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Influence of Induced Environment Oscillations on Limits of Stability in Healthy Adults

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Abstract: (1) Background: Human balance and equilibrium-maintaining abilities have been widely researched up to this day. Numerous publications have investigated the possibilities of enhancing these abilities, bringing the patient back to their original capabilities post-disease or accident, and training for fall prevention. Virtual reality technology (VR) is becoming a progressively more renowned technique for performing or enhancing rehabilitation or training. We aimed to explore whether the introduction of scenery oscillation can influence a person's limits of stability. (2) Methods: Sixteen healthy adults participated in measurements. Each of them underwent 10 trials, during which subjects were supposed to, on acoustic cue, lean as far forward and back as possible, without raising their heels or toes. Two trials were conducted without the use of VR, four with oscillating scenery, one with stationary scenery, one with displayed darkness, and two trials were performed for reference, which did not require leaning nor used VR technology. (3) Results: For the total as well as for each foot separately, COP displacements and velocities were calculated and analyzed. A post-hoc Wilcoxon pairwise test with Holm's correction was performed, resulting in 420 returned p-values, 4 of which indicated significant differences between medians when comparing trials with 0.2 Hz oscillating scenery with trials with eyes open and closed. (4) Conclusions: No statistically significant differences at $\alpha = 0.05$ between reached maximums in trials using VR and trials without it were found, only trials using 0.2 Hz oscillations displayed statistically significant differences when comparing velocities of leaning. The authors believe that such oscillations resemble naturally occurring tinnitus; additionally, low-frequency oscillations are believed to influence postural balance more than high-frequency ones, therefore affecting the velocity and displacements of COP the most.

Keywords: limits of stability; virtual reality; oscillating scenery

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1. Introduction

The ability to control balance and postural stability is vital for humans in order to maintain a stable, upright standing position. Strict coordination between musculoskeletal, proprioceptive, vestibular, and visual perception systems is necessary in order to achieve and maintain proper posture and prevent falling, while also allowing locomotion.

So far, extensive research has been performed in order to enhance all those abilities or bring them back to the initial state if any of the systems responsible for them have been compromised. As a result, more and more methods of diagnosing and rehabilitation are emerging, making use of new technological advancements. For example, R. Bin et al. present an interactive mobile gait training system in [1], while M. Gzik et al. in [2] show an innovative device for quantitative diagnosis and monitoring of the rehabilitation progress of the upper limb.

When it comes to LOS research, two approaches are most commonly used. The first one, as described in [3], requires the participant to reach predetermined points visible on the screen by shifting the center of gravity (COG). The aim of this approach is to reach the target point as fast as possible, and keep the leaned position until visual biofeedback is presented. Afterward, the participant is supposed to return to the initial position, rest for a set amount of time, and proceed to lean toward the next point. The other approach is presented in [4] and requires the participant to lean as far as possible in usually two or four directions (depending on if one or two axes are analyzed), without raising any part of their feet from the measuring platform. The participant is supposed to maintain the leaned position for a set amount of time and then return to the original position. In this type of measurement, the center of pressure (COP) is taken into consideration. Both types of LOS tests provide valuable data on a person's balance-maintaining capabilities and are regarded as reliable tools for assessing a person's postural stability-maintaining capabilities [5].

The aim of this study was to validate whether VR technology can be used to influence subjective limits of stability and therefore be used in order to increase patients' balance-maintaining capabilities, as it has been established that scenery oscillations do influence these capabilities [6]. The hypothesis was that the introduction of scenery oscillations would affect the subject's perception in a manner that would allow it to reach the LOS quicker or achieve greater COP displacement. If validated, attempts at creating exercises and physiotherapy programs could be made, and creating new tools for fall prevention training could be possible. We also aimed to find out if preferences in the use of one of the lower limbs over another affect the subject's LOS, hence the analysis of each foot's COP displacement and COP velocity was conducted separately. Previous research performed in the faculty of Biomedical Engineering of the Silesian University of Technology proved that in the presence of stimuli conflict, subjects begin to show signs of asymmetry in the mediolateral axis of weight distribution on their feet. The performed measurements are first in the series, and serve the purpose of exploring a new approach to fall prevention and diagnosis of possible neurological impairments while providing us with data that should be expected when the examined person is healthy.

As the limits of stability play a crucial role in maintaining a steady and upright position and contribute to fall prevention, the use of virtual reality (VR) technology in physiotherapy and diagnostics has gained popularity. If the performed research returns positive results, our findings will have the potential to contribute to the development of exercises and physiotherapy programs, which could be performed in order to further enhance fall prevention training.

Our methods were based on research performed in [4,7] and redesigned to allow complex analysis of both frontal and backward LOS while taking into consideration the COP from each foot separately, as well as total COP.

To the authors' best knowledge after performing a literature review, no other work exists specifically analyzing the influence of visual surroundings oscillations on LOS, except for the research presented in [8]. However, in said publication, the focus was put on COG instead of COP, and therefore measured were values of velocity in degrees per second (°/s) instead of mm/s.

The difference in this case is vital, as the COG designates the location at which the entire mass of an object can be presumed to be concentrated, thereby preserving the object's translational inertia properties intact. When external forces are applied through the COG of an unconstrained object, they generate no rotations, but induce translation. On the other hand, the COP is the projection on the ground plane of the centroid that represents the vertical distribution of forces. Essentially, the COP signifies the hypothetical point of application for the resultant force vector if it were to be regarded as originating from a singular location [9]. We also aimed to search for preferences in the use of one of the lower limbs over another, hence the separate analysis of each foot's COP displacement and COP velocity.

2. Materials and Methods

2.1. Study Group

The investigations involved 16 individuals (8 women and 8 men) with an average age of 28 (9.4 standard deviation (SD)), a mean body mass of 77.3 kg (14.9 SD), and an average height of 174.4 cm (7.2 SD). All participants took part in the measurements. All participants were recruited from the Biomedical Engineering faculty of the Silesian University of Technology. Participants were volunteers who expressed their willingness to participate in measurements and signed written consent.

Eligibility criteria were as follows:

- Women and men aged between 18 and 40 years;
- No pathological deformations in bones of feet;
- No reports of injuries in lower limbs in the past three years;
- No reports of balance-maintaining ability dysfunctions;
- No motion sickness/simulation sickness.

If throughout the measurement abnormalities were becoming noticeable (e.g., the person was unable to return to the initial position after leaning during trials with scenery oscillations, or swaying was so significant that the leaning phase was undetectable), all measurements performed on that person were discarded.

2.2. Study Design

The measurement stand consisted of a Zebris WinFDM-S stabilographic platform (100 Hz sample frequency, 2560 tensiometer sensors, 34 cm × 54 cm sensing area), and a set of the HTC Vive Cosmos head-mounted display (HMD) used for the projection of three-dimensional images. Three-dimensional sceneries were developed in the Unity 3D environment. Scenery consisted of a furnished room, in which objects were seen by the tested individual at a distance of ~2 m (Figure 1). Data from the Zebris FDM pressure distribution measurement system were gathered using the Noraxon Ultium™ system. During the tests, the scenery oscillated in the sagittal plane at a constant frequency. Oscillations were presented by moving the scenery along the sagittal axis, taking into consideration a slight rotation of the scene by 0.5 degrees. The movement of the scenery was achieved by overlapping the following two movements, and was based on data presented in [6]:

- movement along the sagittal axis (AP direction) of the currently tested participant:

$$y = A_y * \sin(2\pi f_t t)$$

where

f_t—frequency of the scenery movements,
A_y—amplitude of the scenery movements in centimeters, and
t—time.

- movement around the transverse axis of a given test participant:

$$\varphi = A\varphi * \sin(2\pi frt)$$

where

fr—frequency of the scenery movements,
$A\varphi$—amplitude of the scenery movements in degrees, and
t—time.
The following designations were adopted for the purpose of the tests under discussion:
A_y = 15 [cm],
$A\varphi$ = 1 [deg], and
fr = depending on the trial: 0.2 Hz, 0.5 Hz, 0.7 Hz or 1.4 Hz.

Figure 1. Scenery used during measurements.

Informed consent was obtained from all subjects involved in the study. The research procedure included measurements with swaying in the real world and in virtual reality. In the real world, the test was performed with eyes opened (OOO) and eyes closed (OZO). Virtual reality tests were performed for a still scenery (VRN), a displayed darkness scenery (VRC), and an oscillating scenery at frequencies of 0.7 Hz (VR07), 1.4 Hz (VR14), 0.2 Hz (VR02), and 0.5 Hz (VR05). In addition, two control measurements were performed in the real world, without swaying—a calm trial with eyes open (OO) and with eyes closed (OZ) in a standing, upright position.

The subjects were asked to take off their shoes and stand on the measuring platform in an upright position with their arms along their body and their vision focused on a point located in front of them at a distance of ~2.5 m, at the approximate height of their eyes. The order of conducted tests was randomized. The task of the tested person was to stand still, lean out, and return to an upright position after hearing the appropriate sounds. The first type of sound was high-pitched, and after hearing it the tested person leaned forward/backward without lifting their heels/toes off from the ground. After 5 s, the second, low-pitched sound was played, after hearing it, the participant was supposed to return to the starting position. Each measurement lasted 70 s and included four leans—two forward and two backward. The same procedure was used for each of the previously described test conditions. Schemes of measurements performed with and without oscillations are presented in Figure 2.

All analyses took into consideration the time periods from the 14th to 20th, 24th to 30th, 34th to 40th, and 44th to 50th seconds, as those were the times between the sound cues signaling the start and end of leaning. The initial 14 s served as the time for stabilizing the posture of the participant, and each sound cue was played for a second to avoid mishearing and/or skipping the start or end of leaning. The exact times of playing the sound cues were the following (in seconds): 14–15; 19–20; 24–25; 29–30; 34–35; 39–40; 44–45; and 49–50.

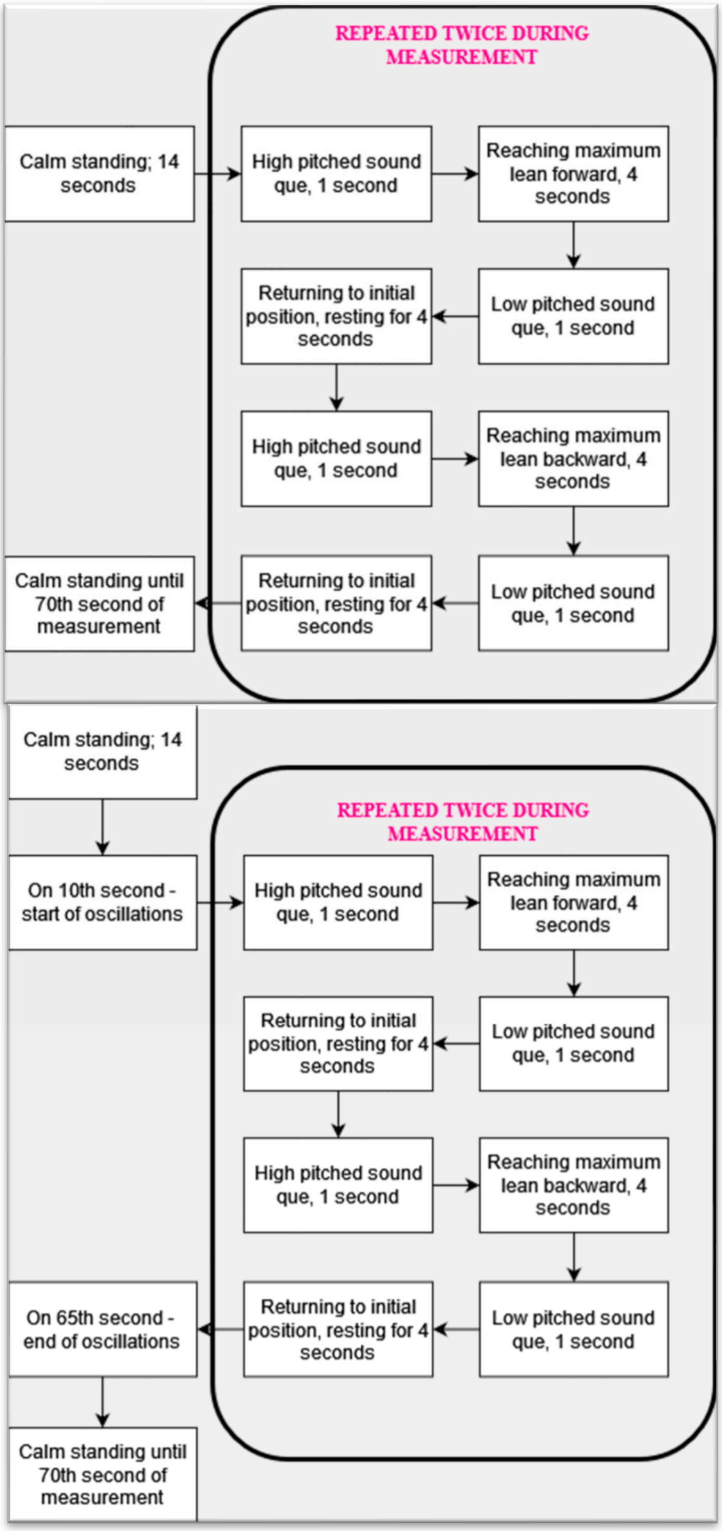


Figure 2. Schemes of measurement trials without oscillations (top graph) and with oscillations (bottom graph).

For each patient, ten measurements were performed, in randomized order. These tests included the following:

- Test with open eyes, without leaning: the participant stood calmly in an upright position without any disturbances and was supposed to focus their sight on one point at around 2.5 m in front of them.

- Test with closed eyes, without leaning: as above, but with closed eyes.
- Test with open eyes and leaning: the participant stood calmly in an upright position and, in response to a high-pitched sound cue, was supposed to lean forward, keep the leaned position for four seconds, and return to the initial position after hearing a low-pitched sound.
- Test with closed eyes and leaning: as above but with closed eyes.
- Test in stationary VR scenery: the participant wore the VR HMD, and the scenery was displayed and stationary. The task of the participant was as described in the trial with eyes open.
- Test in darkness displayed in VR: the participant wore the VR HMD, displaying darkness (the screen was black). The task of the participant was as described in the trial with eyes open.
- Test in oscillating VR scenery (0.2; 0.5; 0.7 and 1.4 Hz): 4 trials were performed with the participant wearing the VR HMD, which was displaying the same scenery as in the test with stationary scenery (shown in Figure 1), but in 10th second of measurement, the scenery began to oscillate in the A/P axis with the chosen frequency. Oscillations were in effect until the 65th second of measurement. Otherwise, the subject performed the leaning as described in the test with open eyes.

2.3. Processed Data

From the Zebris FDM-S platform, 27 value types were recorded, and each gave 7000 registered samples. From those 27 values, all A/P axis COP-related values for the left and right foot separately, as well as the total between both feet were taken into further consideration.

A custom script was created in the Mathworks MATLAB® 2022b environment to process gathered data. The analyzed values for the A/P axis included the following: mean COP range from the start of movement to maximum lean to the front; mean COP range from the start of movement to maximum lean to the back; mean range from max lean to the front to max lean to the back; COP velocity from the start of movement to max leans both to the front and to the back, calculated as the difference in position of COP starting position and its maximum displacement reached during the leaning phase, divided by the difference in time between these points. All said values were calculated for the total COP as well as for the COP of each foot separately (Figure 3).

For each trial type, the medians for all calculated COP values were calculated (e.g., front, back, and total COP displacement ranges for the eyes-open leaning trial were averaged for each of the patients in each trial, so for the eyes-open leaning, the trial total COP range was calculated 16 times, once for each patient) and used for further analysis. COP velocity was calculated as the difference in COP positions between the starting point and max registered during the leaning phase divided by the difference in time at which both values were registered. The exemplary measurement result is shown in Figure 4.

Statistical analysis was performed using the MATLAB R2022b software program. First, basic statistics were calculated for medians, as can be seen in Figure 5. Then, the compared values were tested using the Shapiro-Wilk test to check for the occurrence of normality in the distribution. The results did not confirm the occurrence of normal distributions. Therefore, non-parametric tests were used. To verify whether there were statistically significant differences in the case of the analyzed groups, the ANOVA Friedman test was conducted followed by the pairwise Wilcoxon post-hoc test with Holm correction at $\alpha = 0.05$. All performed tests obtained high test power.

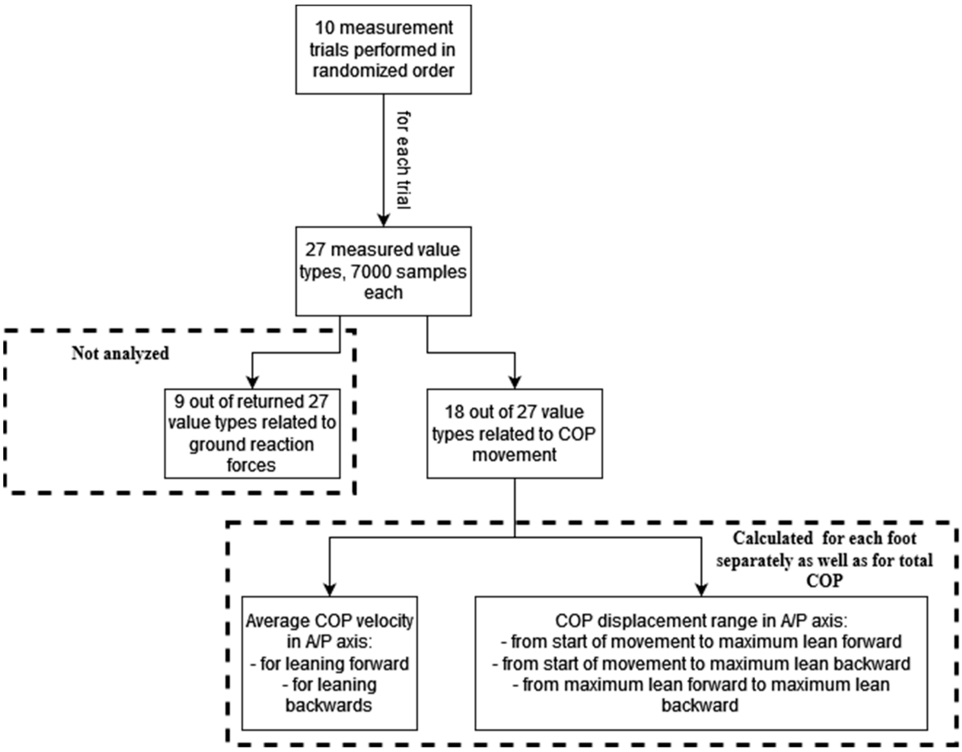


Figure 3. Graphic presentation of selection of analyzed data.

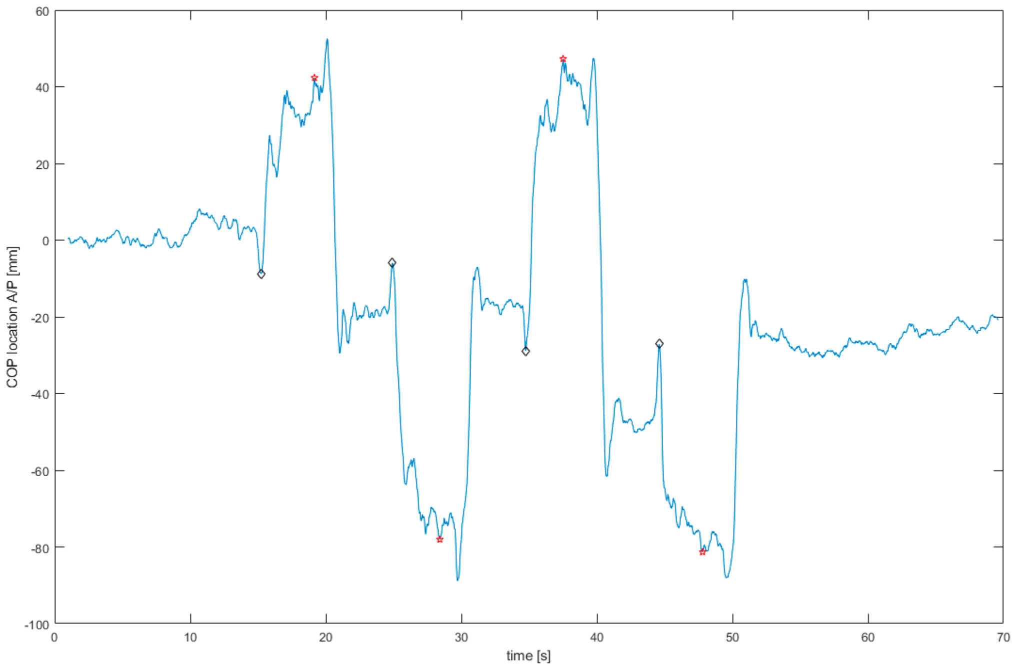


Figure 4. Exemplary COP displacements registered during measurement with use of VR and scenery oscillations at 0.2 Hz. Black rhomboids represent points of leaning start, red stars are points of registered maximums during leaning.

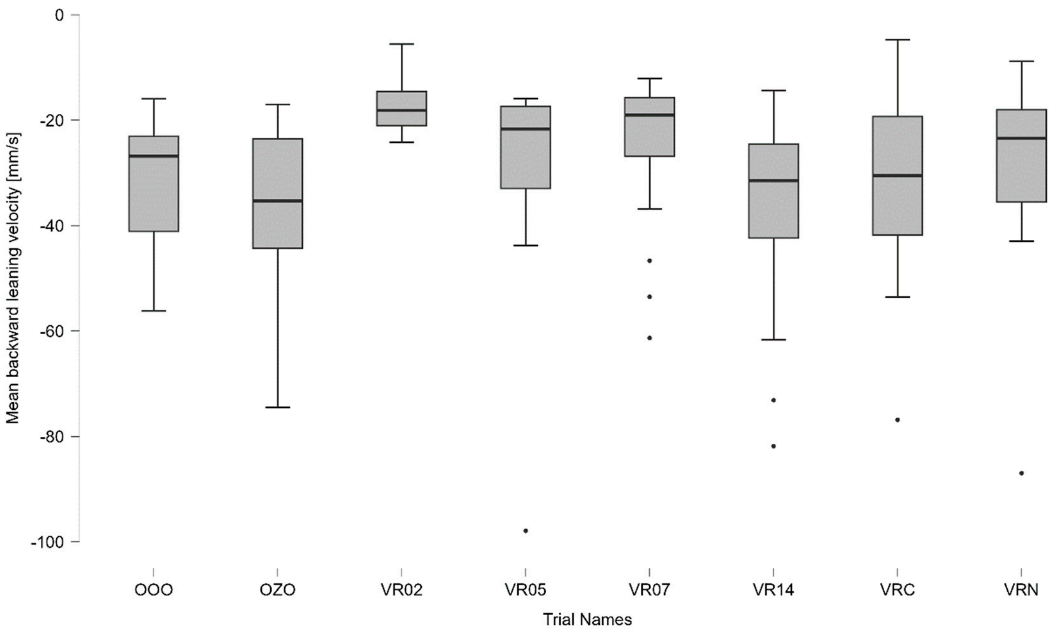


Figure 5. Statistics for differences in mean COP velocities of leaning backward between all trials, averaged for all participants. Top and bottom lines of boxes represent 25th and 75th quartile, the thick line represents the mean value, and whiskers are the standard deviation. Dots represent the outliers.

Sixteen patients participated in each trial, and the gathered data from each (except for two, which required just calm standing in an upright position) had to be divided into four analyzed periods, all containing the beginning of the leaning, keeping the leaned posture, and returning to starting position processes. Each trial consisted of the same sequence of leaning; therefore, in order to find the beginning of leaning to the front, a local minimum was looked for, and for leaning back—a local maximum. For the beginning of movement, a point at which the COP changed directions to the opposite before a sudden increase/decrease in position was taken. The maximum COP displacement was found in the range from the beginning to 1 s before the end of the audio cue signalizing return to the initial position. This range was chosen to avoid registering the maximum responsible for the beginning of returning to the initial position movement, and therefore the effect of inertia moving the COP over the maximum value that could be registered during the lean-keeping phase.

Due to the small number of participants, the normal distribution test did not provide positive results, and therefore a Friedman's two-way ANOVA with the pairwise Wilcoxon post-hoc test with Holm correction was performed in order to find if statistically significant differences were present between any two of calculated groups of results. The statistical effect for the tests was calculated (Kendall's w value algorithm), and in cases with a statistical difference, the returned values were more than or very close to the value of 0.8.

For each trial, the medians were calculated for displacement from the start of movement to maximum forward lean, backward lean, and for the total range from backward to forward. All these medians were calculated separately for the total, left foot, and right foot COP displacements, resulting in 9 medians calculated for each trial. For velocities, medians were calculated for average maximum lean reaching velocity to the front and to the back, also for the total COP velocity as well as for each foot separately, resulting in 6 medians calculated for each trial.

3. Results

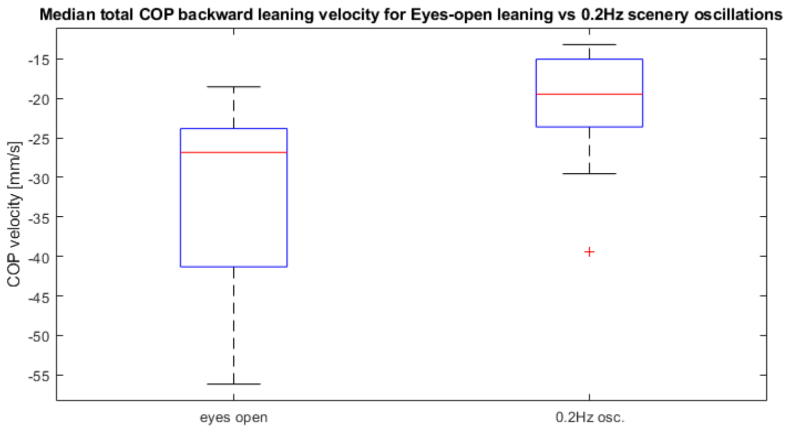
The exemplary COP displacement recording during one of the leaning trials is presented in Figure 5. It can be noticed that during the leaning phases, the COP displacement increased with time, and the end of that phase is characterized by a local peak resulting from propelling the body back to its initial position when the second, low-pitched sound cue was played.

Each calculated median was compared between all performed trials in search for statistically significant differences to search for changes in results achieved by every patient between all of the performed tasks.

Comparing all medians between each of the trials for every patient resulted in 420 median comparisons and calculated p-values resulting from the pairwise Wilcoxon post-hoc test with Holm correction. Out of all returned p-values, only four comparisons resulted in a value $p < 0.05$, which were the following:

- Median total COP backward leaning velocity for eyes-open leaning vs. 0.2 Hz scenery oscillations;
- Median total COP backward leaning velocity for eyes-closed leaning vs. 0.2 Hz scenery oscillations;
- Median left foot COP backward leaning velocity for eyes-closed leaning vs. 0.2 Hz scenery oscillations;
- Median right foot COP backward leaning velocity for eyes-open leaning vs. 0.2 Hz scenery oscillations.

Differences in medians of parameters, which showed statistically significant differences, are shown in Figure 6, and differences in medians of statistically different trials are presented in Table 1. All other values that were compared did not show statistically significant differences.



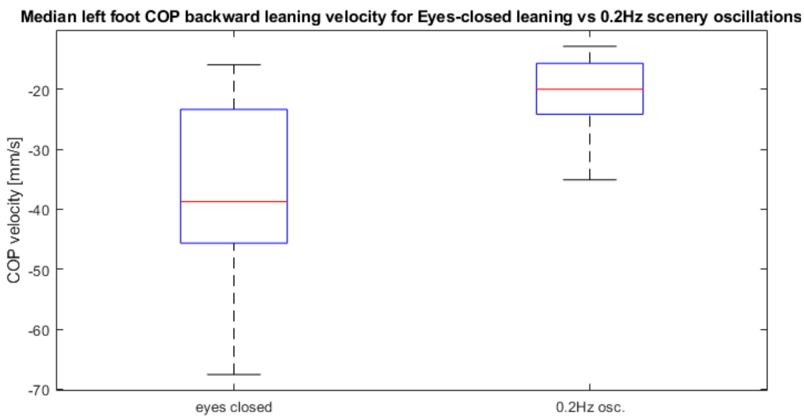
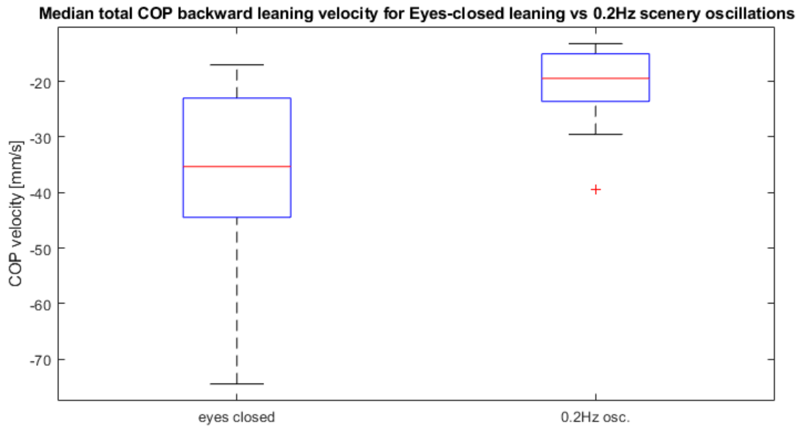


Figure 6. *Cont.*



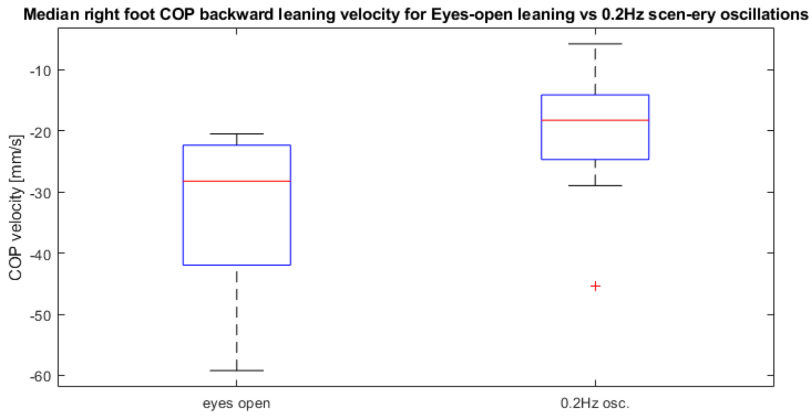


Figure 6. Basic statistics showing differences in medians, standard deviations, and variances between trials showing statistically significant differences. From top: 'Median total COP backward leaning velocity for Eyes-open leaning vs. 0.2 Hz scenery oscillations'; 'Median total COP backward leaning velocity for Eyes-closed leaning vs. 0.2 Hz scenery oscillations'; 'Median left foot COP backward leaning velocity for Eyes-closed leaning vs. 0.2 Hz scenery oscillations'; and 'Median right foot COP backward leaning velocity for Eyes-open leaning vs. 0.2 Hz scenery oscillations'. + marks represent outlier results.

Table 1. Results of Friedman's ANOVA for statistically significantly different types of trials and measured values.

Name of 1st Trial	Name of 2nd Trial	Median of 1st Trial [mm/s]	Median of 2nd Trial [mm/s]	Difference in Medians [mm/s]	*p*-Value	Effect Size
Total COP backward leaning velocity for eyes-open leaning	Total COP backward leaning velocity for 0.2 Hz scenery oscillations	−32.4892	−20.5013	−11.9878	0.0323	0.80
Total COP backward leaning velocity for eyes-closed leaning	Total COP backward leaning velocity for 0.2 Hz scenery oscillations	−34.9797	−20.5013	−14.4784	0.0323	0.80
Left foot COP backward leaning velocity for eyes-closed leaning	Left foot COP backward leaning velocity for 0.2 Hz scenery oscillations	−35.8722	−20.8022	−15.0700	0.0074	0.89

Table 1. *Cont.*

Name of 1st Trial	Name of 2nd Trial	Median of 1st Trial [mm/s]	Median of 2nd Trial [mm/s]	Difference in Medians [mm/s]	*p*-Value	Effect Size
Right foot COP backward leaning velocity for Eyes-open leaning	Right foot COP backward leaning velocity for 0.2 Hz scenery oscillations	−32.2740	−20.1337	−12.1403	0.0257	0.84

It is noticeable that 0.2 Hz oscillations lower the velocity of leaning backward, and the median difference between trials is greater than 10 mm/s in each compared pair of trials; the interquartile range is also at least two times lower for 0.2 Hz scenery oscillations than in eyes open/closed leaning trials.

4. Discussion

Virtual reality is becoming an increasingly extensively used technique for enhancing rehabilitation, performing research on human motorics, and diagnosing physical dysfunctionalities [10–13]. Although the number of reports stating the successful use of said technology for the purpose of making the physiotherapy process more efficient, increasing patients' engagement in exercises, or even allowing them to train in order to keep progressing through physiotherapy at home is increasing, VR does not always guarantee an increase in achieved results. From an analysis of our results, we can conclude that the introduction of VR to measurements of LOS does not allow patients to achieve better results and increase their capabilities of moving their COP over limits that are achieved in conditions of real-life environments with eyes open, best resembling everyday life conditions. As reported in [14], LOS measurements are a viable method of assessing a healthy adult's functional stability; the authors also proposed methods of measuring and analyzing limits of stability. We aimed to find if the introduction of scenery oscillations or of VR itself affects one's LOS, and therefore gives reasons for the initial thinking that it can be used for therapeutic means. To the authors' best knowledge, no other publication about analyzing limits of stability has been published, nor publications analyzing the COP for each foot separately. Revised were PubMed and Infona publication databases, and no records on research performed in similar conditions were found prior to conducted research. We also looked for asymmetry in the use of the lower limbs when reaching LOS.

The beginning of movement point was chosen for our calculations in order to avoid drift of baseline, as during times of rest between leans, the mean position of the COP was usually not the same as it was at the beginning of the measurement until first sound cue signalizing the start of leaning was played; therefore, we believed that participants would lean by a comparable amount in each leaning phase from the point taken as the beginning of leaning to the self-believed limit. We also made attempts to recreate the approach with regression lines presented in [14] for analysis, but swaying induced by VR scenery oscillations and relatively short times of keeping the maximum leaned position resulted in heavily angled regression lines, causing a drastic shift in the point of crossing of said lines, shortening the number of samples that could be taken into account for the analysis of the lean-keeping phase.

Out of 420 compared combinations of medians, only 4 gave positive results (meaning the medians were statistically different). The performed statistical tests were checked for their power value, and the result was always more than or very close to 0.8. This proves that the performed analyses returned statistically significant results. In our research, it turned out that 0.2 Hz oscillations affect the velocity at which maximum backward lean is reached, slowing the process of leaning and also lowering the interquartile range, presenting greater repeatability of results. These results were registered for both feet COP separately as well as for total COP and always included trials with 0.2 Hz scenery oscillations. No other oscillating scenery trial displayed a statistically significant difference, including leaning backward, total COP velocity, and for any individual foot, making the authors conclude that low-frequency oscillations influence the speed at which maximum lean backward is reached. This finding confirms that low-frequency oscillations do influence postural balance and swaying in human beings, and can be confirmed by findings presented in [15–17]. The authors believe that the significant influence of these oscillations might also result from participants adjusting their leaning to remain in phase with the 0.2 Hz oscillations, causing them to lean at the corresponding speed and direction of scenery movement, without experiencing a change of scenery movement direction. This explains why the maximum reached leaning distance was not affected, but the time and, therefore, speed of reaching LOS was. Another conclusion that can be drawn is that a healthy subject does not show a significant asymmetry between lower limbs' COP velocity when reaching backward LOS even when most affecting oscillations are present; this can lead to believing that when destabilizing stimuli work on the A/P axis, the body acts as a whole to prevent falling, and no preference is displayed regarding lower limbs. Therefore, if significant asymmetry becomes apparent, we can presume that one of the systems responsible for balance maintenance is not working as intended.

For our future measurements regarding the analysis of LOS, a change in approach is necessary, as patients did not manage to stabilize their position in maximum leaned positions in the given time of 5 s. Giving participants more time to rest between leans would also be beneficial, as participants would be able to return to their original resting position and keep it while avoiding the short-term learning resulting in a shift in resting COP mean position, which affects the achievable maximum values during leaning phases. It also would be beneficial to increase the number of repetitions for each trial. As has been reported in [18], analyzing COP swaying requires a greater amount of repetitions than its velocity in order to obtain scientifically reliable data. Another limitation of our study was that the measurements were only performed on young adult subjects who did not report any significant or balance-influencing impairments. What is more, during our measurements, HMD was used to display the virtual scenery, and, as has been reported by Wodarski et al. in [19], the use of such a system does influence the capability of maintaining postural balance.

5. Conclusions

It is necessary to give patients sufficient time to stabilize their maximum leaned position during tests of LOS, and performing multiple leans when analyzing maximum voluntary LOS is not advisable. A duration of 5 s is insufficient for a person to reach their maximum lean and the time given for reaching LOS should be increased.

The left and right feet do not participate in leaning at the same levels—statistically significant differences were found only for comparisons performed with 0.2 Hz oscillations, but for the left foot, the significant difference appeared when comparing the eyes closed tests, while for the right foot when the comparison was performed the for eyes open tests.

Oscillations other than 0.2 Hz do not affect the LOS in any significant way. It is suspected that such oscillations might resemble naturally occurring dizziness, or result from attempts to stay in phase with scenery oscillations, as the patient can match their leaning speed to the speed of the scenery movement without experiencing a direction change of said scenery movement, which results in a decrease in LOS reaching speed, but not its distance. The influence of 0.2 Hz and similar oscillations on balance-maintaining capabilities has been confirmed in other publications.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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