Acta of Bioengineering and Biomechanics
Vol. 27, No. 4, 2025

Original paper
DOI: 10.37190/abb/216506

Plantar pressure variations during stair ascending and descending with and without load

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Background: This experimental repeated-measures study investigated how carrying an additional load – symmetrically in a backpack or asymmetrically on one shoulder – affects plantar pressure distribution and contact time during stair ascent and descent. *Methods*: Twelve healthy adults performed six stair-walking conditions (ascent and descent, with and without load). Plantar pressure and contact time were recorded in ten foot regions using a pedobarographic plate. Non-parametric repeated-measures tests were applied (Friedman RM-ANOVA with Wilcoxon signed-rank post-hoc tests using Holm correction), and effect size was quantified using Kendall's *W*. *Results*: Plantar pressure differed significantly across foot regions in both tasks (ascent: $\chi^2(9) = 56.09$, $W = 0.623$; descent: $\chi^2(9) = 58.01$, $W = 0.645$; $p < 10^{-6}$), confirming strong task-related heterogeneity. Rearfoot loading dominated ascent, while forefoot loading prevailed during descent. Load effects were modest and region-specific, with significant increases in Heel Medial and hallux under asymmetric load. Contact time also varied markedly across regions (ascent: $W = 0.831$; descent: $W = 0.849$), but load-related differences were not significant after Holm correction. *Conclusions*: Task strategy (ascent vs. descent) exerts a far greater influence on plantar loading patterns than a small additional load. Asymmetric carriage produces localized changes in PP but does not substantially alter contact time. This parameter may serve as a proxy for gait speed in future mixed-effects models.

Key words: *stair ascending and descending, plantar pressure, pedobarography, additional load*

1. Introduction

Ascending and descending stairs is a common daily activity for humans. While free walking on a flat, hard surface is relatively well-studied, a comprehensive understanding of the phenomena involved in stair activity is still lacking. This is not typically a risky task for healthy individuals [23]. However, it is more demanding than simple gait in terms of energy consumption, stability, joint range of motion, forces and torques generated in the musculoskeletal system. Generally, the kinetics of stair activity differ significantly from simple gait, with observable differences between stair ascent and descent. These variations manifest notably in the kinetics of the movement. Riener et al. [18] provided a comprehensive overview of the kinematic and dynamic parameters of walking on flat surfaces, as well as the changes that occur during stair ascending and descending at different stair inclinations (ranging from 24.0° to 42.0°). The results indicate elevated values of all ground reaction forces (GRFs) (vertical, anterior-posterior, and medial-lateral) and increased flexion angles of the hip and knee joints during walking at stairs at a self-selected, comfortable speed.

Additional load significantly affects changes in gait parameters and ground reaction forces, as demonstrated by Zagrodny et al. [26], which investigated various ways of carrying loads on flat surfaces with the use of thermal imaging camera and pedobarographic force platform. Similar findings were reported in studies by Hrvatin and Rugelj [5] and McCrory et al. [9] conducted on

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Received: October 31st, 2025
Accepted for publication: January 8th, 2026

pregnant women. These results additionally indicate an increased risk of falling, particularly during stair descent. This risk was correlated with changes in GRFs and Center of Pressure (COP) excursion. In these studies, a traditional force platform was used, and the participants walked at a self-selected, comfortable speed.

McFadyen and Winter [10] correlated EMG and kinetic analyses to explain the lower-limb mechanisms involved in normal stair walking. The range of motion of the lower limb during stair walking was found to be greater than during level walking, with the maximal range observed during stair descent [1]. Zachazewski et al. [25] demonstrated that stair descent involves greater inherent instability compared to stair ascent by analysing the displacement of the body's centre of mass. Differences in reaction force patterns between stair walking and level walking were identified using a force platform. A longer cycle duration was observed during stair ascending compared to descending [13]. Additionally, a comparison of plantar pressure distribution between stair walking and level walking was conducted to examine its effect on different foot regions [3]. The study was conducted on a population of young men from South Korea, utilizing measurement insoles placed in their shoes. The foot was divided into seven regions for analysis. Interestingly, for most of the measured regions, lower peak maximum values were observed during stair walking compared to level walking. A limitation of the study was the use of shoe insoles, which, despite their many advantages, measure pressure between the foot and the shoe rather than between the foot and the ground. The aforementioned results are supported by the work of Rao and Carter [17], in which plantar pressure distribution was compared between stair walking and level walking using insoles. Peak pressures (PP) were found to vary across different foot regions depending on the activity, with higher PP observed during level walking compared to stair walking.

Yali et al. [24] analysed muscle activation levels in the lower limbs during stair climbing under various backpack loads. The study involved examining EMG data to evaluate muscle activation patterns during stair ascending and level walking. The results showed that more muscles were activated during stair climbing than during level walking. Stair climbing requires greater moments and powers to support the body against gravity, imposing higher demands on the lower limb muscles compared to level walking. Cho et al. [3] presented additional research on in-shoe plantar pressure during stair walking compared to level walking. The results confirmed that each foot region experienced greater pressure during level walking than stair walking, consistent with previous studies. This research also found that in young, healthy male adults, pressure tends to concentrate on the forefoot and midfoot regions during stair walking.

Nagel et al. [12] investigated plantar pressure patterns in diabetic patients during stair activities. The experiment compared different modes of stair ascending and descending, revealing variations in PP zones depending on the mode of stair walking. Diabetic patients exhibited lower pressures and impulses compared to the control (healthy) group. Notably, the study found no significant effect on foot loading when using a handrail – an important conclusion for our experiment, in which no handrail was used. Overall, studies on the changes in pressure distribution under the feet during stair walking are limited. Such studies are conducted using classic dynamometric platforms or pedobarographic insoles [4].

The present study aimed to evaluate the dynamic pedobarographic profiles and gait characteristics of healthy volunteers during daily stair activities. The presence of a backpack on the shoulder results in different plantar pressure distributions compared to normal stair activities. Understanding the effect of symmetric or asymmetric loads on plantar pressure across all regions of the foot is crucial for a better understanding of the biomechanics of stair activity. This study focuses on answering the research problem of how additional loads influence plantar pressure and contact time at the first and last step of stair when ascending and descending, as plantar pressure experiments using a pedobarographic force platform in such a setup have not been thoroughly investigated in these scenarios before.

2. Material and methods

The research protocol was approved by the Ethics Committee for Scientific Research at Lodz University of Technology (Approval No. 2/2023, dated March 30, 2023). Fundamental information of participants, such as age, height, body weight and overall health status was collected before the experiment. Twelve healthy male individuals with mean (SD) age of 25 (±2) years, body height of 181.5 (±4.67) cm and body mass of 85.21 (±11.29) kg, were participated in this study. The inclusion criteria were age over 18 years and male gender. Volunteers with flatfoot or musculoskeletal disorders were excluded due to their potential negative impact on foot and ankle function [14, 16, 21, 22], which constituted our exclusion criteria.

Therefore, each participant underwent a pedobarographic test to determine the presence of a flatfoot.

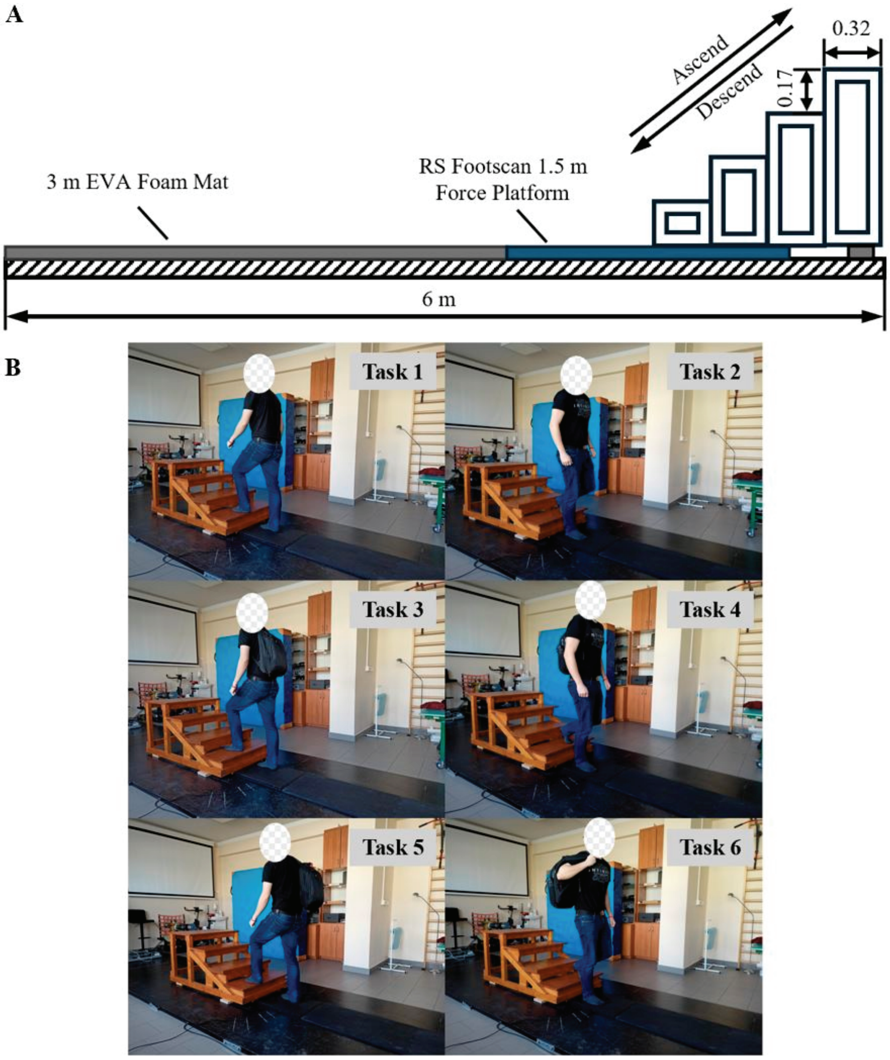

Fig. 1. A) Schematic view of experimental test stand, B) Illustrations of six different tasks

Study type was designed as experimental, repeated measures – each participant completes all six different tasks (Fig. 1B). Conventional stair walking was required of each participant as a control to compare the impact of extra load on foot pressure distribution and contact time during stair activities (Tasks 1 and 2 – ascending and descending without any load). Next, an additional 5 kg weight was added to the backpack to simulate the daily load of students. Task 3 involved ascending with an extra 5 kg load on the back, and Task 4 involved descending with an extra 5 kg load on the back. Finally, Task 5 involved ascending with an extra 5 kg load on the right shoulder, and Task 6 involved descending with an extra 5 kg load on the right shoulder. The 5 kg weight was approximately 5.88% of the average body weight of our volunteers. Each task was executed three times while barefoot. The stairs used in the laboratory had a step height of 0.17 m and a step width of 0.32 m, with an overall width of 0.80 m. The entire setup is shown in Fig. 1.

To maintain natural gait dynamics, participants walked at their self-selected speed during stair ascent and descent. Previous research has shown that walking speed substantially affects plantar pressure magnitude and distribution [6, 8]. This approach is widely accepted and commonly used in stair gait studies [15]. There was 3 m gait path in front of the stair, the last fragment of it was a pedobarographic force platform (as depicted in Fig. 1A). This setup makes it possible to record a natural gait pattern, pressure and force distribution for the last step on the ground level, before start of stair ascend or the last step while stair descend.

The force platform (RS Footscan 1.5 m, 200 Hz) was recording the right foot data for consistent comparison. Especially for stair descending, volunteers were mandatory instructed to use their right foot when initially stepping on the force platform. To facilitate analysis, the footprint was divided into ten regions (Fig. 2). MATLAB was then used for data processing analysis.

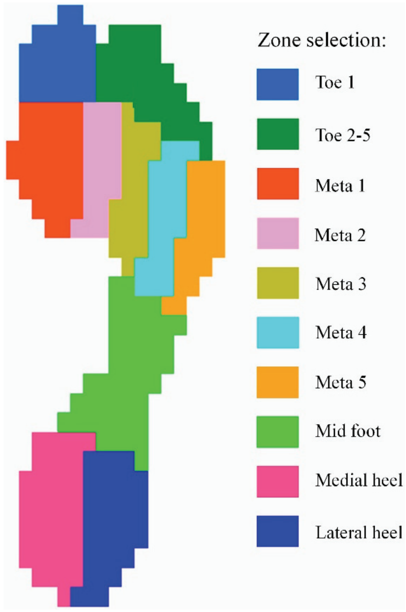

Fig. 2. Foot divided into ten regions (Materialise Footscan 9 Scientific)

3. Statistical analysis

Raw plantar pressure data were processed to obtain peak pressure (PP) and contact time (CT) for ten predefined foot regions. For each participant and condition, values were averaged across three trials. Normality was assessed using Shapiro–Wilk tests; most data deviated from normal distribution ($p < 0.05$). Therefore, non-parametric methods (Friedman RM-ANOVA and Wilcoxon signed-rank tests with Holm correction) were applied for inferential analysis. Differences among foot regions within each task were evaluated using Friedman RM-ANOVA with Kendall's W as an effect size measure. Post-hoc pairwise comparisons were performed using Wilcoxon signed-rank tests with Holm correction for multiple testing. To examine the influence of load (symmetrical backpack vs. asymmetrical shoulder load), Friedman tests were conducted across three conditions (no load, symmetrical, asymmetrical), followed by Wilcoxon tests with Holm adjustment. All analyses were performed at $\alpha = 0.05$. For exploratory interpretation, mean ± SD and standardized effect sizes were reported.

4. Results

The graphs of the pressure versus gait phase curves (Fig. 3) show that when descending stairs, the metatarsal (MT) region of the foot has the first contact with the platform, which begins the support phase. The Toe 1 and Toe 2–5 regions then contact the platform, but their pressure force is much lower than that of the MT regions. The final pressure on the platform comes from the Midfoot, Heel Medial and Heel Lateral regions. The contact of these parts with the ground is accompanied by a slight decrease in the pressure force of the MT and Toe regions. Once the heel regions reach their maximum pressure, the transfer phase begins. Later in this phase, the pressure of the Heel and Midfoot regions decreases rapidly, while the pressure of the MT and Toe regions increases and reaches its maximum. In the last phase of the step, first the MT regions and finally the Toe regions lose contact with the ground. When stairs ascending, contact with the platform starts from the Heel regions. Then the pressure of the Midfoot region increases, and the MT and Toe regions are the last to contact the platform. In the same order, the regions of the foot lose contact with the ground. The application of load has little effect on the pressure force applied to various regions of the foot. Moreover, it can be observed that additional load influences shift of the maximum pressure force relative to the gait phase.

The maximum pressure of the Toe 1 region depends on both the type of activity and the assumed load. Toe 1 generates higher pressure when ascending stairs. In addition, the use of weight increases the pressure force both when going up and down stairs. The way the load is distributed has a marginal effect on the pressure force. The PP of the Toe 2–5 region is almost identical independently from the type of activity and the load used. Among the MT regions, the MT 2 region has the greatest PP while MT 4 and MT 5 regions have the lowest PP values. In the case of these regions, the pressure force depends on the type of activity and is greater when descending stairs. The maximum pressure of the Midfoot region does not depend on the applied load but is greater when descending stairs. PP of the Heel Medial and Heel Lateral regions increases when a load is applied. Moreover, ascending stairs involves much greater pressure from Heel region than descending them. The average PP values for all foot regions are given along with the standard deviation (SD) in Table 1.

Based on the results obtained, the average contact time of each region of the foot with the ground during a given type of activity was calculated together with standard deviation (Fig. 4). When descending the stairs, the Toe 1–5 and MT 1–4 regions remain in contact with the ground longer than when ascending the stairs. For the MT 5 region, contact times are similar in both cases, while for Midfoot, Heel Medial and Heel Lateral, contact times are greater when climbing stairs. The use of additional loads both during descent and ascent has a marginal impact on the contact time of each region of the foot (Figs. 6, 7). The lowest standard deviation was obtained when determining the average foot contact time while descending stairs without load. The use of additional load increased the uncertainty of the results obtained for each region of the foot, but it was definitely the greatest for the MT 5, Midfoot, Heel Medial and Heel Lateral regions. In the same regions, also after applying a load, there was an increase in the standard deviation for ascending stairs, but for the remaining regions, greater uncertainty was obtained for ascending without a load.

5. Statistical analysis of the PP

PP distribution differed significantly across foot regions during both stair ascent and descent (Friedman RM-ANOVA: ascent $\chi^2(9) = 56.09$, $p < 10^{-6}$; Kendall's $W = 0.623$; descent $\chi^2(9) = 58.01$, $p < 10^{-6}$; Kendall's

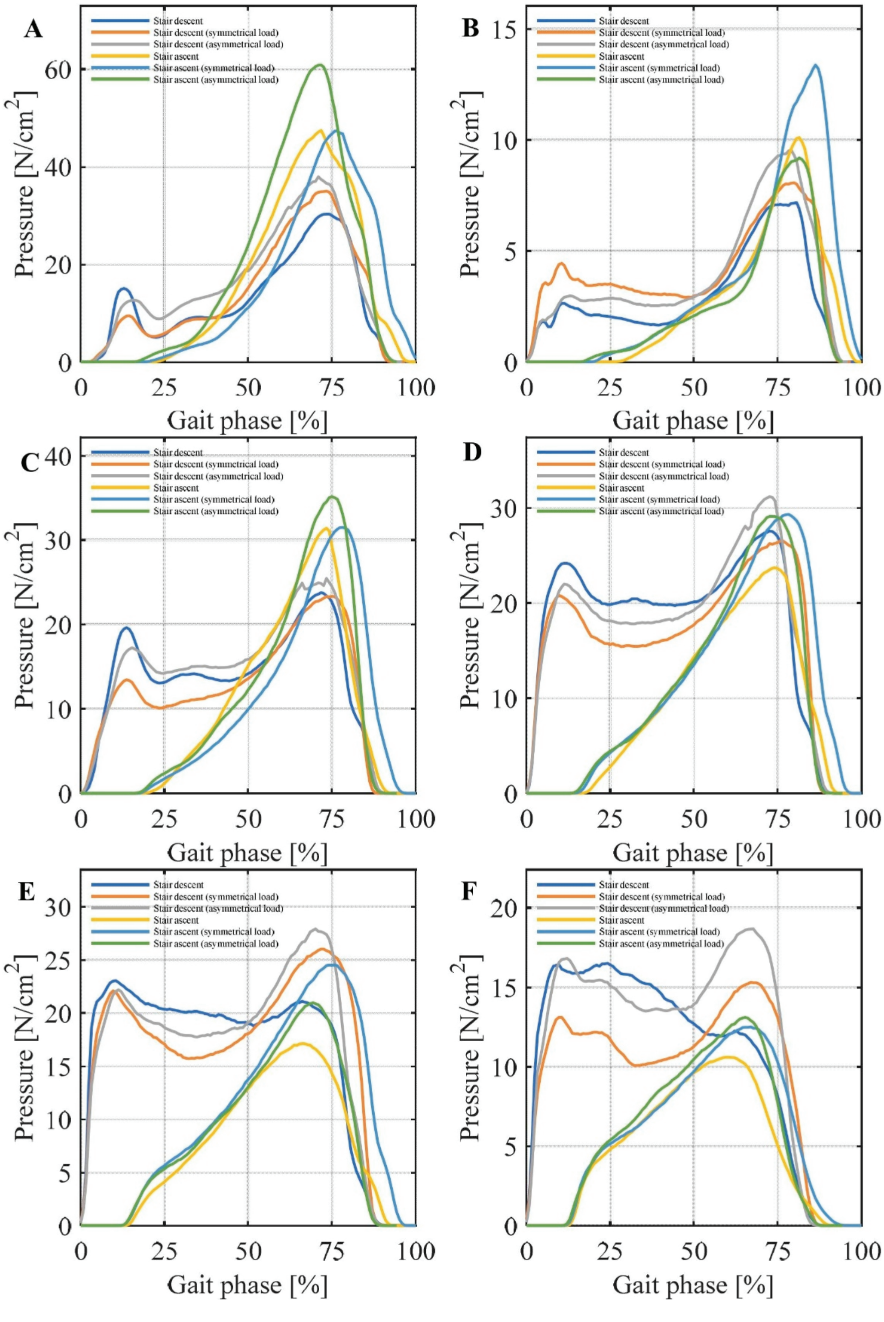

Fig. 3. Pressure vs. gait phase for the foot region:
A) Toe 1, B) Toe 2–5, C) MT 1, D) MT 2, E) MT 3, F) MT 4

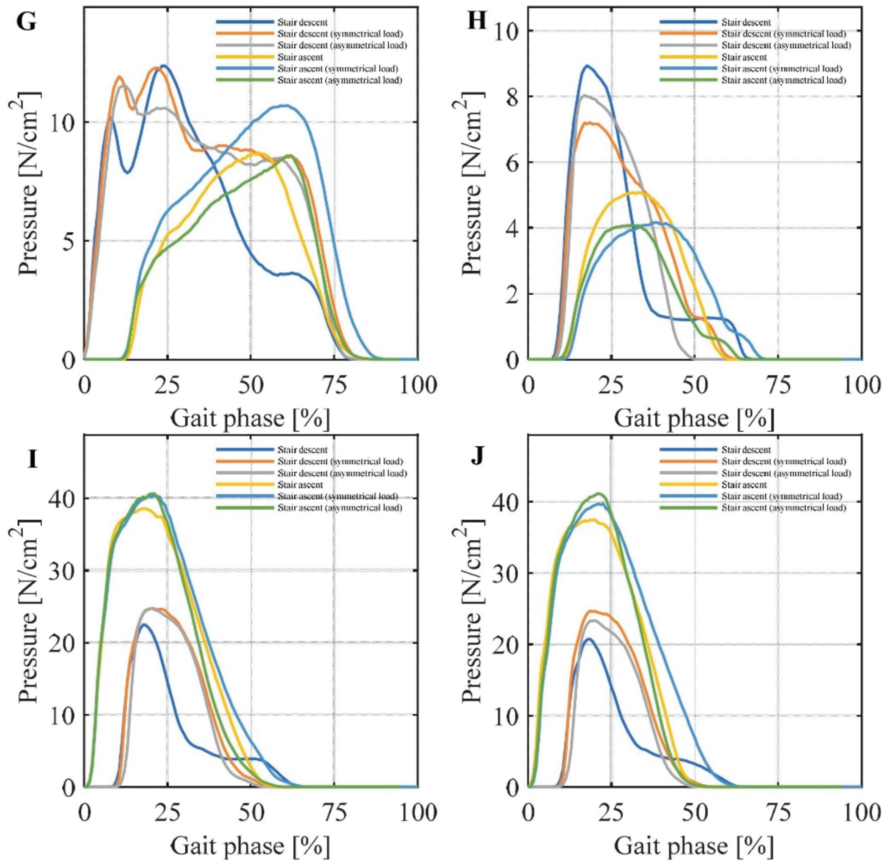

Fig. 3 continued. Pressure vs. gait phase for the foot region:
G) MT 5, H) midfoot, I) heel medial, J) heel lateral

Table 1. Average PP [N/cm^2] and (SD) values for all regions of the foot for each activity

	Stairs descending	Stairs descending with symmetrical load	Stairs descending with asymmetrical load	Stairs ascending	Stairs ascending with symmetrical load	Stairs ascending with asymmetrical load
Toe 1	30.23 (11.64)	33.99 (12.16)	33.31 (12.16)	32.75 (15.64)	38.71 (17.66)	38.74 (14.21)
Toe 2–5	10.03 (6.37)	9.04 (4.71)	10.07 (5.24)	10.86 (9.24)	8.77 (5.55)	10.17 (7.92)
MT 1	28.70 (12.33)	29.45 (12.22)	32.03 (14.05)	26.72 (12.15)	33.64 (10.75)	34.52 (14.86)
MT 2	38.02 (8.60)	41.07 (13.90)	40.72 (8.93)	38.35 (8.77)	39.54 (12.91)	41.27 (10.98)
MT 3	34.33 10.44)	36.27 (10.60)	35.58 (8.64)	32.14 (10.37)	33.14 (11.31)	33.64 (11.14)
MT 4	26.59 (8.44)	27.17 (8.96)	26.59 (8.66)	24.62 (9.34)	23.26 (6.57)	25.12 (7.81)
MT 5	27.93 (11.91)	30.51 (15.40)	29.56 (18.81)	23.51 (14.23)	22.53 (12.64)	22.28 (10.21)
Midfoot	12.08 (8.09)	12.28 (6.34)	11.87 (9.01)	6.83 (4.20)	6.11 (4.26)	6.99 (5.25)
Heel Medial	22.22 (10.21)	27.27 (14.28)	29.32 (13.47)	39.44 (8.09)	45.20 (13.35)	46.66 (12.85)
Heel Lateral	19.62 (9.75)	23.63 (12.45)	26.07 (11.29)	35.93 (7.75)	37.36 (8.65)	38.89 (9.97)

$W = 0.645$), confirming strong heterogeneity (Fig. 4). Rearfoot loading dominated ascent, whereas forefoot loading was more pronounced during descent. Post-hoc Wilcoxon tests with Holm correction indicated that Heel Medial differed significantly from multiple regions in both tasks (e.g., Toe 2–5, Meta 4, Midfoot, Heel Lateral; $p_{\mathrm{Holm}} < 0.05$).

The effect of additional load was region-specific and modest compared to task-related differences. For ascent, Friedman tests across three conditions (No load, Symmetric backpack, Asymmetric shoulder load) revealed significant omnibus effects for Meta 1 ($p = 0.00745$), Toe 1 ($p = 0.0450$), and Heel Medial ($p = 0.0450$). Post-hoc comparisons showed increased PP for Heel Medial under both Symmetric ($p_{\mathrm{Holm}} = 0.0410$) and Asymmetric load ($p_{\mathrm{Holm}} = 0.0410$) vs. No load, and for Toe 1 ($p_{\mathrm{Holm}} = 0.00586$) and Meta 1 ($p_{\mathrm{Holm}} = 0.00586$) under Asymmetric load vs. No load. Differences between Asymmetric and Symmetric loading were not statistically significant.

For descent, omnibus effects were significant only in Heel Medial ($p = 0.00552$). Post-hoc tests indicated increased PP for Asymmetric load vs. No load in Heel Medial ($p_{\mathrm{Holm}} = 0.00586$) and Heel Lateral ($p_{\mathrm{Holm}} = 0.0293$), while Symmetric load showed no significant differences compared to No load (Fig. 5). These find-

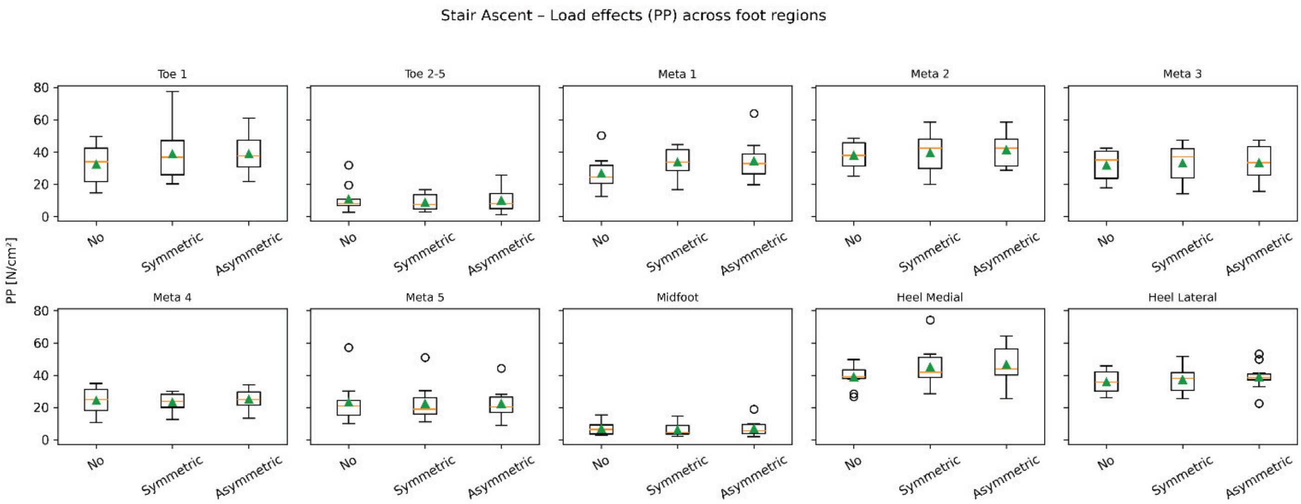

Fig. 4. Stair Ascent – Load effects (PP) across foot regions;
Labels: No (no load), Symmetric, Asymmetric.
Boxes – median and IQR, whiskers – 1.5 × IQR, triangle – mean, outliers plotted individually

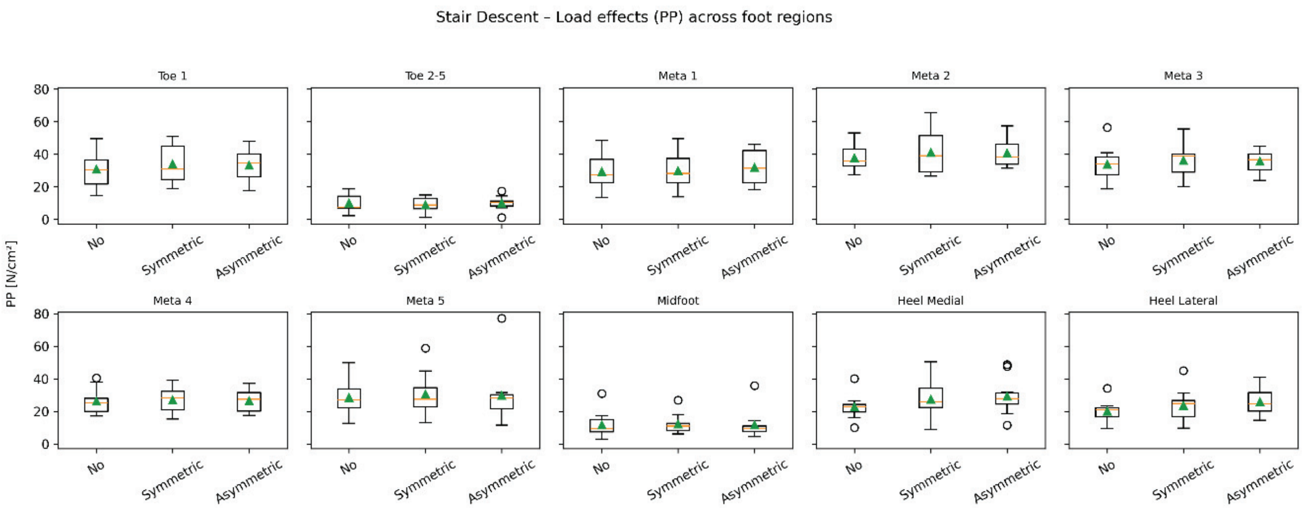

Fig. 5. Stair Descent – Load effects (PP) across foot regions;
Labels: No (no load), Symmetric, Asymmetric.
Boxes – median and IQR, whiskers – 1.5 × IQR, triangle – mean, outliers plotted individually

ings confirm that while backpack load exerts measurable but localized effects – primarily in the heel and hallux – the task-related strategy (ascent vs. descent) remains the dominant factor influencing plantar pressure distribution.

6. Statistical analysis of the CT

Across foot regions CT differed significantly across the ten foot regions during both stair ascent and descent (Friedman RM-ANOVA: ascent $\chi^2(9) = 74.78$, $p < 10^{-6}$; Kendall's $W = 0.831$; descent $\chi^2(9) = 76.45$, $p < 10^{-6}$; Kendall's $W = 0.849$) (Figs. 6, 7), indicating large, task dependent heterogeneity in temporal loading. During ascent, omnibus Friedman tests across load conditions (No, Symmetric, Asymmetric) did not reach significance in any region after correction, suggesting that load had a limited impact on CT compared to task related differences. During descent, the omnibus effect reached significance only in Toe 1; however, Holm adjusted pairwise Wilcoxon comparisons (Symmetric vs. No, Asymmetric vs. No, Asymmetric vs. Symmetric) did not remain significant (unadjusted p for Asymmetric vs. No ≈ 0.050, Holm adjusted $p = 0.150$), indicating that the global difference did not translate into robust pairwise contrasts after controlling for multiple testing.

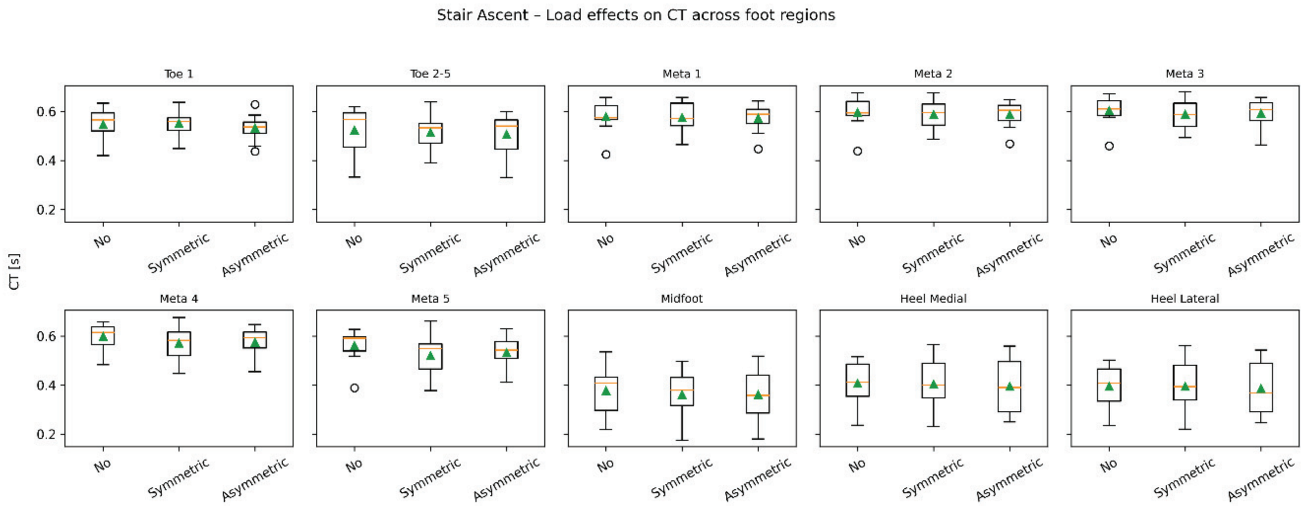

Fig. 6. Stair ascent – load effects on contact time (CT) across foot regions;
Labels: No (no load), Symmetric, Asymmetric.
Boxes – median and IQR, whiskers – 1.5 × IQR, triangle – mean, outliers plotted individually

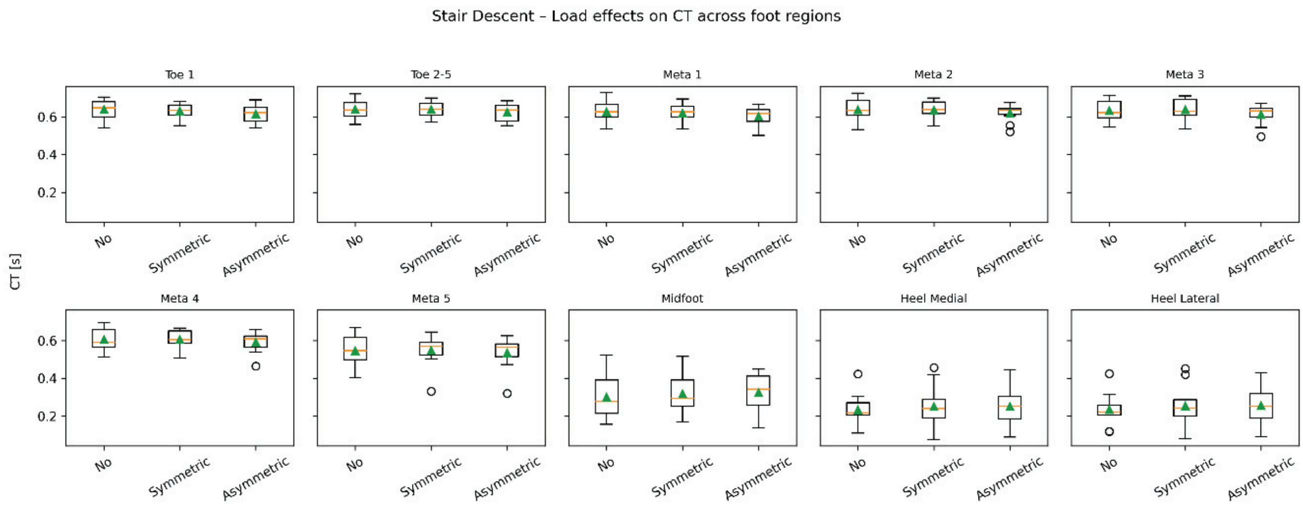

Fig. 7. Stair descent – load effects on contact time (CT) across foot regions;
Labels: No, Symmetric, Asymmetric.
Boxes – median and IQR, whiskers – 1.5 × IQR, triangle – mean, outliers plotted individually

CT reflects the time of the load of each region and serves as a practical proxy for gait velocity. The present results show pronounced regional CT differences driven by task (ascent vs. descent), whereas load effects on CT are small and inconsistent, with no pairwise CT differences surviving Holm correction. This pattern complements the PP findings: the task strategy is the dominant factor, and load (especially asymmetrical) produces at most localized, modest temporal adjustments.

7. Discussion

The pressure values in relation to the gait phase and the relationships between the plantar pressure (PP) values of different foot regions obtained during stair descent are comparable to results found in other studies [3], [17]. However, the absolute PP values obtained in this study are significantly higher than those measured using shoe insoles [3], [17] but are closer to those obtained with a pedobarographic platform [11]. This demonstrates the influence of the device used on the measured values. The standard deviation from the mean PP values is similar regardless of the measurement method used.

For stair ascent, the values are comparable to those described in the literature for the Toe 1–5, MT 1–5, and Midfoot regions, but differ significantly for the Heel region. In other studies, the PP values for the Heel region are the lowest of all foot regions, whereas in the presented graph (Fig. 4), they are higher than those of the other areas. This discrepancy results from the measurement methodology used.

In the cited studies, measurements were taken on the steps of the stairs, while in our study, the last level walking step before ascending the or last after descending step was measured. This can lead to differences in the obtained PP values. The addition of extra load resulted in the greatest increase in the average PP values in the Heel Medial and Heel Lateral areas, which may be attributed to the load being applied to the participants' backs.

Asymmetric loading (backpack on one shoulder) PP increases in Heel Medial and hallux under asymmetric load but note differences between Symmetric and Asymmetric were not statistically significant after Holm correction. At the same time, for asymmetric loads, no increase in PP was observed in the regions on the lateral part of the foot (Toe 2–5, MT 4, and MT 5), and the increase in PP for the Heel Lateral region was not greater than that for the Heel Medial region. It is possible that altering the position of the additional weight, such as holding it in the hand with the arm at the side of the body, could lead to increased PP values in these regions. The use of additional load resulted in a smaller, but still noticeable, increase in PP in the Toe 1, MT 1, and MT 2 regions compared to the Heel regions. This increase is particularly noticeable at the end of the gait cycle, when these regions become the main areas of contact with the ground and bear most of the body's weight. For the Toe 2–5, MT 3, MT 4, MT 5, and Midfoot regions, changes in the PP values are marginal. These changes in PP values highlight the influence of the additional load and the way it is positioned, affecting the pressure exerted by different parts of the foot on the ground. However, it should be noted that, in most cases, these changes are smaller than the measurement uncertainty. Therefore, further research is needed in that case.

Analysing contact times, one may find that a similar relationship between contact times for individual foot regions was observed in other studies [3], although the contact times for each region were longer in those studies. The most significant difference occurs during heel contact, where the contact time is more than twice as long in the cited studies. However, it should be noted that absolute contact times may vary for several reasons, such as the measurement tool used (shoe insoles versus a pedobarographic platform) or walking speed and style. The use of additional load has a marginal effect on the contact times of individual foot regions. The differences observed in contact times highlight large task effect ($W > 0.8$) and non-significant load effect after correction. The differences observed in contact times are smaller than the measurement uncertainty, so further research is needed to precisely determine the impact of additional load on these times, especially that fatigue can altered the behaviour and stability of the joints [2], [7].

8. Conclusions

The aim of the study was to examine the impact of additional load and its distribution method on changes in pressure and contact times of individual foot regions with the ground during stair ascent and descent.

The novelty of our findings is as follows: 1) the additional load on the back resulted in the greatest increase in PP values for the Heel Medial and Heel Lateral regions; 2) when the load was asymmetric, the PP values for both Heel regions increased slightly; 3) during the final phase of stepping, there was an increase in PP values for the Toe 1, MT 1, and MT 2 regions when the body weight was supported on these areas of the foot; 4) measurements of foot contact times with the ground showed a marginal impact of the load on this gait parameter. These results indicate the potential impact of additional load on changes in the pressure exerted by various areas of the foot on the ground. It would be important to examine the effect of loads applied from the front and sides of the participants on the PP values. Additionally, applying a load as a percentage of the participant's body weight and gradually increasing it over time would help obtain clearer results. Those are also some limitations to our studies. During the measurements, participants moved at their chosen speed, which may have increased measurement uncertainty, as movement speed affects both foot contact time [19] with the ground and the PP value [20]. However, this approach allowed participants to move naturally, as they would in everyday activities as it was indicated in the introduction. Each participant wore a backpack with the same load, regardless of their physical condition (body weight, muscle mass, etc.), which also could have influenced the results due to the varying levels of effort exerted by weaker and stronger participants.

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