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The impact of individually selected PORON heel lifts, foot supination, and limb axial alignment on body balance – a multicenter study

Wpływ indywidualnie dobranych podpiętek PORON, supinacji stopy i osiowego ustawienia kończyn dolnych na równowagę ciała – badanie wieloośrodkowe

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Abstract
The center of pressure (COP) on the feet is a crucial parameter providing information about structural and postural balance. A disturbance in this global pattern causes or reflects dysfunctions in the distribution of tension within the body. Postural disorders that manifest as an imbalance of the center of gravity in the sagittal plane lead to multisegmental ergonomic disturbances of the musculoskeletal system, resulting in compensations, pain, and, over time, structural overload changes and defects. Early detection of anterior-posterior load imbalances and their correction is of great importance for the prevention and treatment of musculoskeletal disorders.
Objective. To assess the impact of individually selected PORON heel lifts and lower limb correction in the transverse plane on body balance.
Methods. The study included 96 participants (n=100%), including 62 women (nf% = 64.58%) and 34 men (nm% = 35.42%), aged 15 to 80 years. The

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average weight of the participants was 75 kg (SD = 18.244), their average height was 1.705 m (SD = 0.093), and their average BMI was 24.81 (SD = 5.009). Exclusion criteria. Individuals diagnosed with significant foot and lower limb deformities or conditions significantly affecting body balance. A pedobarographic examination (EPS R2) was conducted while participants stood barefoot. Each test lasted 20 seconds, with a sampling rate of 1 ms (20,000 samples per test). The study included four trials: trial 0 in free standing, trial 1 with a 3 mm PORON heel lift, trial 2 with a 6 mm heel lift, and trial 3 in the lower limb correction test in the transverse plane (rotation).
Results. The study demonstrated a significant effect of using a low PORON offloading heel lift on balancing anterior-posterior pressure distribution on the feet.
The median heel underload in the control test (without correction) was −7.05% (interquartile range [−11.1%; −1.2%]). The greatest change was observed with the 6 mm heel lift (−3.0%; [−7.2%; +3.0%]). The Kruskal–Wallis statistical significance test for comparing all trials showed a significant difference (χ^2[3] = 15.47, p=0.001). The Wilcoxon rank sum test, used to analyze statistical significance between individual trials, indicated a significant difference between trial 0 and trial 2 (p = 0.001) and between trial 0 and trial 3 (p = 0.036). The difference between trial 0 and trial 1 was nearly significant (p=0.054). The study found no significant effect of the interventions on lateral (right–left) pressure distribution (χ^2[3] = 0.87, p = 0.834). Statistical analysis of 10 body balance parameters showed a significant difference between trials only in parameters describing body oscillations in the sagittal plane. The COP–barycenter angle of the feet significantly decreased (χ^2[3] = 15.01, p=0.002), while the mean COP distance along the Y-axis significantly increased (χ^2[3] = 10.01, p = 0.018).
Conclusions. For postural disorders that shift the center of gravity forward and affect balance in the sagittal plane, the use of PORON heel lifts is justified. Given that the PORON material used in the study is an offloading material with a hardness of approximately 15 Shore and that our applied interventions were significantly lower than those previously studied, these solutions reduce the undesired effects of heel elevation while increasing comfort and footwear compatibility.
Manual correction of the lower limb in the transverse plane also positively influences anterior–posterior COP balance, shifting weight distribution backward. The combination of heel offloading and correction of foot overpronation has a significant impact on relieving pressure on the forefoot, improving standing posture ergonomics, and promoting postural re-education from a forward-leaning position.
Statistical analysis. Statistical analyses were performed using the R statistical software, version 4.3.0 (The R Foundation for Statistical Computing, Wirtschaftsuniversität Wien, Vienna, Austria). Given the significant non-normality of variable distribution in the trials, the Kruskal–Wallis test was applied. The Wilcoxon rank sum test (also known as the Mann–Whitney–Wilcoxon test), with Bonferroni correction for multiple comparisons, was used to identify trial pairs where significant differences occurred. Results were considered statistically significant at p<0.05.

Key words
PORON heel lifts, postural balance, foot supination, anterior-posterior pressure

Streszczenie
Środek nacisku (COP) na stopach jest kluczowym parametrem dostarczającym informacji o równowadze strukturalnej i posturalnej. Zaburzenia tego wzorca powodują lub odzwierciedlają dysfunkcje w rozkładzie napięcia w obrębie ciała. Zaburzenia postawy, które objawiają się przesunięciem środka ciężkości w płaszczyźnie strzałkowej, prowadzą do wielosegmentowych zaburzeń ergonomicznych układu mięśniowo-szkieletowego, skutkujących kompensacjami, bólem oraz – z czasem – przeciążeniami strukturalnymi i deformacjami. Wczesne wykrycie zaburzeń obciążenia w kierunku przednio-tylnym oraz ich korekcja mają duże znaczenie w profilaktyce i leczeniu zaburzeń układu mięśniowo-szkieletowego.
Cel. Ocena wpływu indywidualnie dobranych podpiętek PORON oraz korekcji kończyn dolnych w płaszczyźnie poprzecznej na równowagę ciała.
Metody. Badaniem objęto 96 uczestników (n = 100%), w tym 62 kobiety (nf% = 64,58%) i 34 mężczyzn (nm%=35,42%) w wieku od 15 do 80 lat. Średnia masa ciała uczestników wynosiła 75 kg (SD = 18,244), średni wzrost 1,705 m (SD = 0,093), a średnie BMI 24,81 (SD = 5,009). Kryteria wykluczenia. Osoby z rozpoznanymi istotnymi deformacjami stóp i kończyn dolnych lub schorzeniami znacząco wpływającymi na równowagę ciała. Badanie pedobarograficzne (EPS R2) przeprowadzono w pozycji stojącej na boso. Każdy test trwał 20 sekund, z częstotliwością próbkowania 1 ms (20 000 próbek na test). Badanie obejmowało cztery próby: próba 0 w swobodnym staniu, próba 1 z podpiętką PORON 3 mm, próba 2 z podpiętką 6 mm i próba 3 z korekcją kończyny dolnej w płaszczyźnie poprzecznej (rotacja).
Wyniki. Badanie wykazało istotny wpływ zastosowania niskiej odciążającej podpiętki PORON na wyrównanie rozkładu nacisku w kierunku przednio-tylnym na stopach.
Mediana niedociążenia pięty w próbie kontrolnej (bez korekcji) wynosiła −7,05% (rozstęp międzykwartylowy [−11,1%; −1,2%]). Największą zmianę zaobserwowano przy podpiętce 6 mm (−3,0%; [−7,2%; +3,0%]). Test istotności statystycznej Kruskala-Wallisa wykazał istotne różnice pomiędzy próbami (χ^2[3] = 15,47, p = 0,001). Test sumy rang Wilcoxona wykazał istotną różnicę między próbą 0 a próbą 2 (p=0,001) oraz między próbą 0 a próbą 3 (p = 0,036). Różnica między próbą 0 a próbą 1 była bliska istotności (p = 0,054). Nie stwierdzono istotnego wpływu interwencji na rozkład nacisku w kierunku bocznym (prawo-lewo) (χ^2[3] = 0,87, p = 0,834). Analiza 10 parametrów równowagi wykazała istotne różnice tylko w zakresie parametrów opisujących oscylacje ciała w płaszczyźnie strzałkowej. Kąt COP–barycentrum stóp istotnie się zmniejszył (χ^2[3] = 15,01, p = 0,002), natomiast średnia odległość COP wzdłuż osi Y istotnie wzrosła (χ^2[3] = 10,01, p = 0,018).
Wnioski. W przypadku zaburzeń postawy powodujących przesunięcie środka ciężkości do przodu i zaburzenie równowagi w płaszczyźnie strzałkowej zastosowanie podpiętek PORON jest uzasadnione. Materiał PORON zastosowany w badaniu jest materiałem odciążającym o twardości około 15 Shore, a zastosowane interwencje były znacznie mniejsze niż te opisywane w poprzednich badaniach – rozwiązania te zmniejszają niepożądane skutki podwyższenia pięty, zwiększając jednocześnie komfort i dopasowanie do obuwia.
Ręczna korekcja kończyny dolnej w płaszczyźnie poprzecznej również pozytywnie wpływa na równowagę COP w kierunku przednio-tylnym, przesuwając rozkład masy ciała ku tyłowi. Połączenie odciążenia pięty i korekcji nadmiernej pronacji stopy znacząco wpływa na odciążenie przodostopia, poprawę ergonomii postawy stojącej i reedukację posturalną z pozycji pochylonej do przodu.
Analiza statystyczna. Analizy statystyczne przeprowadzono przy użyciu programu R w wersji 4.3.0 (The R Foundation for Statistical Computing, Wirtschaftsuniversität Wien, Wiedeń, Austria). Ze względu na istotną nienormalność rozkładu zmiennych w badanych próbach zastosowano test Kruskala-Wallisa. Do porównań między próbami zastosowano test sumy rang Wilcoxona (znany także jako test Manna–Whitneya–Wilcoxona) z korekcją Bonferroniego dla wielokrotnych porównań. Wyniki uznawano za istotne statystycznie przy p<0,05.

Słowa kluczowe
podpiętki PORON, równowaga posturalna, supinacja stopy, rozkład ciśnienia przód-tył

Introduction

The human body posture is correlated with the position of the center of gravity (COG). Therefore, the alignment of individual body segments significantly influences the direction of pressure distribution and forces within the feet, represented by the projection of the body's center of gravity onto the ground [2, 3]. The bipedal support of the body on the ground in an upright position defines the base of support (BOS), i.e., 70% of the total body mass is located at a distance of two-thirds of the body height above the support plane [4]. In the human body, there is a dependency that postural muscles are most efficient and balanced when the torso and head are directly above the pelvis in an axial position [5]. The torso accounts for about 50% of the total body mass, and even small deviations can lead to significant shifts in the projection of the body's center of gravity (BCOM) [6, 7]. The lowest energy expenditure and proper body balance are maintained when the projection of the body mass center onto the transverse plane (BCOMtrans) lies within the BOS [8]. Optimal energy expenditure is maintained when the body weight is evenly distributed across both feet in the frontal plane [9-12]. In the sagittal plane, the body axis should pass from the external auditory meatus, through the acromion, greater trochanter, and the head of the fibula (lateral malleolus) [13-16]. The center of gravity of the human body then projects along the front part of the lower leg, about 4.5 cm from the axis of the ankle joint. The percentage distribution of pressures during standing is 60% on the hindfoot and 40% on the forefoot [9-11]. Maintaining proper body posture minimizes the moments of stabilizing forces in the lower body joints, particularly in the ankle joints. It also significantly reduces the activity of the calf muscles, providing the most optimized moments for maintaining body balance. Low metabolic energy demands prevent the need to engage the upper body muscles to maintain postural balance [18]. Proper body posture enables efficient and ergonomic function of muscles and internal organs [19].

Upright posture is influenced by visual, vestibular, and proprioceptive signals [2, 20-24]. The role of skin receptors in the sole of the foot in maintaining balanced body posture has also been demonstrated [25, 26]. Iwanenko et al. (1997) showed that proprioceptive stimuli, particularly the projection of the center of pressure (COP) onto the support plane and the ankle joint torque, play a key role as major control parameters of upright posture [27]. Therefore, studying the center of gravity and the reactions of ground forces is essential.

It has been shown that shifting the center of gravity forward by bending the torso in healthy individuals can cause changes in the kinematics of the lower limbs during walking [6, 28]. It has also been shown that when the projection of body mass is near the edge or outside the BOS, the body loses balance. Imbalance results in compensations and destabilization of the body's tensegrity, leading to a significantly costly energy expenditure [8]. This can result in disorders affecting the entire body posture [29-38]. It has been shown that a forward-tilted posture of the body is most strongly correlated with spinal deformities, a postural defect causing negative side effects not only for the musculoskeletal system but also for the overall functionality of the body [29-31]. Forward tilting of the body strongly activates the ankle joint areas [27]. The foot plantarflexes through the eccentric action of the triceps surae muscle [27, 39, 40], which significantly affects the tensions at the Achilles tendon insertion point [18]. This is a compensatory mechanism preventing falling [18]. The forward shift of the center of gravity activates the plantar flexors of the foot, along with the tension and elongation of the plantar fascia. Combined with the eccentric work of the triceps surae, it results in traction at the heel (i.e., stretching the heel in two directions, causing pressure on the apophysis and plantar structures of the heel) [38]. Balancing the body in the forward-tilted posture also causes hip joint flexion [18]. According to the tensegrity model, this results in pelvic anterior tilt and, consequently, the deepening of spinal curvatures [36, 37]. Muscle dysfunction leads to a decrease in their antigravity function (exposing the body to gravitational forces) during normal activities such as standing, walking, running, etc. [17]. This leads to multisegmental compensations throughout the body through pathological reaction chains. Excessive muscle stimulation leads to a decrease in their elasticity and structural changes (atrophy, enthesopathies/ tendinopathies, etc.) [32-35]. In light of the above, it is reasonable to implement therapeutic solutions that support the process of body balance in the sagittal plane. In rehabilitation, a common solution for heel dysfunctions and walking and balance disorders is the periodic use of heel lifts on a firm heel pad, usually about 1-3 cm high [41-44]. The practical experience of the authors of this publication has shown that the use of a less invasive solution, such as a heel lift made of soft material with a significantly lower height, allows for a significant balance of the body in the sagittal plane. Observations have also shown that correcting the axial alignment of the ankle joints and the entire limb with a foot supinator "further corrects anterior-posterior pressures on the feet," significantly influencing the proper alignment of the COP. Based on the authors' experience, an initial hypothesis was formulated that the height of the heel lift and the supinator should be individually selected.

Objective

Evaluation of the effect of individually selected PORON heel lifts and lower limb correction in the transverse plane on body balance.

Study group

The study was multicenter and conducted in Poland. A total of 96 participants (n = 100%), including 62 women (nf% = 64.58%) and 34 men (nm% = 35.42%), aged from 15 to 80 years, participated in the study. The average weight of the participants was 75 kg (SD = 18.244), the average height was 1.705 m (SD = 0.093), and the average BMI index was 24.81 (SD = 5.009). Exclusions: indIviduals with diagnosed significant foot and lower limb deformities or diseases that have a significant impact on body balance.

Methods

Pedobarography, EPS R2 platform with BIOMECH Studio 2.0 software. The study was conducted based on the approval of the Bioethics Committee No. KB-006/46/2022. Participants were fully informed about the study procedure (in particular, about the lack of impact of the study and the interventions on the participant's health). The objectivity of the results was ensured by a double-blind procedure, i.e:

- participants were not informed of the detailed purpose of the activities before the test to avoid influencing their posture control.

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All participants gave informed consent for this procedure – specialists who conducted the study received detailed instructions on how to perform the test and were provided with identical heel lift applications from the authors of the study. All researchers used the EPS R2 pedobarograph with BIOMECH Studio v.2 software in their practice. The researchers were not informed about which specific parameters would be analyzed in the study, and they consciously agreed to this approach.

As part of the study, four experimental trials were conducted:

Trial 0: Free standing of the patient (control trial).

Trial 1: Free standing with a 3mm thick, soft PORON heel lift with a hardness of 15 Shore – Fig. 1a. (After the application was placed, the participant could adjust their posture to a comfortable position).

Trial 2: Free standing with a 6mm thick, soft PORON heel lift with a hardness of 15 Shore – Fig. 1b. (After the application was placed, the participant could adjust their posture to a comfortable position).

Trial 3: Standing position after manual correction of the lower limbs in the transverse plane. This trial was conducted due to the fact that most of the participants exhibited flatfoot alignment with internal rotation of the limb.Based on the knowledge that such a position, through tensegrity relationships, leads to an anterior pelvic tilt, increased spinal curvatures, and may consequently shift the body's center of gravity forward [45-48], a decision was made in this study to examine the effect of manual correction on the shift in the COP (Center of Pressure) position. The manual correction of the lower limbs was performed by rotating the lower limb at the hip joint to the position of axial alignment of the patellae (i.e., after correction, the patellae were oriented "straight ahead"). During the correction, strict control was also maintained over the proper positioning of the foot, i.e., the correction involved addressing the foot's overpronation, aligning the rearfoot to a reference position.

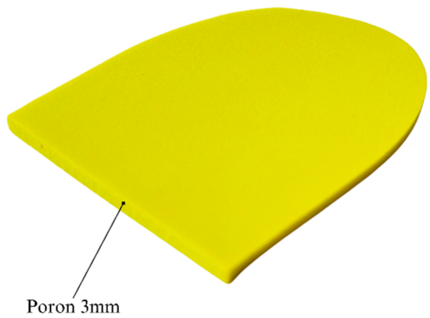

Figure 1a. Poron heel lift of 3 mm thick

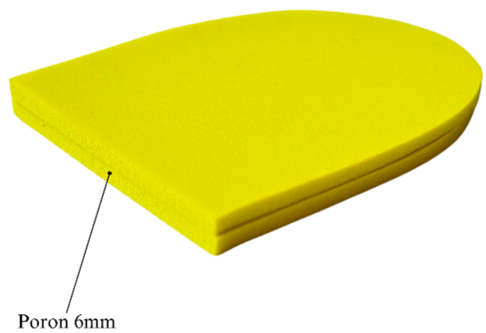

Figure 1b. Poron heel lift of 6 mm thick

The analysis focused on the results of the pedobarographic examination concerning the distribution of the center of pressure (COP): the COP angle and the barycenters of the left and right feet, the anterior-posterior and lateral distribution (Fig. 2), as well as the results of the balance test (Fig. 3).

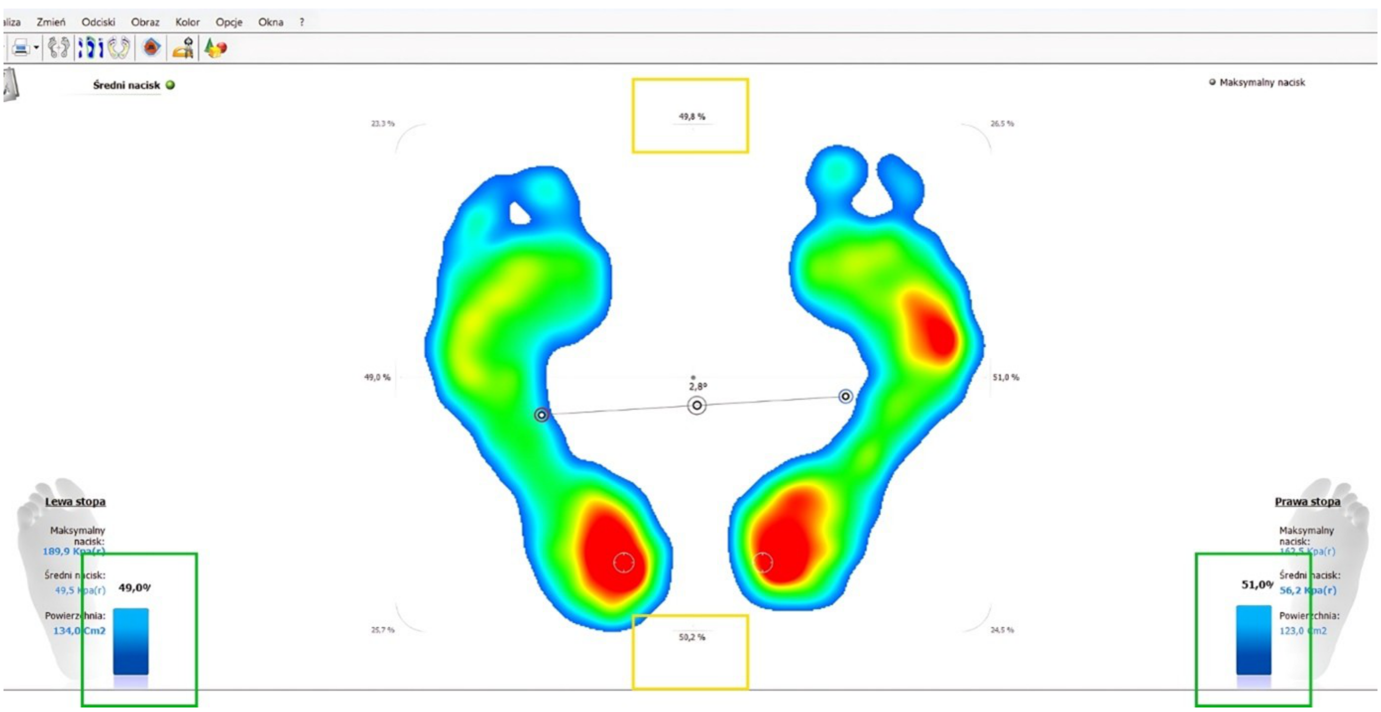

Fig. 2. An example of a pedobarographic study result showing the angle of the COP-foot centers (indicated within the blue circle; here: 2.80), the anterior-posterior distribution (forefoot, here: 48.8% – hindfoot, here: 50.2%; orange frames), and the lateral distribution (left foot, here: 49% and right foot, here: 51%; green frames).

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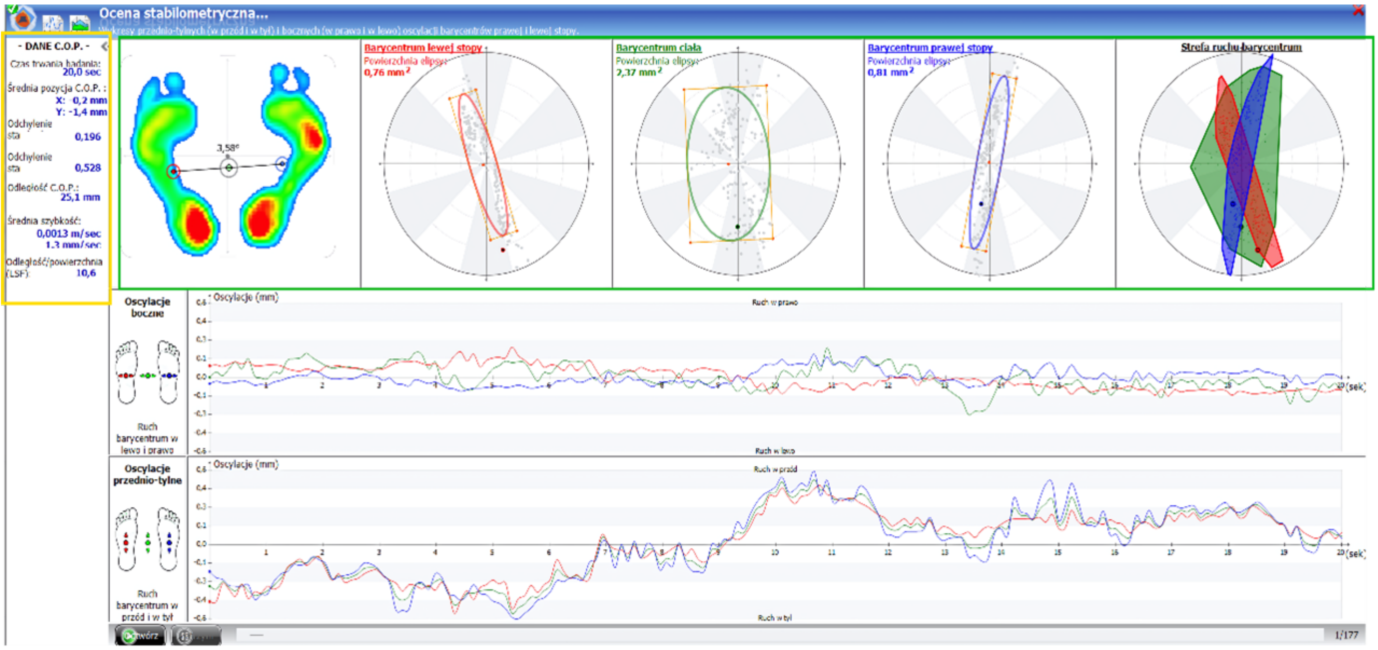

Fig. 3. Example result of a pedobarographic body balance test (i.e., stabilogram), which allows for the observation of body sway ranges via the center of pressure (COP), represented as the point of pressure distribution on the surface, i.e., the vector of the ground reaction force on the plane of the applied feet. In particular:

– Average COP position [X, Y] – means the average result of COP fluctuations (respectively: X- lateral, Y-anterior-posterior) from the zero point, i.e. the obtained results can have both negative and positive values, which significantly affects the result of the mean (results indicated in the orange frame),

– Standard deviations – indicates a classic measure of variation of the COP distribution around the average (results indicated in an orange frame),

– COP distance – is the length of the COP (results indicated in an orange frame),

– Barycenter – is the area of the ellipse area determined by COP motion, respectively for COP and COP motion of the left and right feet (results indicated in the green box).

Statistical Analysis

The statistical analyses were conducted using the R statistical program, version 4.3.0 (The R Foundation for Statistical Computing, Wirtschaftsuniversität Wien, Vienna, Austria). Given the significant non-normality of the variable distribution in the trials, Kruskal-Wallis tests were used [1]. The Wilcoxon rank sum test (also known as the Mann–Whitney–Wilcoxon test) with Bonferroni correction for multiple comparisons was employed to identify pairs of trials where significant differences occurred. Results were considered statistically significant at $p < 0.05$. The statistical analysis of the differences between trials was visualized using plots, where: vertical black lines span from the 1st to the 9th decile, a black dot in the center represents the median value, and red lines represent the characteristics of each individual subject in all four trials.

Research results

In the first stage, the distribution of pressure in the anterior-posterior direction was analyzed (i.e., pressure on the forefoot relative to the hindfoot). Statistical analyses were compared to reference values for the percentage distribution between the hindfoot (60%) and forefoot (40%) [9-11]. Additionally, the variable Back_60 was introduced, which was calculated as the difference between the hindfoot load percentage and the norm (60%). A negative Back_60 value indicates underloading of the hindfoot (and thus a shift in weight to the forefoot). A positive value indicates an increased load on the hindfoot relative to the norm (and underloading of the forefoot). Descriptive results obtained in all the experimental trials are summarized in Table 1.

Table 1. Descriptive results of the percentage distribution of pressure on the hindfoot, for all test trials (Sample 0-3)

Variable	N	Sample [No]	Min	Q1	Median	Q3	Max	Mean	SD
Percentage of forefoot pressure [%]	96	0	24.5	41.175	47.05	51.1	69.6	46.779	8.039
	96	1	23.4	37.65	45.05	48.925	67	43.664	8.324
	96	2	21.5	37	43	47.15	67.9	42.496	8.269
	96	3	23.9	37.025	44.25	48.95	61.1	43.046	8.178
Percentage of rear foot pressure [%]	96	0	30.4	48.9	52.95	58.825	75.5	53.221	8.039
	96	1	33	51.075	54.95	62.35	76.6	56.336	8.324
	96	2	32.1	52.85	57	63	78.5	57.504	8.269
	96	3	38.9	51.05	55.75	62.975	76.1	56.954	8.178
Back_60 [%]	96	0	−29.6	−11.1	−7.05	−1.175	15.5	−6.779	8.039
	96	1	−27	−8.925	−5.05	2.35	16.6	−3.664	8.324
	96	2	−27.9	−7.15	−3	3	18.5	−2.496	8.269
	96	3	−21.1	−8.95	−4.25	2.975	16.1	−3.046	8.178

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The distribution of differences between the percentage of real pressure on the hindfoot and the reference value (60%) is also shown in the graph (Fig.4.).

The Kruskal-Wallis statistical significance test revealed a statistically significant difference for all trials (χ^2 [3] = 15.47, p = 0.001). Detailed results showed significant underload of the hindfoot in all participants in trial 0 (resulting in overload of the forefoot) – the median value of the Back_60 variable in trial 0 was -7.05%. All other trials showed a reduction in hindfoot underload, both in the trial with one heel insert (trial 1), as well as with two heel inserts (trial 2) and during correction aimed at aligning the limb (trial 3). The greatest shift of weight to the hindfoot was observed in trial 2 (-3.0%). The Wilcoxon rank sum test with Bonferroni correction for multiple comparisons, focusing on statistical significance analysis between all trials (i.e., trial to trial), showed a significant difference between trial 0 and trial 2 (p = 0.001) as well as between trial 0 and trial 3 (p = 0.036). The difference between trial 0 and trial 1 was nearly significant (p = 0.054). The results of the comparison of differences between the trials are summarized in Table 2.

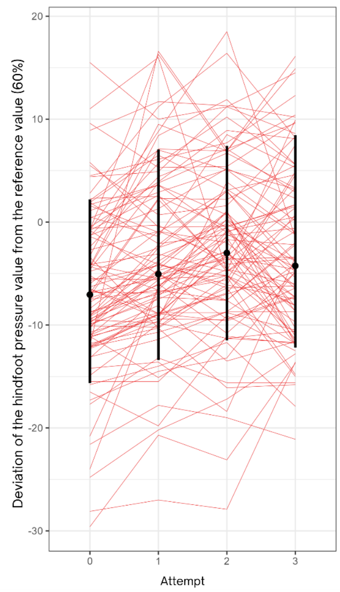

Figure 4. Deviation of the hindfoot pressure value from the reference value (60%)

Table 2. Results of testing differences of all test trials (1.2.3) anterior-posterior loading, compared to 0 (Wilcoxon rank sum test).

Research trials	Test 0	Test 1	Test 2
Test 1	0.054		
Test 2	0.001	> 0.9	
Test 3	0.036	> 0.9	> 0.9

The percentage distribution of lateral pressures (left/right foot) was also analyzed. The descriptive results obtained in all the research trials for this characteristic are summarized in Table 3. (The variable L_R_dif represents the absolute value of the difference in percentage pressure between the left and right foot.)

Table 3. Descriptive results of the percentage distribution of pressure on the rear foot, for all test trials (Sample 0-3)

Variable	N	Sample [No]	Min	Q1	Median	Q3	Max	Mean	SD
Left foot pressure percentage [%]	96	0	34.5	47.6	50.6	52.825	72.8	50.794	6.996
	96	1	32.7	47.9	50.6	52.8	69.8	51.268	6.626
	96	2	34.2	47.625	49.8	53.2	69.3	51.27	6.376
	96	3	36.7	47.7	50.25	52.925	72.3	50.987	5.467
Right foot pressure percentage [%]	96	0	27.2	47.175	49.4	52.4	65.5	49.206	6.996
	96	1	30.2	47.2	49.4	52.1	67.3	48.732	6.626
	96	2	30.7	46.8	50.2	52.375	65.8	48.73	6.376
	96	3	27.7	47.075	49.75	52.3	63.3	49.012	5.467
L_R_dif	96	0	0	2.95	5.1	10.65	45.6	9.388	10.452
	96	1	0.2	2.8	5.2	11.3	39.6	9.102	9.92
	96	2	0.2	2.55	5.4	10.8	38.6	8.919	9.419
	96	3	0	3	5.5	10	44.6	7.829	7.845

For the above descriptive results, the Kruskal-Wallis statistical significance test was conducted, which showed no significant impact of the trials on the lateral shift of the center of pressure ($\chi2$ [3] = 0.87, p = 0.834). The distribution of the L_R_dif variable is illustrated in the chart (Fig. 5), which shows the difference in the percentage of pressure on the left and right foot. The charts depict the distribution of differences between the actual percentage pressure on the left and right foot.

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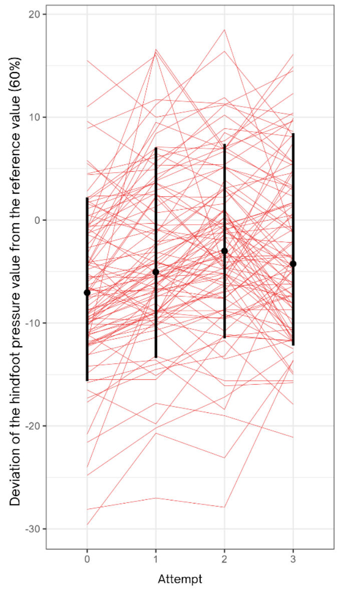

Figure 5. Difference in percentage of pressure distribution on the left and right foot [%]

Subsequently, the analysis focused on the body balance test under the influence of interventions in trials 1-3. The descriptive results of this area are presented in Table 4 and illustrated in Figures 6-15. The statistical testing results (Kruskal-Wallis Test) for the following characteristics are shown in Table 5.

Table 4. Descriptive results of the percentage distribution of pressure on the hindfoot, for all test trials (Sample 0-3)

Variable	N	Sample [No]	Min	Q1	Median	Q3	Max	Mean	SD
Angle of COP – Foot Barycenters [0]	96	0	0	1.275	3.05	5.3	17.8	3.863	3.561
	96	1	0	1	1.9	3.625	16.1	3.003	3.197
	96	2	0	0.6	1.55	3.05	16.3	2.678	3.368
	96	3	0	0.9	1.6	2.825	20.8	2.597	3.147
COP distance [mm]	96	0	9.7	40.9	56.8	76.6	740.2	73.105	82.535
	96	1	9.9	39.625	56.65	86.45	666.4	71.589	74.933
	96	2	8.4	39.725	59.55	78.425	742.7	68.778	77.553
	96	3	4.6	41.55	56.2	84.675	426.9	70.114	56.36
COP speed [mm/s]	96	0	1	2.1	2.9	3.925	37	3.735	4.073
	96	1	0.9	2	2.8	4.325	33.3	3.801	4.202
	96	2	1	2.1	2.9	4.1	37.1	3.5	3.841
	96	3	0.9	2.175	2.8	4.05	21.3	3.578	2.742
Average COP distance in X axis (COP_X) [mm]	96	0	−2.8	−0.625	−0.1	0.8	17.36	0.377	2.31
	96	1	−3.1	−0.6	0.1	0.725	4.9	0.243	1.359
	96	2	−2.9	−0.6	0	0.8	5.1	0.227	1.338
	96	3	−2.5	−0.5	0.15	0.6	6.1	0.223	1.296
COP_X standard deviation	96	0	0.118	0.564	0.964	1.369	5.247	1.127	0.851
	96	1	0.123	0.532	0.829	1.406	8.991	1.112	1.055
	96	2	0.172	0.49	0.882	1.288	3.324	1.009	0.668
	96	3	0.171	0.536	0.816	1.356	8.66	1.131	1.086
Average COP distance in Y axis (COP_Y) [mm]	96	0	−4.1	−2.225	−1.5	−1.075	1.4	−1.601	1.019
	96	1	−5.5	−2.725	−1.7	−1.175	1	−1.97	1.105
	96	2	−4.5	−2.8	−2	−1.375	1.4	−2.003	1.073
	96	3	−4.8	−2.725	−2	−1.375	0.4	−2.077	1.186
COP_Y standard deviation	96	0	0.377	0.957	1.268	1.862	8.737	1.643	1.247
	96	1	0.352	0.871	1.333	2.427	14.465	1.919	1.8
	96	2	0.278	0.949	1.48	2.126	5.513	1.823	1.218
	96	3	0.388	0.9	1.397	1.942	6.035	1.706	1.212
Barycentre of the Body [mm²]	92	0	−4.5	10.902	19.47	42.775	387.75	39.672	59.483
	92	1	1.67	8.802	20.505	50.805	342.03	43.546	59.477
	92	2	0.3	8.503	21.14	42.752	287.36	35.615	48.191
	92	3	2.27	9.717	16.645	32.62	348.96	35.889	53.665

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Variable	N	Sample [No]	Min	Q1	Median	Q3	Max	Mean	SD
Barycentre of the left foot [mm²]	92	0	0.28	2.248	3.955	9.557	146.12	10.472	21.23
	92	1	0.1	1.94	3.775	10.033	138.63	10.418	18.689
	92	2	0.18	1.918	3.715	9.932	40.17	6.681	7.158
	92	3	0.4	2.013	4.36	10.358	80.04	9.482	14.595
Barycentre of the right foot [mm²]	92	0	0.67	1.89	4.815	9.642	112.45	10.297	17.354
	92	1	0.6	2.04	5.34	10.045	176.55	13.65	28.73
	92	2	0.24	1.86	4.725	11.155	144.95	9.602	17.828
	92	3	0.66	2.352	4.475	9.867	124.68	9.876	16.617

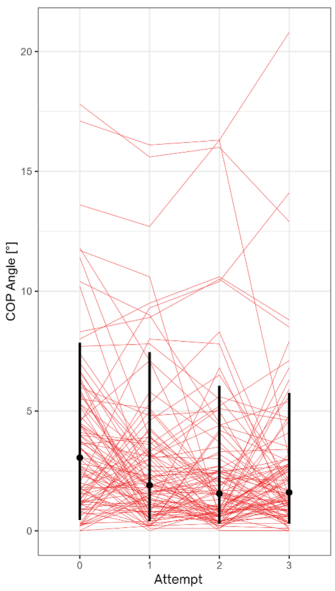

Figure 6. COP Angle [°]

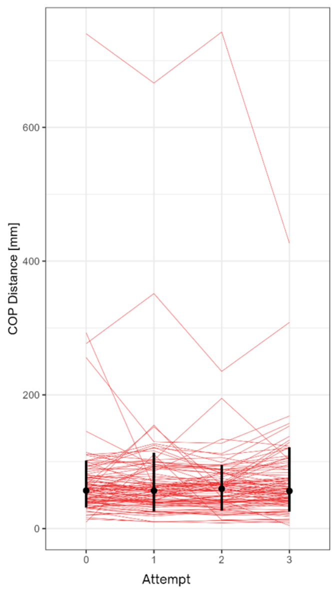

Figure 7. COP Distance [mm]

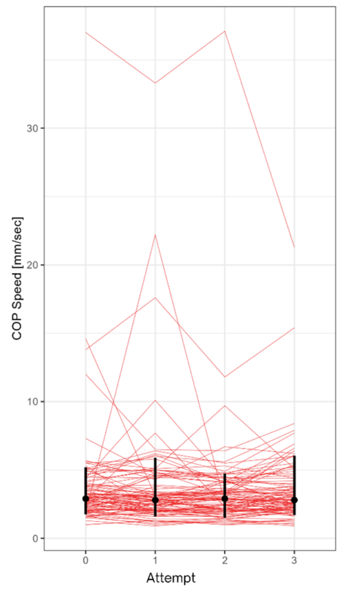

Figure 8. COP Speed [mm/sec]

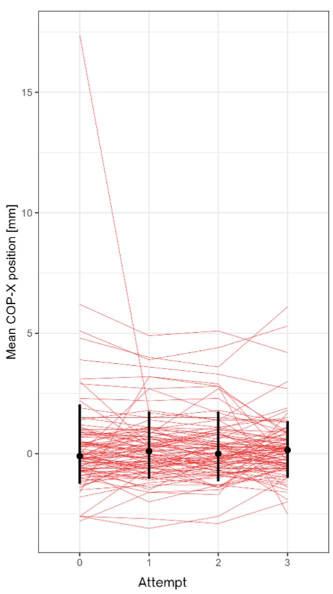

Figure 9. Mean COP-X position [mm]

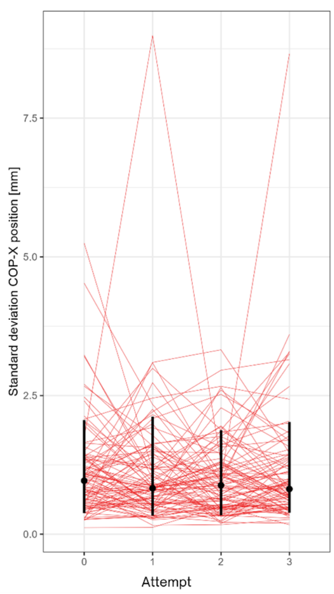

Figure 10. Standard deviation COP-X

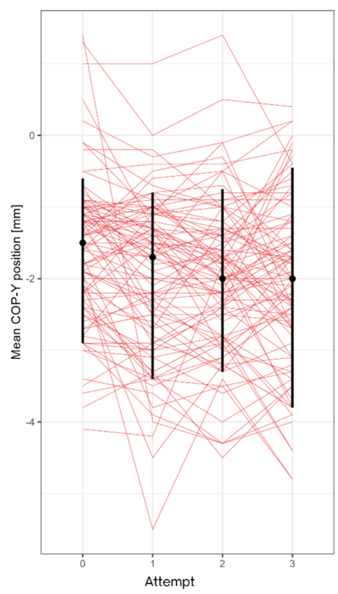

Figure 11. Mean COP-Y position [mm]

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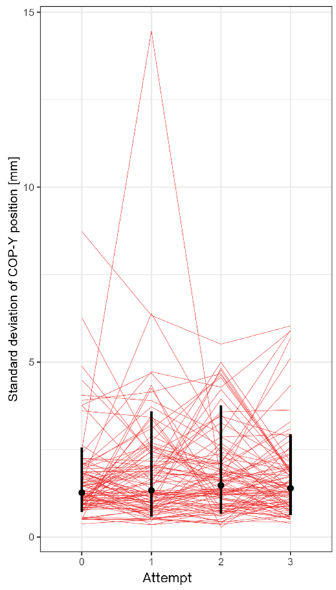

Figure 12. Standard deviation of COP-Y position [mm]

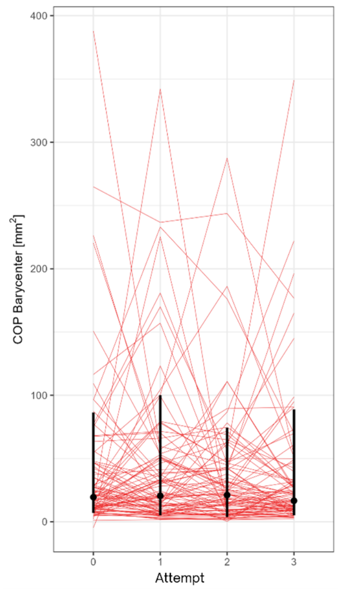

Figure 13. COP Barycenter [mm²]

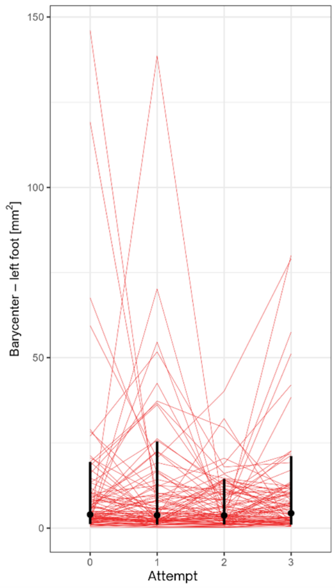

Figure 14. Barycenter – left foot [mm²]

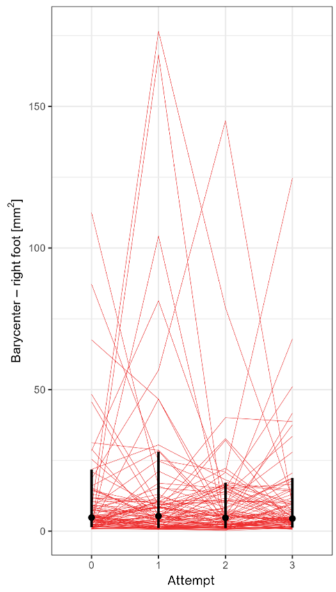

Figure 15. Baryceneter – right foot [mm²]

Table 5. Kruskal-Wallis statistical significance tests performed for the results of the body balance test listed in Table 4

	Result of the Kruskal-Wallis χ2 statistical significance test [3]	p
COP-barycenter angle of feet	**15.01**	**0.002**
Distance COP	0.15	0.985
COP speed	0.37	0.945
Average COP distance in X axis (COP_X) [mm]	0.15	0.985
COP_X standard deviation	0.87	0.834
Average COP distance in Y axis (COP_Y) [mm]	**10.01**	**0.018**
COP_Y standard deviation	1.53	0.676
Posture barycenter [mm²]	1.44	0.697
Left foot barycenter [mm²]	0.56	0.905
Right foot barycenter [mm²]	0.37	0.947

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The results above demonstrated statistical significance only in parameters illustrating changes in the sagittal plane. This applies to both the relationship between the foot barycenters and COP, as well as the distance of the COP path in the sagittal plane (average COP distance on the Y-axis). The Kruskal-Wallis statistical significance test in these areas showed a significant difference across all trials for the COP-Foot Barycenter angle (χ^2 [3] = 15.01, p = 0.002). This angle decreased, which translates to the alignment of the foot barycenters, thus balancing the relationship between the right and left foot centers of pressure. This is an important result from the standpoint of overall body balance. The median COP-Foot Barycenter angle for all subjects in trial 0 was 3.05, in trial 1 (single heel insert) it was 1.9, while for trials 2 and 3, the angle reduction result was comparable, i.e., 1.55 and 1.6, respectively. The Wilcoxon rank sum test, aimed at analyzing statistical significance between all trials of the COP-foot barycenter angle (i.e., trial-to-trial), showed a significant difference (i.e., $p < 0.05$) between trial 0 and trial 2 (p = 0.004) and between trial 0 and trial 3 (p = 0.008). The results of testing the differences between trials are summarized in Table 6.

Table 6. Results of testing differences of all test samples (1.2,3) of COP-barycenters of feet in relation to sample 0 (Wilcoxon rank sum)

	Test 0	Test 1	Test 2
Test 1	0.192		
Test 2	0.004	0.889	
Test 3	0.008	> 0.9	> 0.9

The statistical significance test also showed a significant change in the mean anterior-posterior oscillation distance of the COP in the sagittal plane (COP_Y), with χ^2 [3] = 10.01, p = 0.018. The Wilcoxon rank sum test, aimed at analyzing statistical significance between all trials (i.e., trial to trial), showed a significant difference (i.e., $p < 0.05$) between trial 0 and trial 2 (p = 0.047), as well as between trial 0 and trial 3 (p = 0.033). The results of testing the differences between the trials are summarized in Table 7.

Table 7. Results of testing differences for all experimental trials (1, 2, 3) in the mean distance of anterior-posterior oscillations compared to trial 0 (Wilcoxon rank sum)

	Test 0	Test 1	Test 2
Test 1	0.283		
Test 2	**0.047**	> 0.9	
Test 3	**0.033**	> 0.9	> 0.9

Considering that trial III was focused on testing body balance using manual correction to the axial alignment of the patella and correcting flatfoot deformities (when necessary), the analysis also evaluated the effect of this correction on the Arch Index (AI), which describes the foot arch indicator. The reference value for this index is 21-28% [49]. Table 8 summarizes the results of testing the differences between trial 0 and trial 3. Only the results of trial 3 (compared to control trial 0) were analyzed.

Table 8. Descriptive statistics of the Arch Index (AI) for the left and right foot in control condition (trial 0) and after lower limb manual correction (trial 3)

Variable	N	Sam							
AI indicator for left foot	96 96	0 3	0.83 3.4	17.255 22.07	22.39 25.415	26.368 27.452	33.34 49.03	21.09 24.521	6.997 5.814
AI indicator for right foot	96 96	0 3	0.6 4.86	19.655 23.072	23.76 25.42	26.053 28.28	39.32 39.09	21.845 24.689	7.246 5.395

The above results indicate that, under the influence of the intervention (i.e., lower limb correction in the transverse plane - rotation), the Arch Index (AI) increased for both the right and left foot. At this stage, a side conclusion to the study emerges, suggesting that this correction significantly impacts the correction of foot overpronation. The Kruskal-Wallis test of statistical significance for these results showed a significant change in AI for both the left foot (χ^2 [3] = 22.83, $p < 0.001$)

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and the right foot (χ^2 [3] = 18.66, $p < 0.001$). The Wilcoxon rank sum test, focusing on statistical significance between trial 0 and trial 3, yielded $p = 0.003$ for the left foot and $p = 0.007$ for the right foot. The results of the AI index differences between all trials are illustrated in Figures 17 and 18.

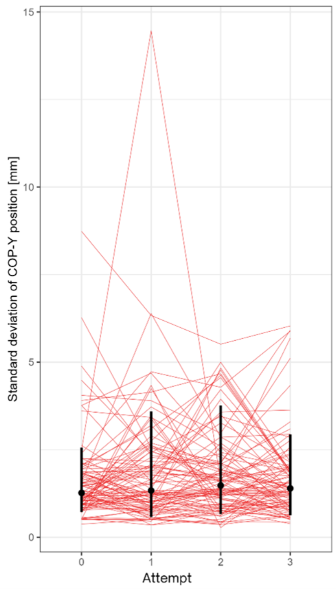

Figure 16. AI – left foot [%]

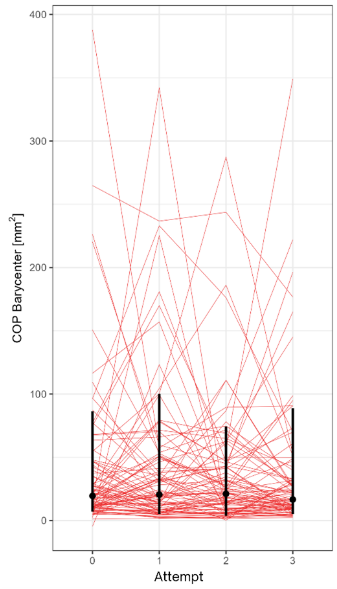

Figure 17. AI – right foot [%]

Discussion

Disruptions in the projection of the center of mass in the sagittal plane cause multisegmental tension imbalances throughout the body, leading to compensations, pain, dysfunction, and even degenerative changes. Most research publications recommend therapy for locally occurring pain, specific defects, or musculoskeletal dysfunctions. However, few studies focus on evaluating the impact of therapy on balancing pressure distribution in the sagittal plane in the context of the entire body posture [17, 29-38].

Research by Kurien et al. (2020) showed that a 1 cm heel elevation placed in a shoe significantly improves gait patterns in individuals with Cauda Equina syndrome [50]. Barton et al. (2009) found that heel elevation significantly normalizes the activity of paravertebral muscles, emphasizing the importance of this discovery for individuals with lower back pain (LBP) [51]. Sato et al. (2021) demonstrated that a 10 mm heel elevation in elderly individuals significantly affects the alignment of the spine in the sagittal plane, i.e., reducing the angle of thoracic kyphosis. Additionally, the researchers noted that the use of heel orthotics significantly improved gait parameters, such as increased speed and stride length, and activated the big toe and toes [52]. Research by Bartonek et al. (2011) conducted on children with motor disorders showed that individually selected heel elevation elements ranging from 1 cm to 3 cm significantly affected children's posture. This is one of the few studies that highlights how heel elevation balances the sagittal plane, reducing anterior pelvic tilt and straightening the posture from a forward-tilted position [53]. The authors also emphasized the critical aspect of the need for individualized selection of heel elevation orthotics [53, 54].

The use of heel elevation has most commonly been studied in cases of pain and dysfunction around the calcaneus, Achilles tendon, and plantar fascia. The reduction of pain due to heel elevation is explained by the shortening of the distance between the initial and final attachment points of the triceps muscle [55]. Ultrasound studies of the Achilles tendon conducted by Wulf et al. (2016) after applying a 1.2 cm heel elevation showed a significant decrease in the stretching load on the Achilles tendon [56]. Similar results were obtained by Lee et al. in electromyographic studies on a male population with heel lifts ranging from 1.9 cm to 5.7 cm (1987) and in a female population (1990) with women wearing heels from 2.5 cm to 7.5 cm [57]. Research by Valentini et al. (2009) indicated that a 2 cm heel elevation significantly acts as a protective mechanism for the muscles in the lower leg-foot relationship, reducing the degree of energy absorption upon heel strike and lowering the maximum values generated during push-off. This suggests a considerably reduced engagement of the triceps muscle due to the plantar flexion of the ankle joint caused by the heel lift [58]. Alghamadi et al. (2024) demonstrated that the use of a 2 cm heel lift in individuals with Achilles tendon insertion tendinopathy immediately relieved pain and positively affected gait parameters, with the effect lasting throughout a two-week therapy period [59]. Kogler et al. (1995) also showed that by shortening the distance between the calcaneus and the metatarsal bones through heel elevation, the load on the plantar fascia is reduced [60]. Heel elevation has wide applications in the rehabilitation program described by Masci and Alfredson (2013) for patients with partial or complete Achilles tendon ruptures, where a 2 cm heel lift was used during verticalization and rehabilitation, and then removed after three months of therapy [61].

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Research on the use of heel elevation during exercises like barbell squats remains controversial. Elevating the heel by 1 to 5 cm reduces the dorsiflexion angle at the ankle joint and the forward lean of the body [62-69]. According to Sayers et al. (2020), this approach aims to reduce shear forces in the lumbar spine [70]. In studies conducted during squats by Lee et al. (2019), it was found that heel elevation does not significantly affect the kinematics of the torso and knees [71]. However, it should be noted that participants in the study performed squats only until the hip joints were level with the knees, which did not allow for observation of the full range of motion (ROM) in the knee joint [72]. Despite the findings of Lee et al. (2019), they also observed that knee flexion increased with heel elevation [71]. Pangan et al. (2021) in their literature review noted that most studies on heel elevation during squats focus on the kinematics of deep squats, with far fewer studies assessing the impact on kinetics [73]. Mestelle et al. (2017) demonstrated that a 1.1 cm heel lift significantly reduced patellofemoral joint tension, which could have implications for the therapy of runners and athletes experiencing pain in this area [74]. Lindenberg et al. (2011) found that elevating the heel by 24 mm significantly increased knee flexion angles during the initial phase of walking (landing) [75].

The scientific findings cited above indicate the significant impact of heel elevation on localized dysfunctions, particularly in the feet, knee joints, and the heel region (especially concerning heel pain and Achilles tendon attachments). However, none of these studies evaluated the effect of heel elevation on the overall distribution of pressure throughout the entire body.

It is worth noting that most researchers assessed heel lifts ranging from 1 cm to 5 cm in height. Not all publications specify the hardness of the materials used, and none of the studies reviewed included the use of soft materials, as was the case in our study.

Our research results clearly demonstrated that placing a soft material with a thickness of 3 mm under the heel significantly influences the redistribution of anterior-posterior pressure. Specifically, in individuals with a forward-shifted center of pressure (COP), the use of a soft heel lift caused a notable shift of body weight toward the heels.

The study conducted by Ramanathan et al. (2008) found that the use of heel-lifting insoles shifts body weight forward. However, their research focused on standard pharmacy-purchased insoles, and their methodology does not provide details regarding the height or hardness of the insoles used. The authors only noted that the insoles had varied shapes. Their discussion was based on the assumption that shifting the center of pressure (COP) forward reduces heel loading, which they associated with decreased pain [76-78].

It is important to note that these conclusions are theoretical and significantly differ from the findings of other researchers. Zhang and Li (2016) investigated the impact of heel elevation on COP displacement and pressure distribution using materials of varying thickness (from 16 mm to 34 mm) and different properties (comparing flexible and rigid materials). Their results showed that as the height of the material increased, pressure on the forefoot also increased. Additionally, they found that both excessively soft and overly rigid materials negatively affected dynamic balance control. Their conclusions emphasized the need for caution when using thicker materials and justified the importance of selecting flexible materials [77].

This finding is particularly surprising, considering the biomechanical aspects of postural balance. The studies cited in this section differ significantly from most of the research discussed earlier. We were unable to determine the exact cause of these discrepancies. However, based on our experience, we believe that research on foot-supporting elements must be conducted in a way that allows the test subject to adjust their posture to new conditions. In our pilot studies, we observed that when test subjects were not instructed to make adjustments, they tended to maintain a static posture after placing their feet on the heel lift. Every change in support conditions requires a natural balancing response and an adjustment to the most ergonomic posture.

Ultimately, it is important to note that a significant forward shift in pressure can lead to traction on the calcaneal tuberosity, causing compression, pain, and structural changes [79, 80]. This area has also been extensively studied by the authors of this publication in the pediatric population, particularly in cases of Sever's disease [38]. Therefore, it is difficult to justify Ramanathan et al.'s conclusion that shifting the center of pressure (COP) forward has a pain-relieving effect on the heel. While this shift may reduce direct contact pressure between the heel and the ground, biomechanical principles suggest that it increases tensile forces on both the Achilles tendon and the calcaneal tuberosity.

Moreover, the studies reviewed do not provide information on whether shifting the COP forward normalized anterior-posterior pressure distribution or simply increased pressure on the forefoot (as there are no references to baseline values).

Given that pain relief is a key factor emphasized by most researchers studying the use of heel lifts, further investigation into the hardness of materials used in these applications is warranted. Our study demonstrated a significant improvement in COP balance when using PORON, a material classified among the most effective for pressure relief due to its lack of shape memory [81].

It has been demonstrated that orthopedic insoles supporting the arch significantly improve body balance and promote proper pressure distribution on the plantar surface of the foot during both standing and walking [78, 82, 83]. Additionally, it has been shown that an arch supinator relaxes the plantar structures of the foot, particularly the plantar fascia [60].

Alfaro-Santafe et al. (2021) found that custom-made orthoses with an arch supinator provided significantly greater improvement in children with Sever's Disease compared to pre-made heel lifts of 6 mm in height [84]. The combination of a heel lift with an arch supinator was investigated by Zhang et al. (2017), who demonstrated that such foot orthoses significantly reduced ML-COP displacement and velocity during walking, thereby improving medial-lateral stability [85].

Lee et al. (2019) conducted a comparative analysis of the effects of heel elevation and a custom-fitted arch supinator on Achilles tendon strain during running in individuals with flat feet. Their findings indicated that both the heel lift and the arch-supporting orthosis reduced Achilles tendon loading [86].

The results of our study significantly complement previous

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research by examining the impact of foot supination, achieved through limb correction in the transverse plane (based on the patellar long-axis index), on COP. Statistical analysis revealed a significant influence of supination on both the balance of anterior-posterior pressure distribution and balance parameters in the frontal plane.

Notably, we demonstrated a positive effect in balancing the COP_barycenter angle of the feet, which reflects the symmetry of left and right foot loading. Additionally, our findings show that correcting limb alignment substantially improves the Arch Index (AI), which positively influences the correction of foot overpronation.

Conclusions

In postural disorders causing a forward shift of the center of mass and imbalance in the body's sagittal plane, it is advisable to use PORON heel inserts. PORON material used in this study is a pressure-relieving material with a hardness of approximately 15 Shore, and the applications used in our study are significantly lower than those previously studied, the use of these solutions reduces the undesirable effects of heel elevation and increases comfort and shoe fit. Manual correction of the lower limb in the transverse plane also positively influences the anterior-posterior COP balance, shifting the body weight towards the rear. The combination of heel unloading and correction of foot overpronation significantly impacts both unloading the forefoot, improving the ergonomics of the standing position, and postural re-education from a forward-tilted posture.

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