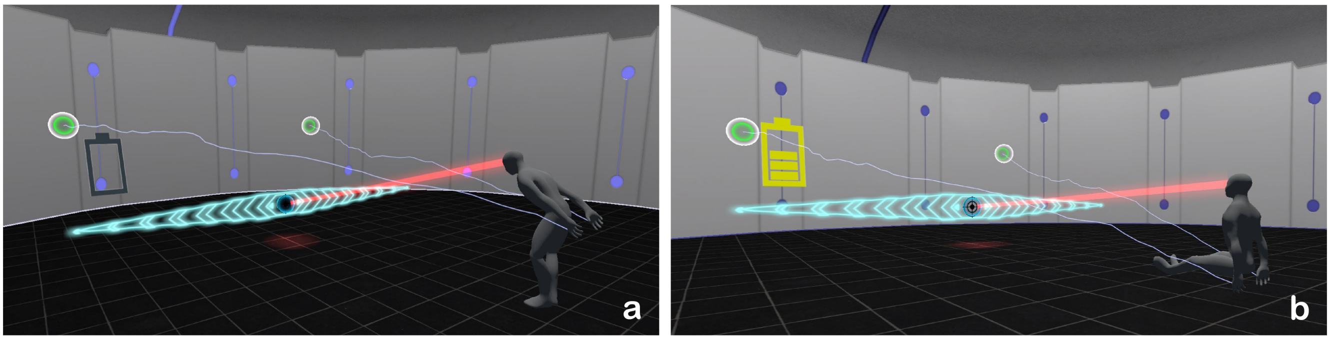

Figure 1. Virtual environment and interactive virtual objectives depicted in a third-person perspective. (a) An avatar placed at the center of the virtual scenario illustrating the erect with anterior slope and (b) the seated postures performed by the experiment participants.

3.2 Study Design and Participants

We initially recruited 26 middle school volunteers, all of whom were healthy and had not undergone spinal surgeries or procedures that restrict movement. In addition, to reduce potential biases in VR experiments, exclusion criteria were established for conditions such as claustrophobia, labyrinthitis, acrophobia, or dizziness; however, no participants were excluded according to these criteria. The experiment received approval from the Ethics Committee of the Federal University of Uberlândia, Brazil (#18,605,019.6.0000.5152), and the informed consent forms were signed by all participants and their legally responsible adults. The experimental sessions were conducted on the school premises and were overseen by a therapist, who is also one of the authors of this article.

The volunteers were divided into an experimental group, which used immersive VR equipment, and a control group, which followed the same protocol, but without VR assistance. The experiment sessions were aligned with the schedule of the physical education class—Wednesdays from 7:00 am to 12:20 pm. The participation of the volunteers in the experiment was dependent on school activities; absent students missed sessions and had incomplete participation in the experiment. Therefore, participants who attended fewer than three sessions were excluded from the statistical analysis, resulting in the removal of data from four participants.

The demographic data for the final sample of participants ($n = 22$) is presented as follows. Both the experimental and control groups were composed of 11 participants. The mean age of the participants in the experimental group was approximately 12.09 years ($SD = 0.71$), while in the control group, the mean age was approximately 11.91 years ($SD = 0.71$). In terms of gender distribution, the experimental group consisted of five males and six females, while the control group consisted of seven males and four females. Regarding weight, the volunteers in the experimental group had an average weight of 40.77 kg ($SD = 7.07$), while those in the control group had an average weight of 41.83 kg ($SD = 6.70$).

3.3 Apparatus

For our experimental setup, we utilized an HTC Vive Kit[1], which includes a wearable head-mounted display (HMD) for visual immersion and two motion-tracked handheld controllers, and a Wii Balance Board[2] as a force platform for virtual interaction. The HMD offers a 90Hz refresh rate, a 110 degree field of view, and dual OLED screens with a 1080x1200 pixel resolution per eye. Both HMD and handheld controllers feature infrared sensors for tracking of six degrees of freedom (6DoF). Furthermore, we used a high-resolution Baroscan baropodometer[3] to measure plantar pressure before and after the execution of the protocol.

The system was run on a personal computer with 16GB RAM, an NVIDIA GeForce GTX 1060 graphics card, and a 7th generation Intel Core i7 processor. The baropodometer has 4,096 sensors on an active surface of 50x50 cm, which supports static and dynamic analysis at 10 frames per second (Figure 2). The measured parameters included anteroposterior and laterolateral weight distribution, average and maximum pressure, contact surface, pressure center of each foot, and weight distribution in the rearfoot and forefoot. Each baropodometric analysis lasted 30 seconds.

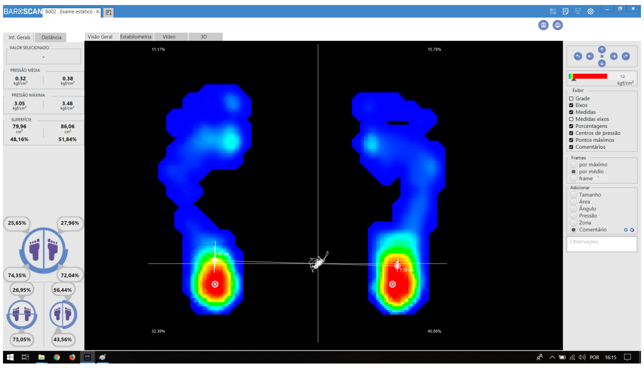

Figure 2. Example of a baropodometric analysis obtained from an experiment using Baroscan.

3.4 Virtual Environment, Interaction Metaphor, and Experimental Procedure

The game engine used to develop the VE was Unity 3D[4], compatible with both the HTC Vive HMD and the Wii Balance Board through a dedicated software library. The HTC Vive controllers determined the user's hand position within

[1]https://www.vive.com/us/support/vive/

[2]https://www.nintendoblast.com.br/2011/06/plug-and-blast-balance-board-wii.html

[3]https://www.baroscan.com/baroscan/

[4]https://unity.com/solutions/edtech

the VE, while data from the Wii Balance Board were converted into coordinates to control the orientation of interactive virtual objects.

Before the application was executed, a physiotherapist placed the corresponding participant in an ideal corrective posture that symmetrically activates the intended muscles. As the VR application started running, an automatic calibration process adjusted the position of the interactive virtual objects based on the participants' initial posture. This calibration was necessary due to anatomical differences between participants. The virtual objects served as references to be adjusted according to the ideal posture determined by the physiotherapist, as will be better clarified later.

All tasks take place within a single purpose-designed VE that accommodates various interactions. To avoid information overload, the virtual scenario contains only essential elements relevant to the designed interactions. The visual design of the environment was intentionally neutral to steer away from resembling a rehabilitative setting, thereby focusing participants' attention on the interactive elements. Virtual objects, interface elements, and lighting configurations vary for each type of task to better align with the specific exercise being conducted.

The VE incorporates interactive virtual objects linked to physical equipment. A horizontal blue object rotates according to the weight distribution captured by the Wii Balance Board (see Figure 3a and b and Figure 4). This interaction metaphor was designed to highlight the symmetry in the participant's weight distribution between both sides of the body.

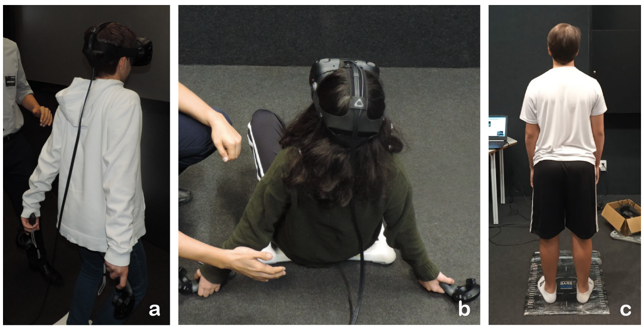

Figure 3. Apparatus used in the experimental setup. (a) Participants performing the erect with anterior slope and (b) the seated postures while interacting with the VE using the HTC Vive Kit and the Wii Balance Board. (c) Data collection process featuring a participant using a high-resolution Baroscan baropodometer, conducted both before and after the set of sessions.

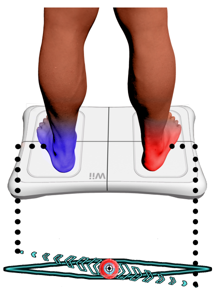

Figure 4. Visual feedback of participant's weight distribution. The blue horizontal object rotates according to the weight data collected by the Wii Balance Board.

The handheld controllers track the participant's hand positions, which are virtually represented by two green spheres—one for each hand. The position of the green left sphere corresponds to the location of the participant's left hand in the real world, while the green right sphere corresponds to the location of the participant's right hand in the real world (refer to Figure 5). The white spheres positioned on the left and right sides of the battery representation remain static throughout the interaction; they serve only as reference positions. During the maintaining of their posture, participants must align the green spheres with the two target white spheres.

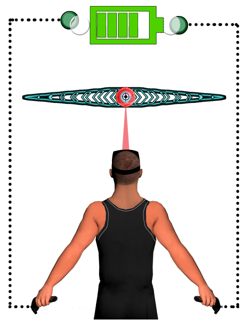

Figure 5. Visual feedback of participant's hand positions. The placement of the green spheres represents the real-world positions of the participant's hands.

The primary interaction in the VR application involves a red beam emitted from the center of the HMD (in the "middle of the user's head"). The participant's objective is to hit the main target located in the center of the virtual scenario (see Figure 6). Each successful hit adds one point to a battery representation. Once the battery is fully charged, the lighting conditions in the VE improve and then the battery discharges. This interaction is repeated until the user experiences any discomfort.

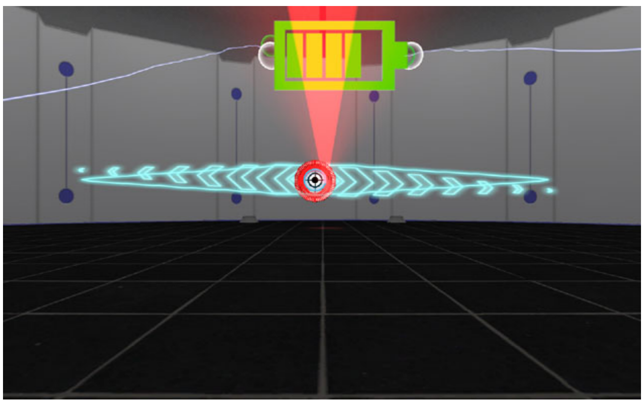

Figure 6. Interaction Metaphor: The user's objective is to charge a battery by hitting the main target with their head position. Additionally, they must engage with the VE and maintain a specific posture, guided by the positioning of their hands and the weight distribution on their feet.

Both groups performed the same experiment using the same trackable devices, with the data capture settings identical for both. The only difference in experience between the groups lies in the use of immersive VR technology with visual feedback as an assistive tool for the therapeutic process. The experimental group used the HMD while maintaining their postures, along with trackable devices, whereas the control group maintained their postures without any vi-

Table 1. Summary statistics of the paired differences ΔX between before and after the therapeutic interventions. Total means pooled sample.

Differences	Group	n size	Mean	Median	Sd
	Control	11	-0.04	-0.02	0.06
ΔFP	Experimental	11	-0.04	-0.02	0.08
	Total	22	-0.04	-0.02	0.07
	Control	11	-0.03	-0.13	0.50
ΔMFP	Experimental	11	-0.14	-0.04	0.35
	Total	22	-0.08	-0.08	0.42
	Control	11	0.04	0.02	0.14
ΔWD	Experimental	11	-0.04	-0.06	0.14
	Total	22	-0.00	0.01	0.14
	Control	11	-1.21	-0.52	1.74
ΔFCP	Experimental	11	-1.55	-1.43	2.36
	Total	22	-1.38	-1.10	2.03
	Control	11	-0.02	-0.01	0.07
ΔRW	Experimental	11	-0.01	-0.02	0.06
	Total	22	-0.01	-0.02	0.06
	Control	11	-0.03	-0.02	0.06
ΔFCS	Experimental	11	-0.01	-0.01	0.06
	Total	22	-0.02	-0.02	0.06

sual assistance but still used trackable handheld controllers and the force platform, just like the experimental group.

3.5 Statistical Analysis

Instead of the typical left/right foot and anterior/posterior ratios [Matsuda and Demura, 2013; Martins *et al.*, 2019; Ma *et al.*, 2020], we based our postural assessments on the absolute paired difference given by $D = |X_1 - X_2|$, where X_1 denotes a left foot measurement/posterior weight, and X_2 refers to the correspondent right foot measurement/anterior weight. This is because, unlike the ratio X_1/X_2, the absolute difference D is a symmetric measure, although possibly non-normal. Besides, as the magnitude of scoliosis is correlated with the difference in foot pressure between the left and right feet [Park *et al.*, 2009; Ma *et al.*, 2020], we expect the intervention to reduce the value of D. Thus, the closer D is to zero, the better the left-right balance. For our purposes, we consider the paired difference between before and after interventions within each group as $\Delta X = D_{\text{after}} - D_{\text{before}}$, where we refer to X as foot pressure (FP), maximum foot pressure (MFP), weight distribution (WD), foot center of pressure (FCP), rearfoot weight (RW), or foot contact surface (FCS). We performed the Wilcoxon test for medians of ΔX, $H_0 : \mu_{\Delta X} \geq 0$ *versus* $H_1 : \mu_{\Delta X} < 0$. We also tested the difference between ΔX values from experimental and control groups using the two-sample Wilcoxon statistic for $H_0 : \mu_{\Delta X}(\text{experimental}) \geq \mu_{\Delta X}(\text{control})$ *versus* $H_1 : \mu_{\Delta X}(\text{experimental}) < \mu_{\Delta X}(\text{control})$. Wilcoxon's effect size (r) is considered large, if $r \geq 0.5$; moderate, if $0.3 \leq r < 0.5$, and small, if $r < 0.3$ [Grissom and Kim, 2012]. We performed our analysis using R (version 3.6.0) packages rstatix, stats, and ggpubr[5].

[5] https://www.r-project.org

4 Results

Figure 7 depicts the box plots of the paired differences D concerning foot pressure (FP), maximum foot pressure (MFP), weight distribution (WD), foot center of pressure (FCP), rearfoot weight (RW), and foot contact surface (FCS), where the dashed lines refer to the overall median before the intervention by pooling both groups. These plots suggest that all the medians from the experimental group decreased after therapeutic interventions. The same occurred in the control group except for weight distribution (WD). Notably, when comparing the paired differences between before and after interventions within each group (Table 1), we observe negative means and medians, except for weight distribution (WD) from the control group. Hence, from a descriptive statistical point of view, the therapeutic interventions are reflected in our baropodometric measurements.

Moderate to large effect sizes shown in Table 2 suggests that interventions may provide a better left-right balance. Despite the small sample size in both groups, the medians of foot center of pressure (FCP) were significantly negative (p-value ≤ 0.03), with large effect sizes. We obtained small effect sizes when comparing medians between the experimental and control groups. However, except for foot contact surface (FCS) parameter, we found moderate effect sizes for the experimental group, but small for the control group. There is evidence of postural improvements after therapeutic intervention, including for the VR-assisted group, as indicated by the reduction of differences in foot pressure (FP) between the left and right feet [Park *et al.*, 2009; Ma *et al.*, 2020].

5 Discussions

The current investigation expands on our previous publication by analyzing essential baropodometric parameters for posture evaluation. Our earlier study emphasized the bene-

Table 2. Wilcoxon's test statistic (W), p-value, and effect size (r). Significant (p-value ≤ 0.03) and large effect sizes found for ΔFCP.

Variable	Source	n size	W	p-value (P)	r	Magnitude
ΔFP	Control	11	16.00	0.07	0.46	moderate
	Experimental	11	15.50	0.06	0.47	moderate
	Between	22	57.00	0.42	0.05	small
ΔMFP	Control	11	26.00	0.29	0.19	small
	Experimental	11	18.00	0.10	0.40	moderate
	Between	22	52.50	0.31	0.11	small
ΔWD	Control	11	44.00	0.84	0.29	small
	Experimental	11	21.00	0.16	0.32	moderate
	Between	22	42.00	0.12	0.26	small
ΔFCP	Control	11	11.00	**0.03**	0.59	**large**
	Experimental	11	10.00	**0.02**	0.62	**large**
	Between	22	58.00	0.45	0.04	small
ΔRW	Control	11	24.00	0.23	0.24	small
	Experimental	11	20.00	0.14	0.35	moderate
	Between	22	60.00	0.50	0.01	small
ΔFCS	Control	11	16.00	0.07	0.46	moderate
	Experimental	11	25.00	0.26	0.21	small
	Between	22	72.00	0.78	0.16	small

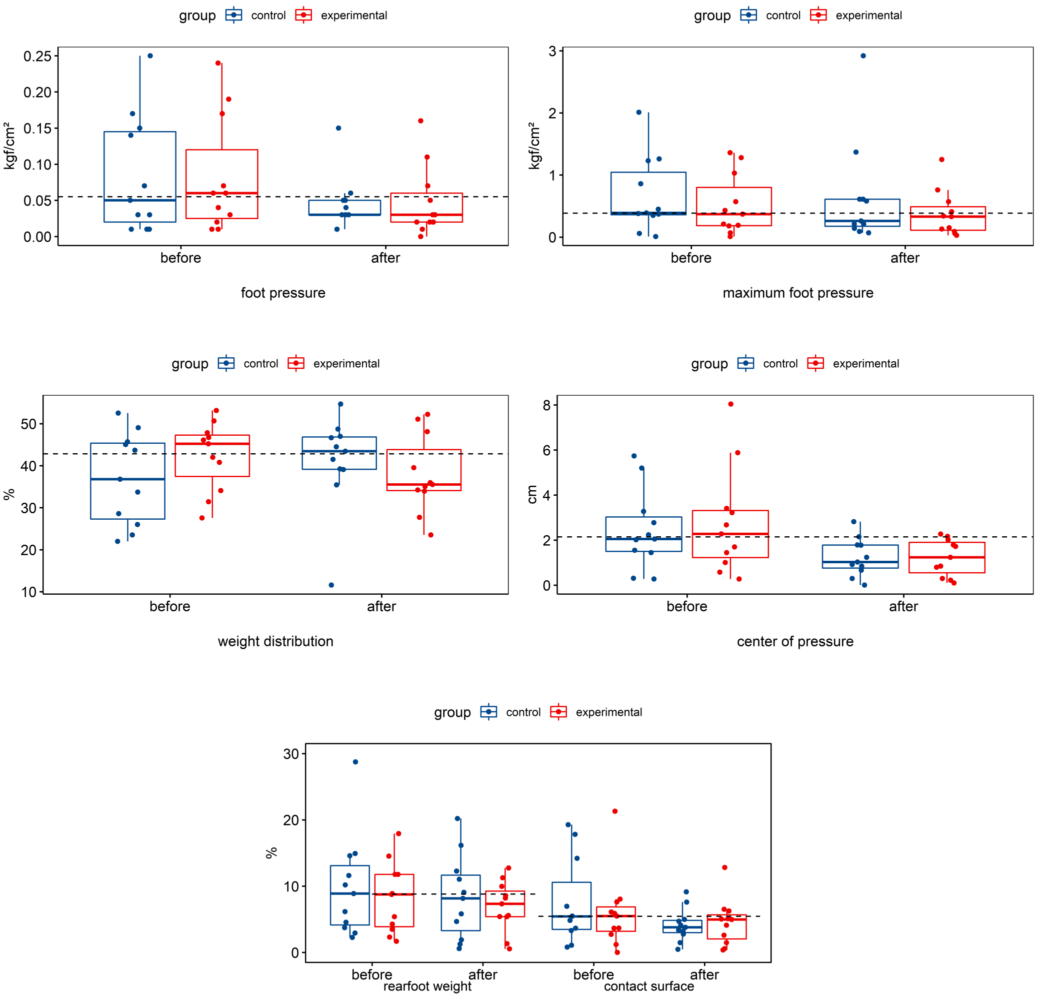

Figure 7. Box-plots showing the distributions of the absolute paired differences (D) between left and right feet baropodometric data. The dashed line denotes the overall median of D before the intervention. The dots are individual observations. The box plots indicate a decrease in the median values for the experimental group after therapeutic interventions. A similar pattern was observed in the control group, except for weight distribution.

fits of VR in postural rehabilitation, such as increased tolerance time while maintaining posture and improved arm stability [Moraes *et al.*, 2022]. In this study, we further investigated the topic, suggesting that VR's interactive and proprioceptive capabilities can significantly improve plantar pressure parameters and, consequently, postural control. Overall, our results are consistent with related works and reinforce the effectiveness of combining technological approaches to enhance therapeutic outcomes, highlighting the utility of baropodometry as a supporting tool for both clinical practice and research, particularly in postural evaluation.

As indicated in Table 2, the control group showed small magnitude changes in maximum foot pressure (MFP), while the experimental group demonstrated moderate magnitude changes. Given that higher pressure peaks could indicate stress during postural control [Valentini *et al.*, 2011], our results suggest that visual immersion and weight distribution feedback in postural therapy may assist patients in achieving better balance control during posture maintenance. Furthermore, the reduction in foot pressure (FP) in both groups indicates better postural control, which corroborates the assumption that specific exercises improve posture [Martins *et al.*, 2019; Bacha *et al.*, 2015].

Both groups showed a significant reduction in foot center of pressure (FCP) displacement after the sessions. However, when comparing them, the experimental group showed significant improvements in most of the evaluated parameters. Consistent with findings from Vie *et al.* [2013], inversion of the fatiguing static foot can alter reflex control of foot muscles, as the prevailing action of these muscles could impair proprioceptive control of their antagonistic muscles. Since our protocol requires considerable effort in foot inversion and eversion for postural maintenance in both groups, we infer that VR-assisted postural interventions may lead to improved muscle control and reduced muscular imbalances through proprioceptive assistance. However, more studies are needed to support this assumption.

According to other studies [Bacha *et al.*, 2015; de Oliveira Almeida *et al.*, 2015], increased plantar pressure stress is associated with postural sway and higher pressure peaks correlate with the tension required to maintain balance. However, neither group showed significant changes in foot contact surface (FCS), even though the control group demonstrated changes of moderate magnitude. In addition, the protocol did not cause any changes in foot conditions that could affect unsteady gait and foot rotation symptoms. Regardless, our findings indicate an improved rearfoot weight distribution (RW) when VR supported the therapy. Furthermore, in accordance with a related work [Cavanagh *et al.*, 1987], the experimental group exhibited a better foot weight distribution (WD). When comparing the final weight distribution (WD) of both groups (Figure 7), rearfoot weight (RW) had a greater reduction in the experimental group too.

The use of baropodometry is concentrated in the clinical context and lacks extensive scientific research [Rosário, 2014]; there are only a few studies that connect baropodometry to physical activities, which makes it challenging to support new research proposals [Martins *et al.*, 2019]. The complexity of maintaining balance suggests that even minor changes in other sensory systems can influence it [Souza *et al.*, 2014]. Leveraging this, baropodometric data can complement other diagnostic methods, aiding in clinical decision-making and facilitating more individualized treatment plans [Costa *et al.*, 2019; Ma *et al.*, 2020]. Similarly, VR technology opens new avenues for clinical treatments. It can help professionals better understand the progress of balance- or coordination-related pathologies and introduce more accurate, comprehensive, and dynamic evaluation approaches [Casanova *et al.*, 2015]. Therefore, our results indicate that the integration of VR with baropodometric analysis can support both the diagnostic and treatment processes in postural rehabilitation.

This study had limitations with respect to a limited time frame and a small sample size. Due to school activities, it was not possible to extend the experiment, and the size of the physical education classes limited the number of participants. Furthermore, baropodometer hardware limited the range of parameters we could examine; therefore, it was not possible to collect data on foot pressure parameters such as metatarsal, midfoot, and toe pressure. Although we observed promising short-term outcomes, more therapy sessions with a broader range of parameters would be needed for a comprehensive understanding of long-term muscular development.

6 Conclusions

This study investigated the effects of postural therapy supported by immersive VR on baropodometric parameters. Our work highlights baropodometric parameters after postural exercises combined with VR and suggests that its use in postural therapies, thorough proprioceptive assistance, contributes to reducing differences in foot pressure between the right and left feet. When analyzed separately, both groups showed improvements in some parameters, such as foot pressure (FP) and foot center of pressure (FCP). However, maximum foot pressure (MFP), weight distribution (WD), and rearfoot weight (RW) parameters demonstrated more noticeable improvements exclusively in the experimental group, with moderate effect sizes. Thus, our findings were consistent with our hypothesis.

Despite the limitations of this study, the potential benefits of using VR technology in gait and posture are evident. The identification of a parameter—weight distribution (WD)—showing improvement exclusively in the experimental group when comparing pre- and post-intervention differences, together with predominantly better results in this group—weight distribution (WD), rearfoot weight (RW) and maximum foot pressure (MFP)—, suggests that VR technology may enhance the effectiveness of traditional therapies without negatively impacting patient performance. However, it is crucial to emphasize that the solution presented in this paper is not intended to replace the expertise of a qualified professional or to diminish the value of traditional approaches. Instead, it aims to support postural therapies and further research in this area. In addition, we acknowledge the importance of engaging end users in the design process. Therefore, in future work, our aim is to involve patients in the creation of VR solutions to support postural therapy through participatory design practices. This approach can empower patients to co-design a customized solution that effectively meets their needs, ensuring greater user acceptance of the developed technology [de Faria Borges *et al.*, 2014].

This research corroborates the value of baropodometric analysis for a more accurate evaluation of postural changes, aligning with previous studies demonstrating differences in plantar weight distribution after targeted exercises [Martins *et al.*, 2019; Cano-Mañas *et al.*, 2020]. Existing baropodometric research predominantly addresses the connection between plantar pressure and specific health conditions related to posture; there is a lack of research, however, that addresses plantar pressure parameters in the context of therapeutic interventions not directly aimed at foot-related symptoms.

To build on these gaps, future studies should aim for longer follow-up periods, larger sample sizes, and employ more advanced plantar pressure measurement devices with a broader set of evaluation features. We also recommend a deeper exploration of the role of immersive interfaces in assisted postural therapies, investigating long-term effects on foot muscle adaptation using baropodometric analysis.

Declarations

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Authors' Contributions

ÍM, DO, AC, and EL contributed to the conception and design of the study. The preparation of material and data collection was carried out by ÍM and DO. RM performed data curation and formal analysis. The original draft was written by EP, ÍM, and RM, with a subsequent review and editing performed by EL and AS. Project administration and resources were provided by AC. All authors have read and approved the final manuscript.

Competing interests

All the authors affirm that there are no conflicts of interest concerning this research.

Availability of data and materials

The data generated and analyzed in this study, the R script used for the analysis, and a demonstration video of the VR environment are available at the following link: https://github.com/iamoraes17/svr2024.

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