

Article

Evaluation of Plantar Pressure and Stability Parameters in a Forefoot Offloading Footwear: A Comparative Study

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Abstract

Forefoot offloading footwear is widely used in postoperative care, trauma management, and the prevention of diabetic foot ulceration, where redistribution of plantar load must be achieved without compromising gait stability. This study evaluated plantar pressure and centre of pressure characteristics of a new side-specific forefoot offloading footwear design in comparison with commonly used clinical and retail footwear. Twelve healthy adults completed treadmill walking trials at 4.0 km/h under five footwear conditions. Plantar pressure data were collected using an in-shoe pressure measurement system and analysed for peak pressure, average pressure, force–time impulse, centre of pressure velocity, and centre of pressure excursion index across seven anatomically defined plantar regions. Across all conditions, consistent left–right asymmetry in plantar loading was observed, although overall variability between footwear designs was modest. The experimental footwear demonstrated pressure and impulse distributions comparable to retail and universal offloading footwear, without increasing hallux loading. Centre of pressure measures were generally consistent between side variability, indicating controlled rollover and preserved gait stability. These findings suggest that side-specific sole geometry can support balanced forefoot load management without introducing instability in healthy walking and provide a foundation for future bilateral testing in clinical populations at risk.

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1. Introduction

Forefoot offloading footwear is a clinically valuable intervention for reducing mechanical stress on the forefoot during postoperative recovery, the management of trauma, and the treatment of diabetic foot ulceration. By altering gait mechanics and redistributing plantar loads, these footwear aim to facilitate tissue healing and prevent further injury.

However, the design of such footwear involves complex trade-offs between effective offloading and potential effects on gait stability. A growing body of research has examined how variations in footwear design influence both plantar pressure distribution and lower limb biomechanics, providing important insights to guide clinical practice [1,2].

Plantar pressure parameters, including peak pressure and force time integral, are well established as meaningful indicators of offloading effectiveness. Numerous studies have used these measures to evaluate the ability of rocker-bottom and forefoot offloading footwear to reduce forefoot loading during walking [1–5]. However, there are inherent limitations when attempting to compare absolute pressure values across different studies. Variations in pressure measurement systems, differences in data collection protocols, and inconsistencies in masking and analysis techniques can all affect reported outcomes [1,2,6]. As a result, direct comparison of pressure magnitudes between studies is not reliable.

Although complementing plantar pressure assessment with additional biomechanical analyses provides valuable additional insight, this is not always feasible in a clinical setting. Combining kinematic and kinetic measures can provide a more comprehensive understanding of how footwear design influences dynamic stability during gait. In particular, parameters such as centre of pressure progression velocity and centre of pressure progression angle offer clinically relevant surrogate measures of stability. These metrics reflect the interaction between footwear geometry and postural control strategies and can provide valuable insights into the practical implications of design choices for at-risk populations [2]. Although the proposed study focuses on plantar pressure outcomes, these considerations inform the interpretation of pressure findings and highlight the potential clinical relevance of our design evaluation.

Recent work has shown that the positioning of the rocker apex and the geometry of the heel rocker are critical determinants of both plantar pressure distribution and gait stability. A previous study [7] systematically examined the effects of apex angle, apex position, and rocker angle on forefoot plantar pressures in individuals with and without diabetes. The authors demonstrated that an apex position at sixty percent of footwear length, an apex angle of approximately ninety-five degrees, and a rocker angle of twenty degrees provided optimal reduction of forefoot pressures. Shifting the apex beyond sixty percent of footwear length resulted in increased forefoot loading, while lower rocker angles were less effective in reducing peak pressures. These findings provide clear evidence that careful tuning of rocker geometry is essential to achieve effective offloading without adversely affecting gait mechanics.

Complementing this work, Farzadi et al. [8] investigated how different placements of the heel rocker apex influenced lower limb biomechanics. The authors found that varying the position of the heel rocker apex had a marked effect on ankle range of motion and knee joint moments during walking. Anterior placement of the heel apex reduced ankle range of motion at initial contact but increased it during single limb support. Both anterior and aligned placements of the heel apex increased knee joint moments, which may introduce dynamic instability during stance. Although this study was conducted in healthy participants, the findings have important implications for clinical populations where altered joint moments could exacerbate balance deficits or increase fall risk. These results further reinforce that rocker design must be considered as an integrated system, balancing offloading effectiveness with biomechanical stability. Preece et al. [9] provided further evidence regarding the optimisation of rocker sole footwear for clinical application. In this large study involving individuals with diabetes and a healthy control group, the authors demonstrated that systematic variation of apex position and rocker angle produced consistent effects on plantar pressures. Moving the apex position distally increased peak pressures under the second to fourth metatarsal heads, while increasing rocker angle

produced significant pressure reductions. Importantly, a group-optimised configuration delivered substantial offloading across all forefoot regions and performed similarly in both healthy and diabetic participants. This supports the potential for effective prefabricated designs that can be applied in routine clinical practice.

Additional mechanistic insights were provided by Healy et al. [10], who explored the interaction between static and dynamic rocker sole parameters in diabetic footwear. Their pilot study highlighted that not only fixed features, such as apex angle and heel-to-forefoot height differential, but also dynamic roller angle behaviour during gait, influenced offloading performance. The greatest pressure reductions were associated with designs that combined a small apex angle and low heel-to-forefoot differential with favourable dynamic behaviour. These findings emphasise the importance of evaluating both static design parameters and the functional behaviour of the sole during walking. While the studies above have largely focused on the relationship between rocker geometry and plantar pressure reduction, others have examined the broader biomechanical adaptations induced by offloading footwear. Paton et al. [2] demonstrated that a commercially available forefoot offloading footwear produced substantial reductions in forefoot pressures but also altered postural control. The footwear induced a posterior shift in centre of pressure position and increased tibialis anterior muscle activity, potentially increasing stability demands during gait. Notably, adding a contralateral footwear raise mitigated these effects without compromising offloading performance, highlighting a simple and effective strategy to improve balance.

Sole rigidity is another key factor influencing offloading outcomes. Fuller et al. [1] compared a conventional postoperative footwear design with a rigid rocker-bottom design and demonstrated that greater sole rigidity, combined with well-placed rocker geometry, significantly reduced forefoot pressures and force–time integral. However, increased heel force–time integral was also observed, reflecting a redistribution of load that may have implications for postural control. This highlights the need to consider both pressure outcomes and gait adaptations when evaluating footwear performance.

Taken together, these studies demonstrate that achieving effective forefoot offloading requires careful integration of multiple design factors, including rocker apex angle and position, heel rocker geometry, dynamic sole behaviour, and sole rigidity. The interactions between these features influence not only plantar pressure outcomes but also broader biomechanical adaptations that affect gait stability. Evidence suggests that an optimised balance of these elements is critical to delivering effective and safe offloading in clinical footwear. Despite these advances, most footwear currently used in clinical care are universal in design, meaning they can be worn on either foot. This approach simplifies manufacture and stock management but overlooks anatomical and mechanical differences between the left and right feet. The sole geometry and rollover path are therefore identical on both sides, which may limit offloading efficiency and gait stability. Whether left–right specific offloading designs offer clinical advantages over universal designs remains an open question. In addition, clinical risk is not determined by pressure alone. Load duration, load rate, and the control of shear and torque are also relevant to tissue stress but are rarely evaluated alongside pressure in routine assessments.

This study addresses these gaps; evaluating a new design of forefoot offloading footwear using structured plantar pressure measurements and centre of pressure metrics that reflect path efficiency and progression velocity. This within-participant contralateral comparison provides a practical way to evaluate side-specific geometry without relying on between-group comparisons of absolute pressure magnitudes. We compare conditions where the experimental footwear is worn on one side and retail footwear is worn on the contralateral side in order to test whether a left–right-specific design better manages forefoot loading and rollover under matched gait conditions within the same participant. Our

analysis focuses on whole-foot and regional peak pressure, force–time impulse, and centre of pressure measures. These outcomes allow us to examine redistribution of load across stance and to infer whether the experimental footwear facilitate a smoother and potentially less shearing rollover while maintaining stability. This study, therefore, provides an initial, clinically relevant assessment of whether a left–right-specific offloading design can deliver advantages over universal construction in footwear for people at risk of plantar complications.

2. Methods

2.1. Participants

Twelve healthy adult volunteers (six male and six female) were recruited for this study. The mean age of participants was 40.1 years (range 22 to 57 years). The mean height was 169.9 cm (range 155 to 183 cm), and the mean body weight was 75.3 kg (range 57 to 95 kg). Footwear sizes ranged from UK size 4.5 to 10.

Participants were eligible for inclusion if they were free from any known lower limb musculoskeletal pathology, peripheral neuropathy, or balance disorder that could influence gait. All participants provided written informed consent prior to testing. Ethical approval for the study was granted by the University Research Ethics Committee.

2.2. Footwear Conditions

Participants were tested under five footwear types (as described in Table 1), each evaluated using a contralateral testing design in which the experimental footwear was worn on one foot and retail footwear was worn on the opposite side.

As shown in Figure 1a–e, these included retail footwear (baseline condition), the experimental forefoot offloading footwear (Footshield), and three commercially available forefoot offloading footwear: Footwear 1 (Darco), Footwear 2 (Benefoot), and Footwear 3 (Kerraped) (Table 1 outlines the characteristics of all footwear). Figure 1a shows both the standard retail footwear (left) and the modified version (right).

Table 1. Comparison of footwear properties.

Footwear Condition	Left and Right Specific	Upper	Fastening	Outsole and Rigidity	Rocker Geometry Details	Heel Height	Sole Thickness	Insole and Other Features
Retail footwear (reference)	Yes (stand-left and right)	Leather, low opening	Lace	Moulded flexible PU sole	Minimal rocker	15 mm	Heel differential 5 mm	Shoe adapted to match the heel height of the treatment shoes.
Experimental Footwear Footshield boot	Yes	Fabric upper	Velcro straps	Rigid evidence-based sole and heel unit	Toe-out angle 10 degrees. Rocker apex at 60 percent of shoe length. Rocker angle 20 degrees. Heel pitch 10 mm Rocker bottom stated. Detailed rocker parameters not stated	25 mm	15 mm	Removable memory foam insole with microfibre top cover. (Optional offloading hex insole—not used in the study). Removable toe cap. Wide entry. Square toe shape. Large volumetric range capacity.
Darco All Purpose Boot	Universal (either foot)	Fabric upper	Velcro straps	EVA outsole with rocker profile		25 mm	15 mm	Removable insole.

Benefoot Original Medical Shoe	Universal (either foot)	Fabric upper	Velcro straps	Flared TPR outsole with rocker bottom. PolyPro shank in outsole for flexion control	Rocker bottom present, with moderate profile relative to the other tested footwear. Detailed geometric parameters not specified by the manufacturer.	22 mm 15 mm	Dual density 3/16-inch insole, modifiable. Reinforced heel counter. Padded collar and topline.
Kerraped All Purpose Boot	Universal (either foot)	Fabric upper	Velcro straps	EVA type insole and durable outsole.	Minimal rocker.	20 mm 10 mm	Black EVA insole.



(a)



(b)



(c)



(d)



(e)

Figure 1. (a): Reference footwear (REF). (b): Experimental Footwear—Footshield (FSL). (c): Experimental Footwear—Darco (DAL). (d): Experimental Footwear—Benefoot (BFL). (e): Experimental Footwear—Kerraped (KPL).

The experimental footwear were worn on the left foot with retail footwear worn on the right foot. The order of footwear conditions was randomised for each participant to minimise potential order effects.

The selection of footwear models for this study was guided by their routine use within publicly funded healthcare settings in the United Kingdom. The included offloading shoes represent commonly issued options within hospital and community services for postoperative care, trauma management, and diabetic foot management.

Rather than attempting to survey the full commercial market, which includes a wide range of products with variable availability and regulatory status, the present work focused on footwear types that are readily accessible to clinicians and patients within established care pathways.

This approach was intended to ensure that the findings are directly relevant to current clinical practice and to facilitate meaningful comparison with a newly developed, side-specific design under conditions that reflect real-world provision.

2.3. Data Collection

Plantar pressure data were collected using the XSENSOR X4 (XSENSOR, Calgary, Canada) in-shoe pressure measurement system. This system has demonstrated validity and repeatability sufficient for clinical assessments, with peak pressure measurement errors below ten percent and reliability errors within fifteen percent across clinically relevant pressure ranges [11]. Pressure insoles were placed inside each footwear condition and securely fitted to minimise movement artefact. Participants walked on a treadmill at a constant speed of 4.0 kilometres per hour, which corresponds to the most economical walking speed in humans [12]. Data (sampled at 100 Hz) were recorded continuously for 45 s under each footwear condition and proprietary software from XSENSOR was used to reduce the data.

2.4. Outcome Measures

The primary outcomes were peak plantar pressure, peak load, impulse, centre of pressure (CoP) velocity, and CoP progression index. The CoP progression index was calculated as the ratio of the CoP excursion in the mediolateral direction to the total foot width, expressed as a percentage, where lower values represent a straighter and more efficient pressure trajectory during stance. All other parameters were extracted for seven anatomically defined regions of the plantar surface: medial heel, lateral heel, midfoot, first metatarsal, central metatarsals, lateral metatarsals, and hallux (Figure 2).

Foot region masking was applied manually but consistently across all participants by the same individual to define regions. CoP velocity and CoP progression angle were calculated from the temporal and spatial progression of the CoP trajectory during stance. Plantar pressure data were collected and reduced using XSENSOR software. (Ver 1.5.3.51).

All processed data were independently cross-checked by two authors to ensure data integrity. For clarity in presentation, we are reporting only the left foot data, in which experimental footwear was worn.

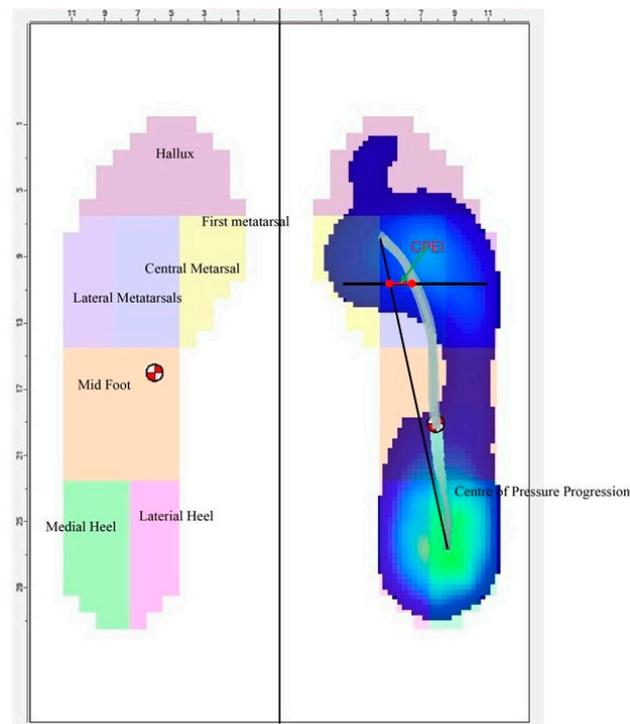


Figure 2. Plantar Masking Scheme and the indication of CoP measurements.

2.5. Data Analysis

Data were first examined for cohesiveness to ensure consistency and absence of artefacts. From each 45-s recording, five consecutive steady state gait cycles from the middle of the trial were identified for each participant and each footwear condition. Cycle identification was performed using the XSENSOR software gait cycle detection and verified visually for consistency. These five cycles were used for all subsequent analyses to minimise the influence of treadmill acceleration or deceleration and short-term stride variability. For each participant and condition, pressure and CoP parameters were averaged across these selected cycles. Descriptive statistics were computed for all outcome measures. Repeated-measures analyses were then performed to compare peak pressure, average pressure, impulse, centre of pressure velocity, and progression angle across footwear conditions.

3. Results

The overall average data and the associated standard deviations are given in Figures 3–5 and Tables 2 and 3. No significant differences were observed across footwear conditions for the recorded outcome measures. To account for known sources of measurement variability in in-shoe plantar pressure systems, including reported errors in the range of approximately 10 to 20 per cent across clinically relevant pressure levels, all results in this study are presented with accompanying measures of dispersion. Group means are reported together with standard deviations, and graphical summaries include error bars to illustrate between-participant variability within each footwear condition and plantar region. This approach allows the reader to interpret observed differences in the context of the inherent measurement uncertainty and the natural variability of gait, rather than relying solely on nominal thresholds of statistical significance.

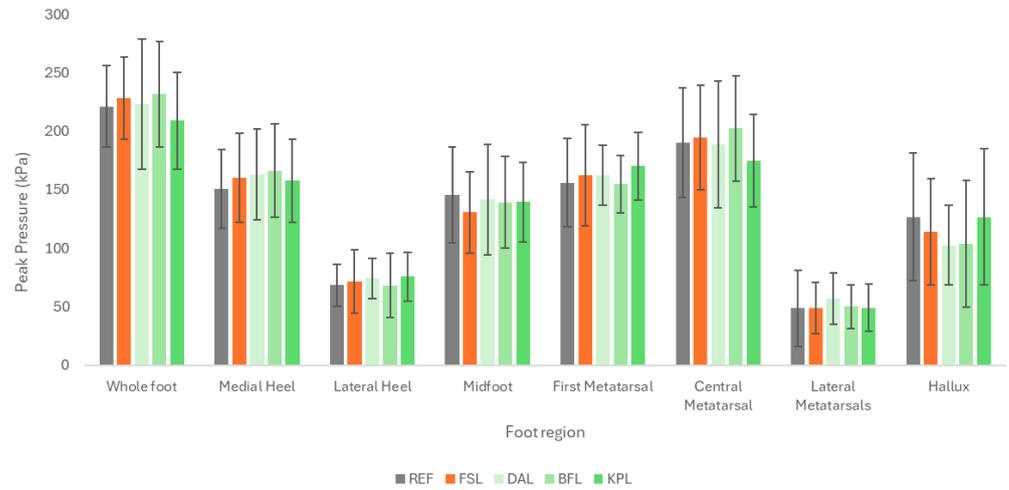


Figure 3. Peak Plantar Pressure.

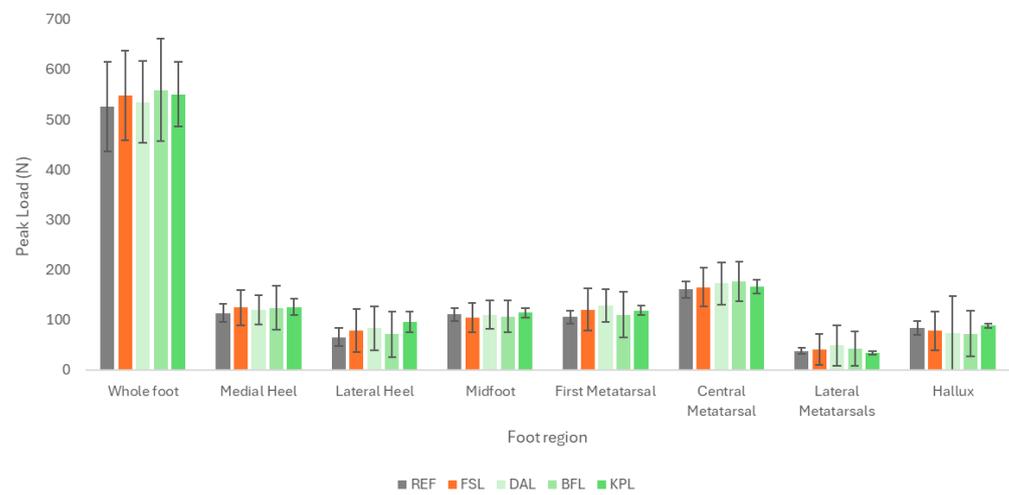


Figure 4. Peak Load.

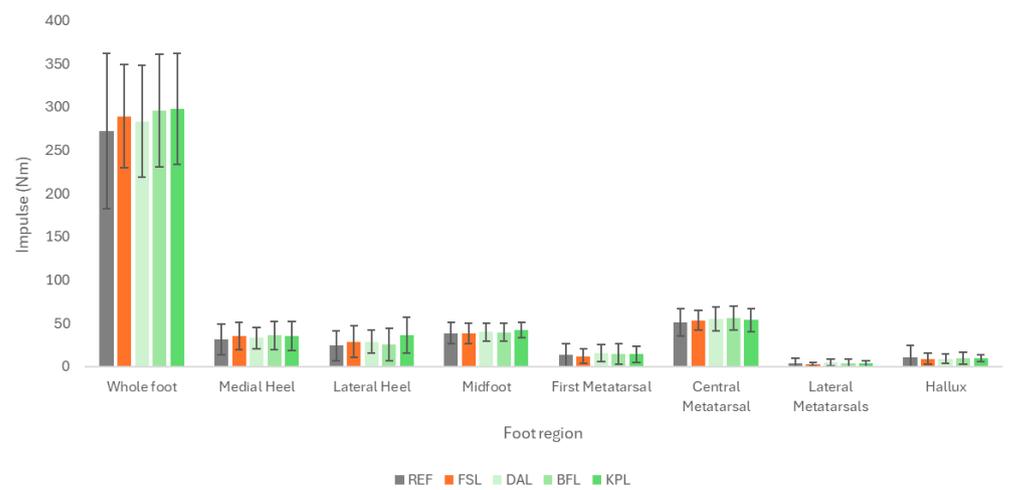


Figure 5. Impulse.

Table 2. CoP Velocity (mm/s).

	Average	St. Dev
REF	26.28	2.60

FSL	25.97	2.65
DAL	25.54	2.58
BFL	25.32	2.24
KPL	25.56	1.79

Table 3. CPEI (%).

	Average	St. Dev
REF	6.95	3.62
FSL	5.39	5.01
DAL	6.14	5.41
BFL	6.04	4.59
KPL	5.53	4.74

3.1. Peak Plantar Pressure

Whole-foot peak pressure values ranged from approximately 209.03 to 231.60 kilopascals and the regional pressures ranged between 48.68 and 202.37 kilopascals, as shown in Figure 3. When averaged across participants, the Footshield design showed fore-foot peak pressures that were broadly comparable to retail footwear and typically fell within the lower to middle range of all test conditions. In several participants, Footshield reduced first and central metatarsal peak pressures relative to retail footwear, although this was not consistent across all individuals.

The Darco, Benefoot, and Kerraped footwear demonstrated greater variability. In some participants, higher pressures were observed at the central metatarsals or hallux. Differences between footwear types were smaller in the heel and midfoot regions. Overall, all footwear redistributed pressure to some extent, and no single design consistently produced the lowest values across all regions or participants.

3.2. Peak Load

Whole-foot peak load values ranged from 525.74 to 559.11 Newtons across conditions, as shown in Figure 4. The mean peak loads for Footshield were comparable to those recorded in retail footwear. Some participants demonstrated small reductions in the first and central metatarsal regions. Benefoot and Kerraped displayed greater variation, with some instances of higher forefoot loads, while Darco generally fell within a moderate range. Across conditions, these findings suggest that all footwear types primarily redistributed rather than reduced total loading.

3.3. Impulse

Impulse values, representing cumulative load over time, ranged from 272.04 to 297.91 Newton seconds, as shown in Figure 5. Footshield impulses were similar to or slightly lower than retail footwear in several participants, particularly in the central metatarsal and hallux regions. Other experimental designs showed mixed patterns, with occasional increases in hallux or first metatarsal impulses. These data indicate that all footwear influenced load transfer differently between participants, with Footshield generally falling within the lower to middle range of measured impulses.

3.4. Centre of Pressure (CoP) Velocity

As indicated in Table 2, the mean centre of pressure velocity values were tightly grouped between 25.32 and 26.28 millimetres per second across all conditions.

No footwear type produced a consistent increase or decrease in progression velocity. Across participants, Footshield velocities were within one to two percent of retail footwear

values and demonstrated slightly smaller variability in some cases. Similar findings were observed for Darco, Benefoot, and Kerraped.

3.5. Centre of Pressure (CoP) Index

Centre of pressure CPEI values ranged from 5.39 to 6.95 percent across participants, as shown in Table 3.

Lower percentages than baseline condition, indicating straighter pressure paths, were observed inconsistently across conditions. Footshield values were generally within the lower to middle range of the dataset and were comparable to or slightly lower than retail footwear in several participants. Darco, Benefoot, and Kerraped showed greater variability, including isolated higher values that indicated greater mediolateral deviation of the pressure trajectory in some trials. These findings show that differences in CoP curvature were modest across footwear types, with Footshield demonstrating less variation between participants in several conditions.

3.6. Summary

Across footwear conditions, absolute differences in plantar pressure, load, and impulse were modest. The experimental Footshield design produced results that were comparable to retail footwear across all measured parameters. In several participants, Footshield showed smaller variation between trials and between regions of the foot. The other offloading footwear demonstrated a wider spread of results, particularly in the forefoot and hallux regions. All footwear conditions produced some degree of plantar pressure redistribution, although the pattern of redistribution was not consistent across participants or regions of the foot. The data indicate that the specific geometric features of the experimental footwear did not introduce instability or alter gait timing. Instead, they supported a balanced rollover pattern across stance while maintaining overall stability.

4. Discussion

This study examined plantar pressure, impulse, and centre of pressure characteristics across several forefoot offloading footwear designs, including a newly developed left-right-specific footwear and established commercially available footwear. The overall variability across footwear types was small, suggesting that all designs performed within a similar mechanical range under the tested conditions. The principal contribution of this study lies in the study design and the selection of outcome measures, rather than in demonstrating clear mechanical superiority of a single footwear type. A contralateral within-participant approach allowed side-specific geometry to be evaluated under matched gait conditions, reducing the influence of between-participant differences in walking strategy and anthropometrics. Within this framework, differences in regional loading and centre of pressure progression are interpreted as relative effects of sole geometry. This approach extends prior work that has primarily focused on absolute pressure reductions by incorporating centre of pressure measures that reflect rollover behaviour and dynamic stability.

The experimental footwear demonstrated plantar pressure and impulse values comparable to retail footwear and to other offloading footwear, with slightly lower variability across participants. Hallux loading did not show a consistent increase in the experimental footwear condition relative to the other designs, which is clinically relevant because distal transfer to the hallux is often undesirable in high-risk feet. The observed pattern suggests a balanced rollover, with forefoot load redistribution occurring without a clear penalty at the hallux. This aligns with recent work showing that optimisation of material properties and sole geometry can influence how load is distributed across the plantar surface, even when overall pressure reductions are modest [13].

Centre of pressure outcomes further support this interpretation. Across participants, Footshield displayed centre of pressure indices that were generally lower, or more consistent, between left and right feet compared with the other footwear conditions. This pattern reflects smoother and more stable progression of pressure through stance, suggesting a controlled rollover and effective dynamic balance. None of the footwear conditions caused notable changes in centre of pressure velocity, indicating that gait timing remained consistent across all designs. These findings are consistent with evidence that footwear and insole design features influence not only plantar pressure but also the efficiency and stability of centre of pressure progression, which has implications for balance control in clinical populations [14,15].

All footwear types produced some degree of plantar load redistribution, although the pattern varied between participants and between regions of the foot. This variation reflects the individuality of gait mechanics and highlights that offloading is achieved through redistribution rather than complete reduction of load. In this dataset, redistribution patterns were not uniform across individuals or footwear types, which supports the need for future work that explores participant-specific responses and links pressure outcomes to additional mechanical measures. However, the experimental footwear design achieved this redistribution without introducing imbalance or instability, suggesting that its geometry facilitates a coordinated and stable rollover process. The patterns described above are reflected in the group mean values and variability presented in Tables 2 and 3 and in Figures 3–5. Similar inter-individual variability in response to forefoot offloading footwear has been reported in recent comparative studies of commercially available designs [16].

These findings complement the existing literature showing that rocker apex position, rocker angle, and heel geometry are central to effective pressure management and gait stability [2,9,10]. More recent work has further demonstrated that changes in rocker and apex configuration can influence regional pressure patterns, even when global pressure metrics remain similar across conditions [17]. The present data extend this evidence by indicating that a left–right-specific design can deliver comparable or improved mechanical performance relative to universal footwear, particularly in terms of consistent centre of pressure progression between the left and right feet.

Correct design of forefoot offloading footwear is fundamental to protecting vulnerable tissues and maintaining mobility in patients recovering from surgery, trauma, or diabetic ulceration. Footwear that achieves balanced pressure distribution and stable rollover can play an important role in reducing mechanical stress and supporting recovery. Conversely, inadequate geometry may compromise both load redistribution and balance control, potentially increasing the risk of re-injury or delayed healing. The current findings reinforce that clinical footwear solutions should be grounded in biomechanical principles and validated through structured testing to ensure that design refinements translate into functional and clinical benefits.

While these results are encouraging, they should be interpreted within the methodological scope of the study, which prioritised controlled, within-participant comparison over broad clinical generalisation. Observed differences should be interpreted in the context of between-participant variability and known in-shoe measurement uncertainty, which is why variability is presented using standard deviations. The analysis involved healthy participants walking under controlled conditions, and the magnitude of between-condition differences was modest. Further research is required to determine whether these findings generalise to clinical populations, including individuals with diabetic neuropathy, post-surgical recovery, or altered foot morphology. Future studies should assess the experimental footwear when worn bilaterally to capture its full rollover mechanics and explore the integration of kinetic measures such as load rate and shear to provide a

more complete understanding of mechanical protection and gait stability in at-risk groups.

5. Conclusions

The experimental footwear demonstrated balanced load distribution and consistent centre of pressure progression, without evidence of increased hallux loading or compromised stability. These findings suggest that anatomically specific geometry may support controlled rollover and effective forefoot load management under the tested conditions. Further research in clinical populations and under bilateral use conditions is required to determine whether these mechanical patterns translate into improved long-term tissue protection and recovery outcomes.

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

Data Availability Statement: Data are available upon request.

Conflicts of Interest: Jose Gomez-Galdon Perez, Adam Horrocks, Esmé Franklin and Simon Dickinson are employed by Talarmade Limited who provide the footwear named Footshield commercially. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Abbreviations

BF, Benefoot; BFL, Benefoot Left; BFR, Benefoot Right; COP, Centre of Pressure; CPEI, Centre of Pressure Excursion Index; DA, Darco; DAL, Darco Left; DAR, Darco Right; EVA, Ethylene Vinyl Acetate; FS, Footshield; FSL, Footshield Left; FSR, Footshield Right; km/h, Kilometres per hour; kPa, Kilopascals; KPR, Kerraped Right; N, Newtons; N-s, Newton seconds; PU, Polyurethane; REF, Retail Footwear; XSENSOR, XSENSOR X4 In-Shoe Pressure Measurement System.

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