Midfoot Pressure Analysis in Individuals with Flat Feet While Climbing Stairs Using a Pressure Sensing System

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ABSTRACT

Flat feet, or *pes planus*, present a prevalent condition impacting mobility and quality of life, warranting an understanding of its biomechanical implications. This study aimed to quantify pressure differentials in the midfoot region between individuals with flat feet and those without during stair ascent. The pilot study evaluated one individual with clinically diagnosed flat feet and one healthy individual, both meeting specific inclusion criteria. The participants ascended stairs while a pressure sensing system consisting of force-sensitive resistors (FSRs) recorded midfoot pressures.

The findings revealed that FSRs positioned along the medial longitudinal arch exhibited lower mean pressure values in individuals with flat feet, while FSRs on the lateral longitudinal arch displayed higher mean pressures in the same group. These results suggest a compensatory shift in pressure distributions, highlighting the altered loading patterns associated with flat feet.

These findings have significant implications for physical therapy, underscoring the importance of arch strengthening exercises to improve foot stability and redistribute pressure more effectively. By integrating pressure mapping into rehabilitation strategies, therapists can create personalized treatment plans, ultimately improving outcomes for individuals with flat feet. This study contributes to the broader understanding of foot mechanics and emphasizes the need for targeted interventions in managing flat foot pathology.

INTRODUCTION

Flat feet, or *pes planus*, is a prevalent condition affecting both youth and adults, significantly impacting mobility and quality of life [1, 2]. This condition is characterized by the flattening of the medial longitudinal arch under pressure, leading to various gait alterations. Clinical evaluation readily identifies flat feet, marked by a collapse of the medial longitudinal arch, changes in foot strike angles, impaired outward movement, reduced forward push-off, and misalignment of the heel and forefoot [3].

Flat feet are a complex condition resulting in a multitude of symptoms with a range of severity. Symptoms stem from depression in the arch of the foot, impingement along the outer edge and rearfoot, and changes in the loading process [3]. Frequent symptoms of flat feet include Achilles tendinitis and pain in the plantar fascia, ligamentous weakness and hyperflexibility, and pain during activities [4]. These issues can extend beyond the foot, contributing to musculoskeletal pain in the knees and hips [5]. Typical conservative treatments for flat feet are physical therapy, which addresses the underlying weak intrinsic foot muscles and stretches tight foot structures, and foot orthoses, which alleviate pain and discomfort by correcting the alignment and biomechanics of the foot [6].

Stair climbing represents a common daily activity that imposes unique biomechanical demands on the foot, making it an ideal scenario for studying pressure distribution patterns. The pressure of the midfoot region while climbing stairs can be collected with force-sensitive resistors (FSRs), which can be implemented to effectively measure pressure across various regions of the sole of the foot [7]. FSRs can quickly relay data into an array over a specified duration, finding particular application in medicinal technology as a means to monitor foot pressure during rehabilitation activities [8]. This study aims to investigate the relation between the midfoot pressure of flat and normal feet individuals while climbing stairs, enhancing our understanding of the biomechanical implications of flat feet.

MATERIALS AND METHODS

Participants

The research was performed on one individual with clinically diagnosed bilateral flat feet for more than five years. Additionally, one healthy individual with normal feet was recruited. Participants were required to satisfy the conditions: no prior surgery on the lower body, no traumatic injury, a body mass index of less than 32, and no musculoskeletal disorders. Although this pilot study was limited to two participants, it provides valuable preliminary data for understanding midfoot pressure distribution in flat and normal feet. Future studies will require larger participant groups to validate these findings.

Equipment

A pressure sensing system consisting of four force-sensitive resistors (FSRs) was used to gather numerical data for the pressure in the midfoot region. The FSRs were calibrated using varied measured weights in Newtons and reading the corresponding analog results, which were then graphed (Fig. 1). The four FSRs were arranged in a square-shaped array on the insole of the right shoe (Fig. 2). The individual FSRs measured approximately 2.5 centimeters in diameter and were less than 0.60 millimeters thick. A pressure of at least 4.9 Newtons is required to activate the FSR, and an individual FSR can measure up to 490 Newtons of pressure. The numerical data received consisted of four independent force readings in Newtons, one from each FSR. The chosen data collection rate was 33.3 Hz, with less than a 1 millisecond response time and with each FSR giving a reading simultaneously. The FSRs were fitted into the right shoe and then connected to an Arduino Uno board (Fig. 3), which was connected via a cable to a computer. Participants were given the same pair of shoes, a Nike Air Force 1 Low, which fit properly on the participants to ensure consistency.

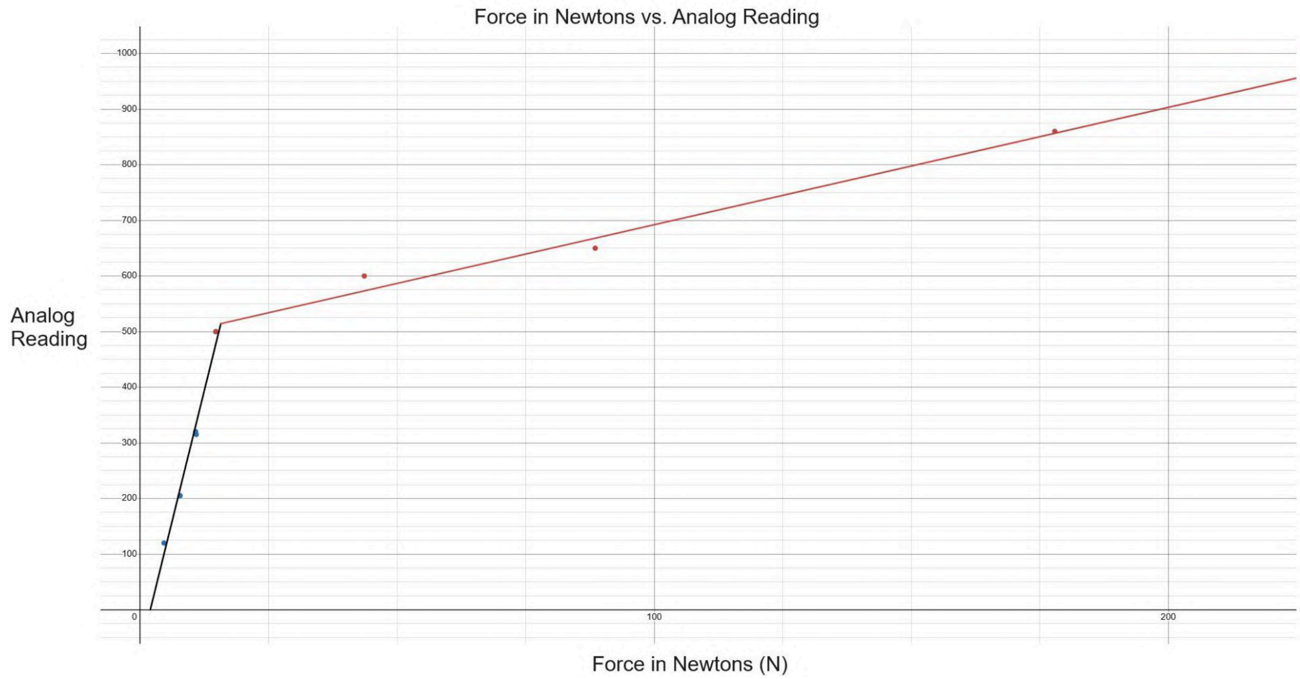

Figure 1: Force in Newtons vs. Analog Reading Graph. The graph was used to measure the force of the foot on the FSRs of the shoe in Newtons.

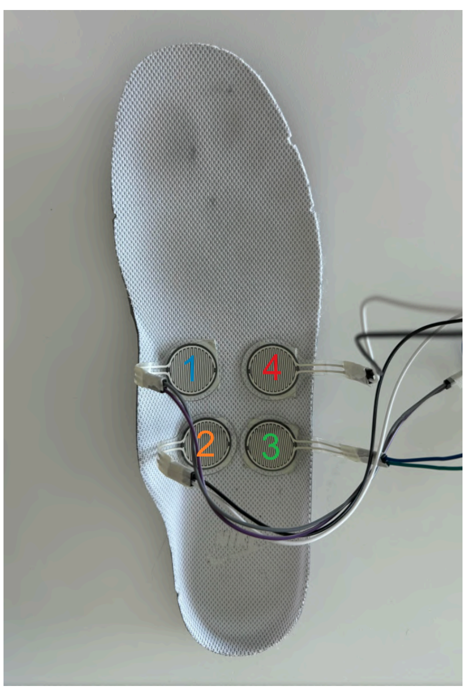

Figure 2: The four FSRs were arranged as shown, with 1 and 2 placed along the medial longitudinal arch and 3 and 4 placed along the lateral longitudinal arch.

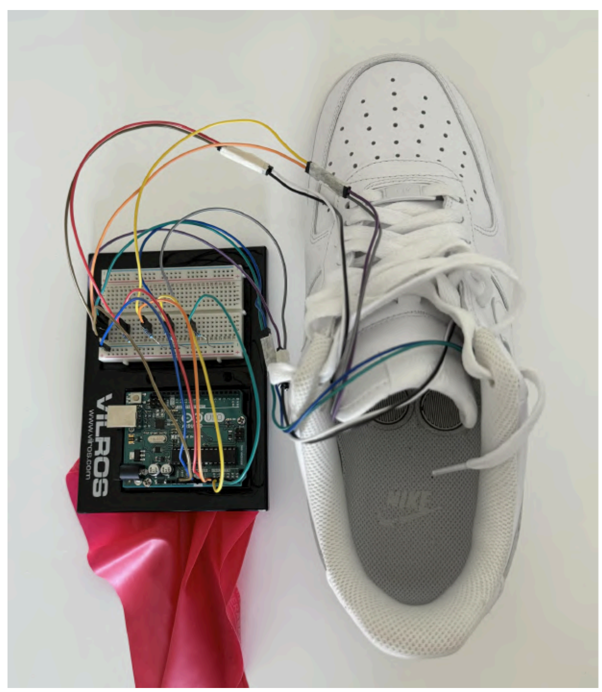

Figure 3: The Arduino Uno board connected to the FSRs on the insole of the shoe.

Experiment Protocol

Participants were fitted with the pressure sensing system as shown (Fig. 4, Fig. 5). The Arduino Uno board was comfortably attached to the leg using a therapeutic band. The participants laced both shoes normally, and the device was designed to be unobtrusive while moving, minimizing the risk of the device causing participants to alter their regular method of climbing stairs. Then, participants were asked to ascend a set of stairs where they were encouraged to maintain a relaxed position and walk up stairs normally.

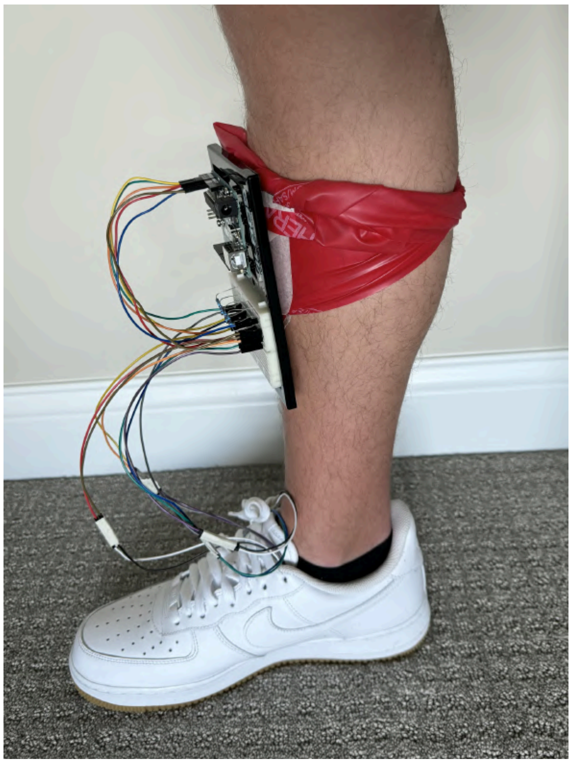

Figure 4: The interior side view of the system.

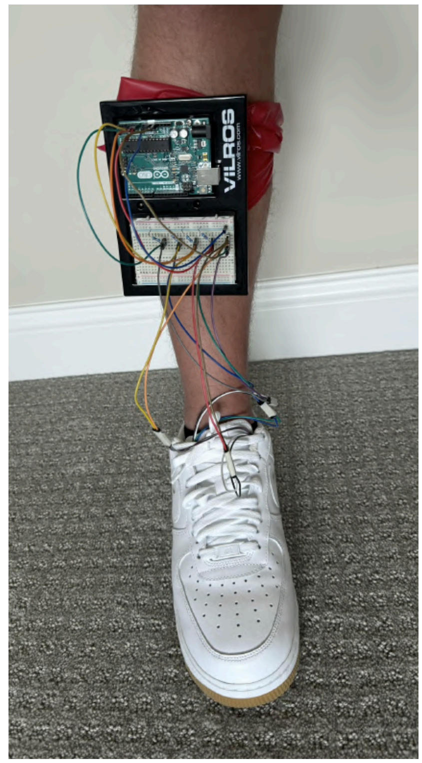

Figure 5: The front view of the system.

Data Analysis

During the experimental trials, the pressure sensing system recorded four independent force readings in Newtons, reflecting the forces exerted by the different regions of the midfoot during stair ascent. The collected data were analyzed to compare pressure distributions across the midfoot region between individuals with flat feet and those with normal feet. This comparison aimed to identify any distinct pressure patterns associated with flat feet. Further, the mean pressure per step was calculated to quantify and compare the average pressure in each midfoot region experienced by each participant. The analysis sought to reveal significant differences in pressure distribution and dynamics between the flat and normal feet individuals.

RESULTS

The data received for the flat feet individual (Fig. 6) and normal feet individual (Fig. 7) is displayed. The data was taken over a 20-second interval, with every step taken at a relaxed, comfortable pace for the participants. These data visually represent the force in each FSR for every step.

In the following figures, the individual FSRs are labeled 1-4 in their respective color, which corresponds to Fig. 2 both in number and color.

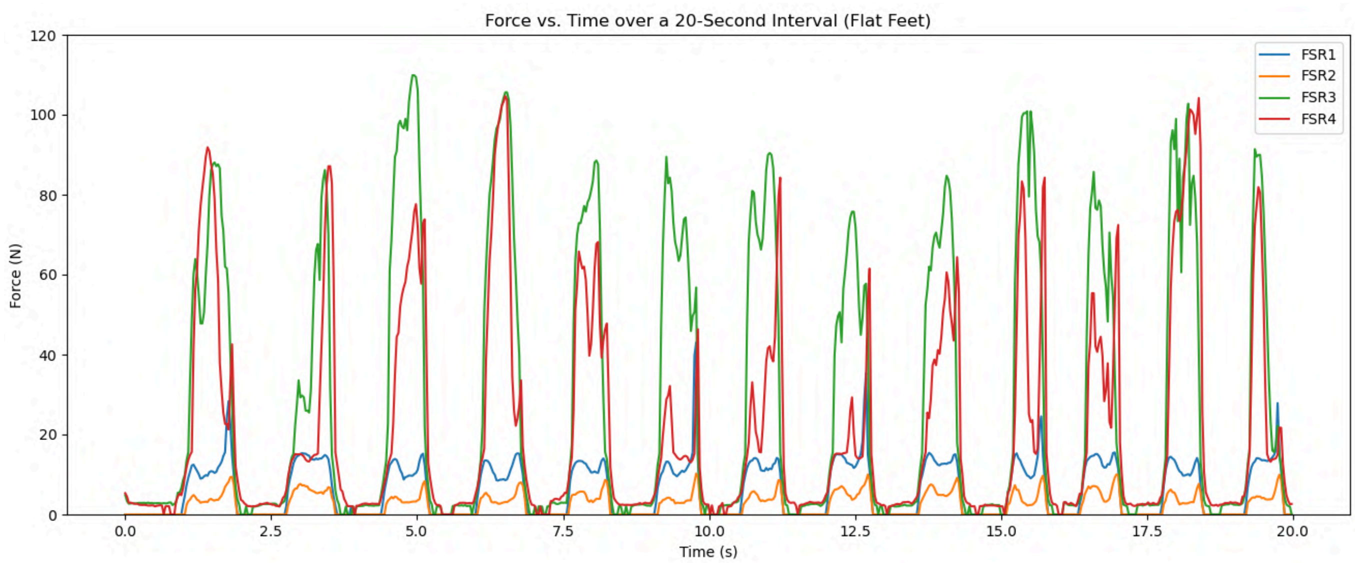

Figure 6: The force versus time graph for the flat feet individual.

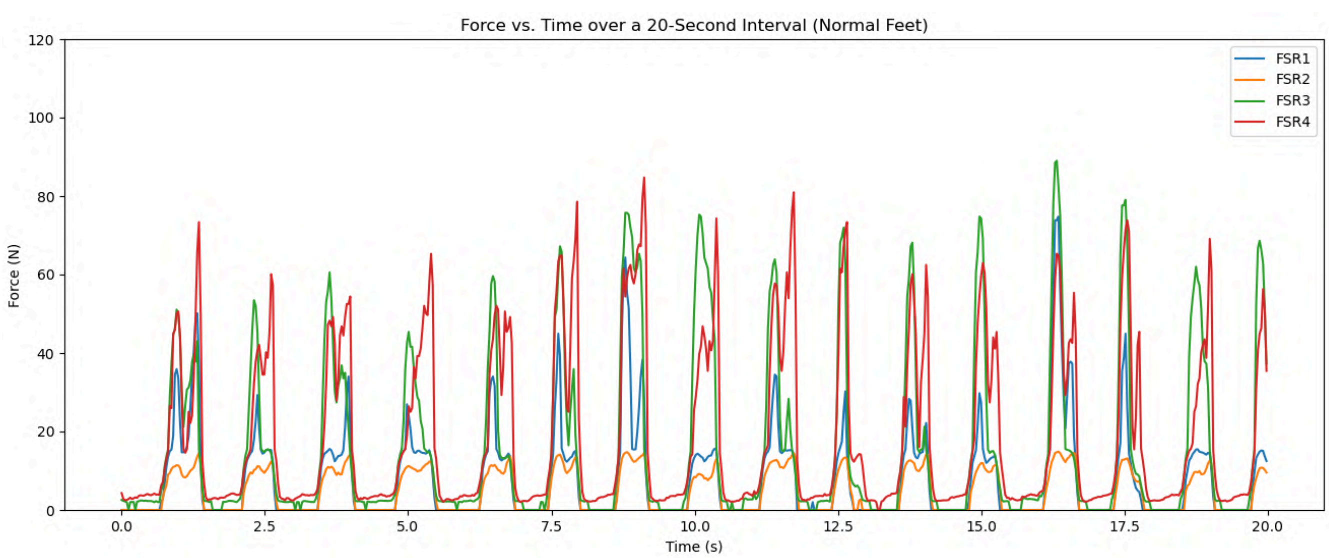

Figure 7: The force versus time graph for the normal feet individual.

Figures 8, 9, 10, and 11 compare flat feet and normal feet FSR forces, with flat feet represented as the blue line and normal feet represented as the red line. The time vector for normal feet was scaled by a factor of 1.23 to match the step rate of the flat feet individual for visualization purposes.

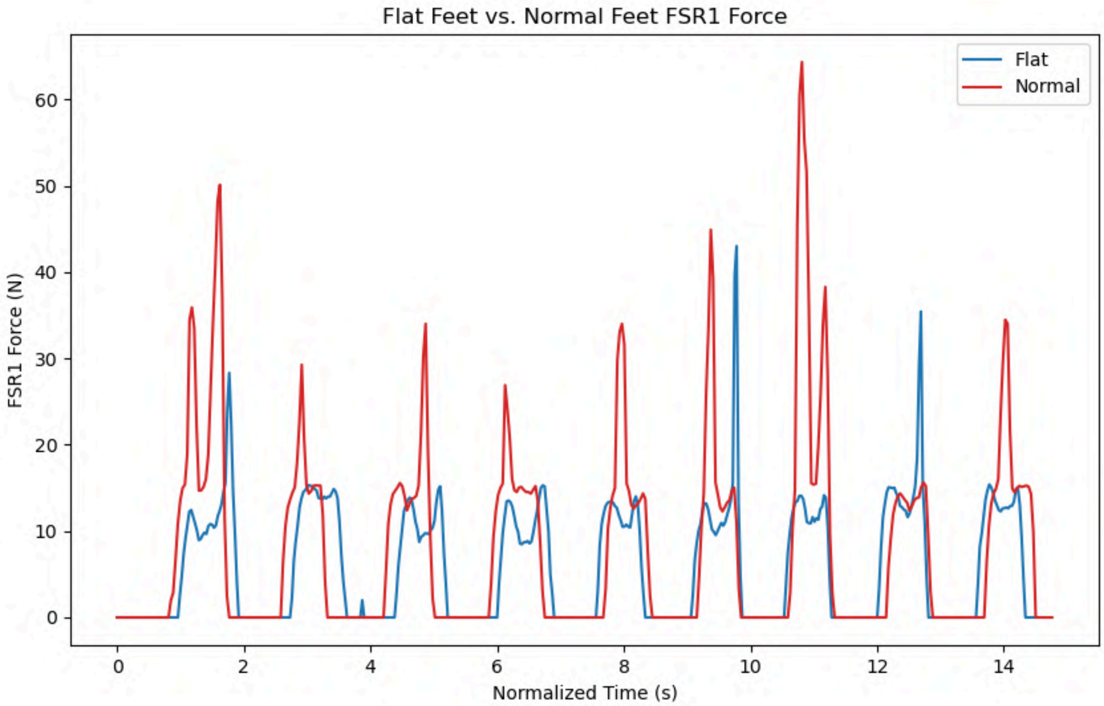

Figure 8: The FSR1 force versus time graph for the flat feet and normal feet individuals.

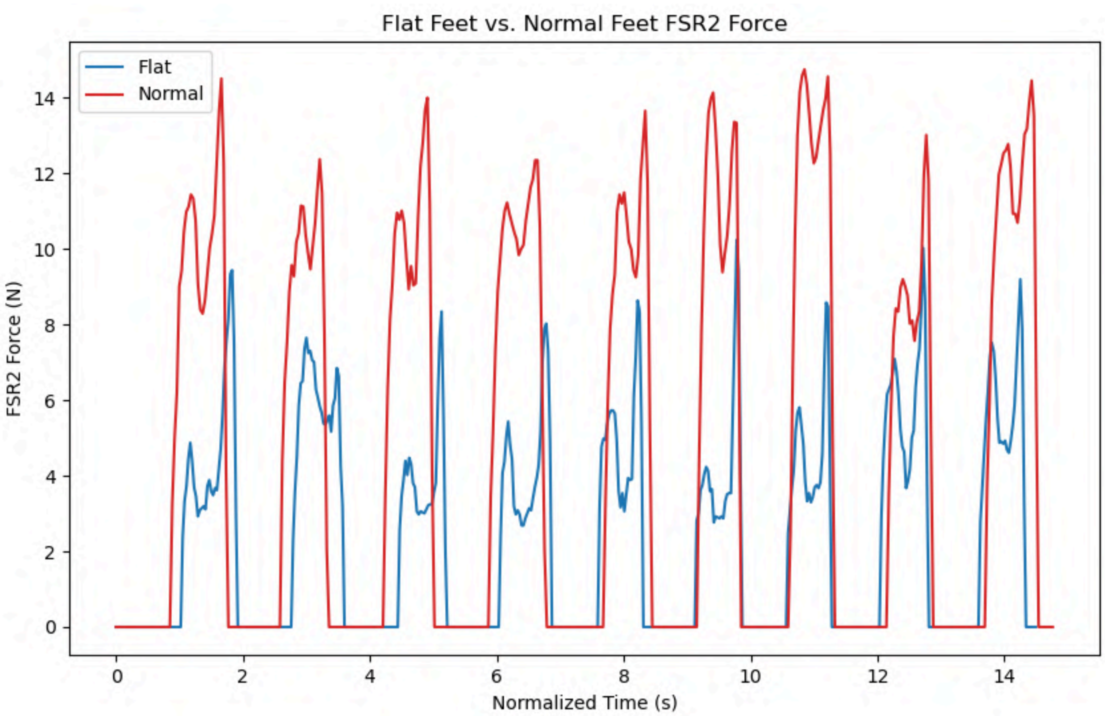

Figure 9: The FSR2 force versus time graph for the flat feet and normal feet individuals.

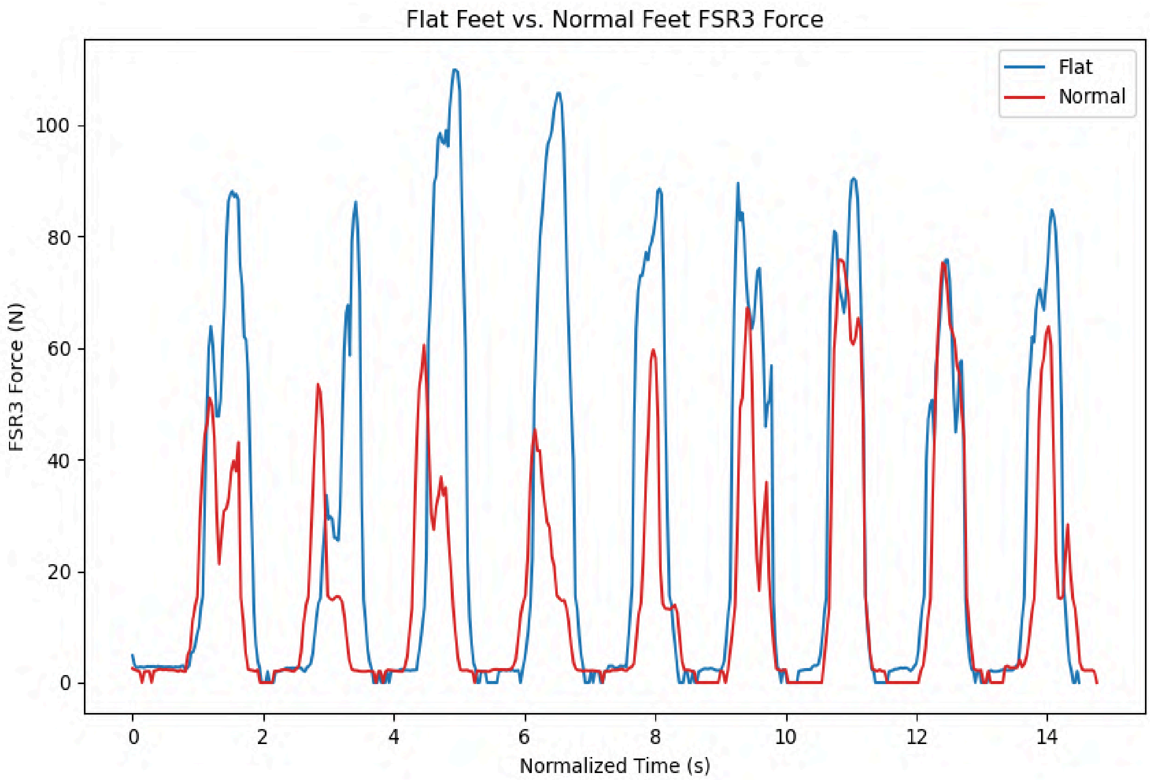

Figure 10: The FSR3 force versus time graph for the flat feet and normal feet individuals.

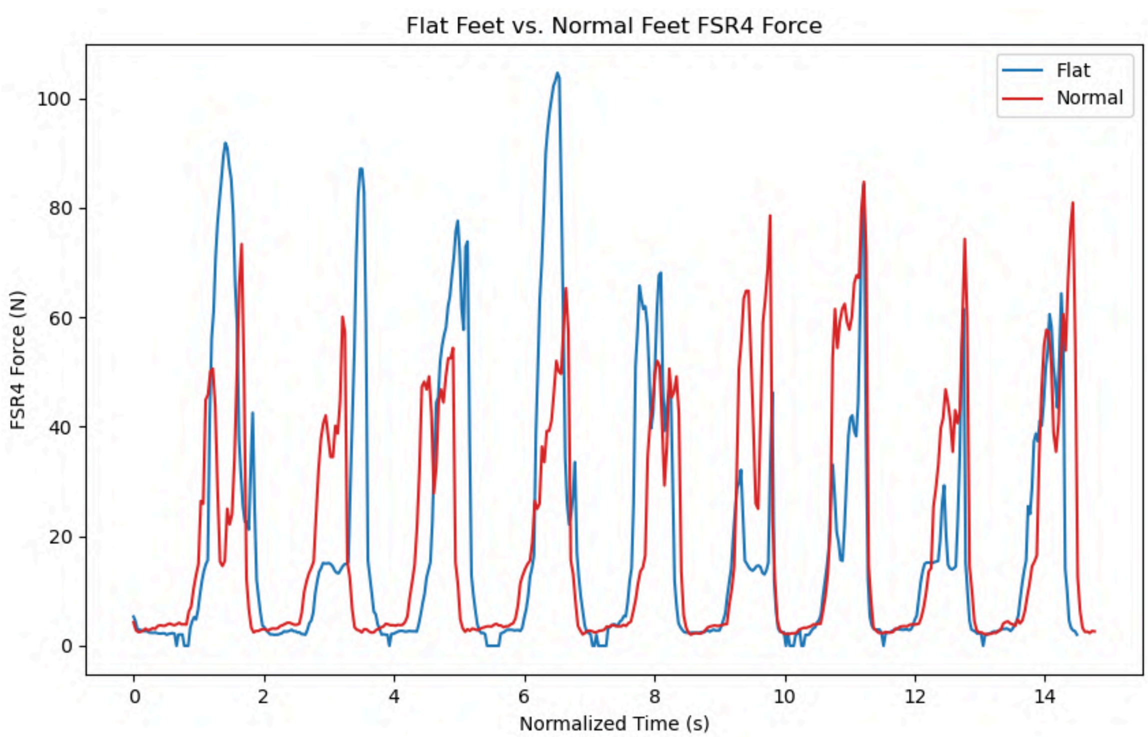

Figure 11: The FSR4 force versus time graph for the flat feet and normal feet individuals.

As shown in Figures 8 and 9, FSR 1 and FSR 2 exhibit consistently higher force values for the normal feet individual. In contrast, FSR 3 in Figure 10 presents higher forces for the flat feet individual. In Figure 11, the flat and normal feet participants exhibit similar force values.

Figures 12 and 13 show the mean FSR force over one representative step. One representative step is the average across 13 steps for flat feet and 20 steps for normal feet. Each step was detected by using a cutoff value for the applied force on FSR4. Figure 14 is a visual comparison of Figures 12 and 13 on the same graph.

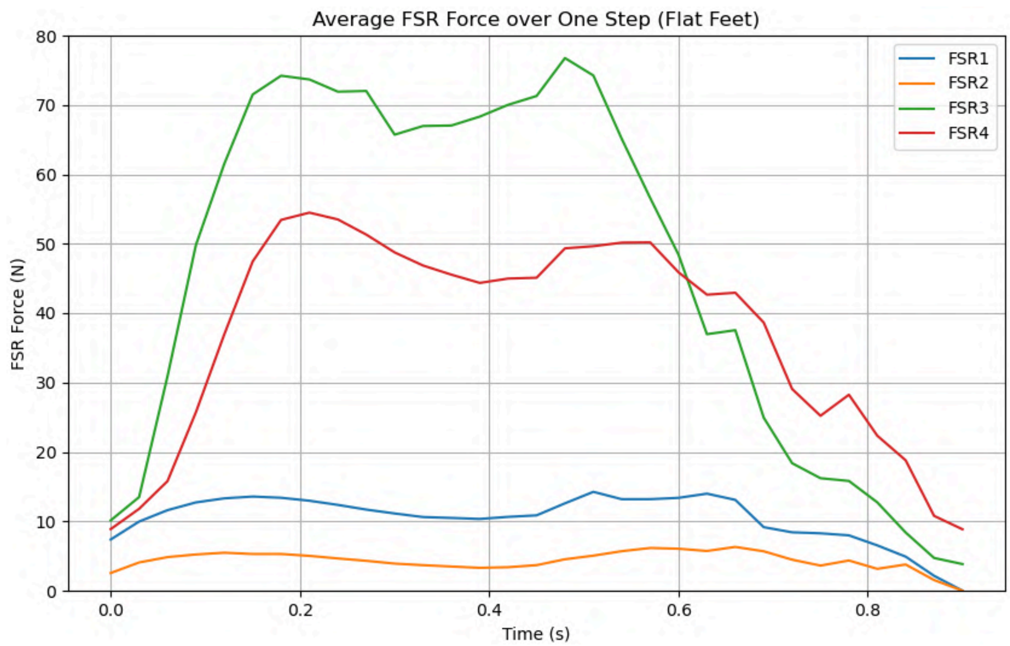

Figure 12: The average FSR force over one step for the flat feet individual.

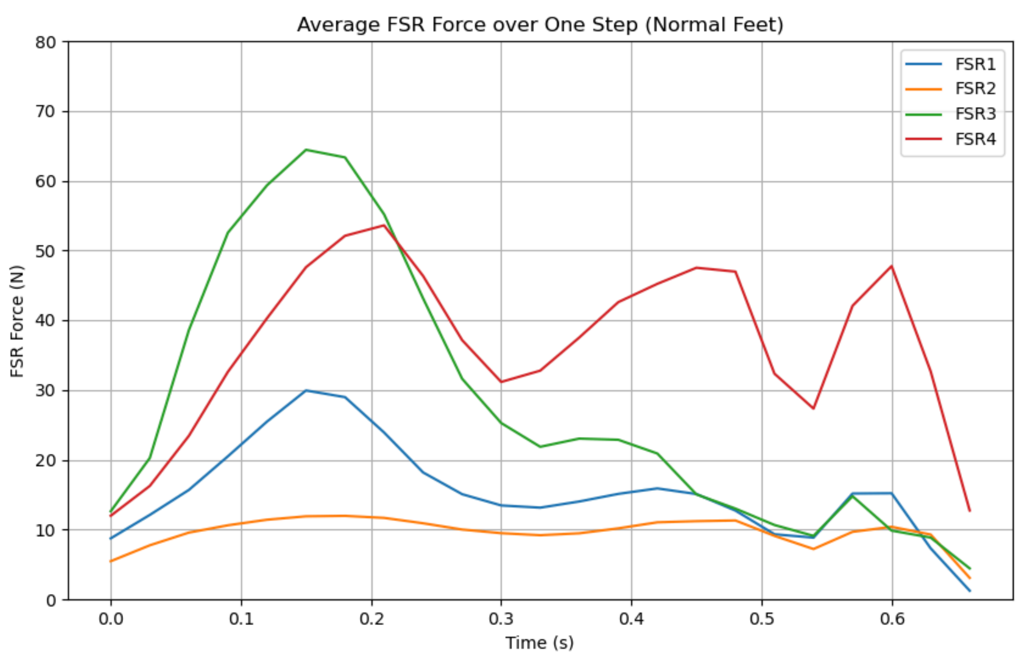

Figure 13: The average FSR force over one step for the normal feet individual.

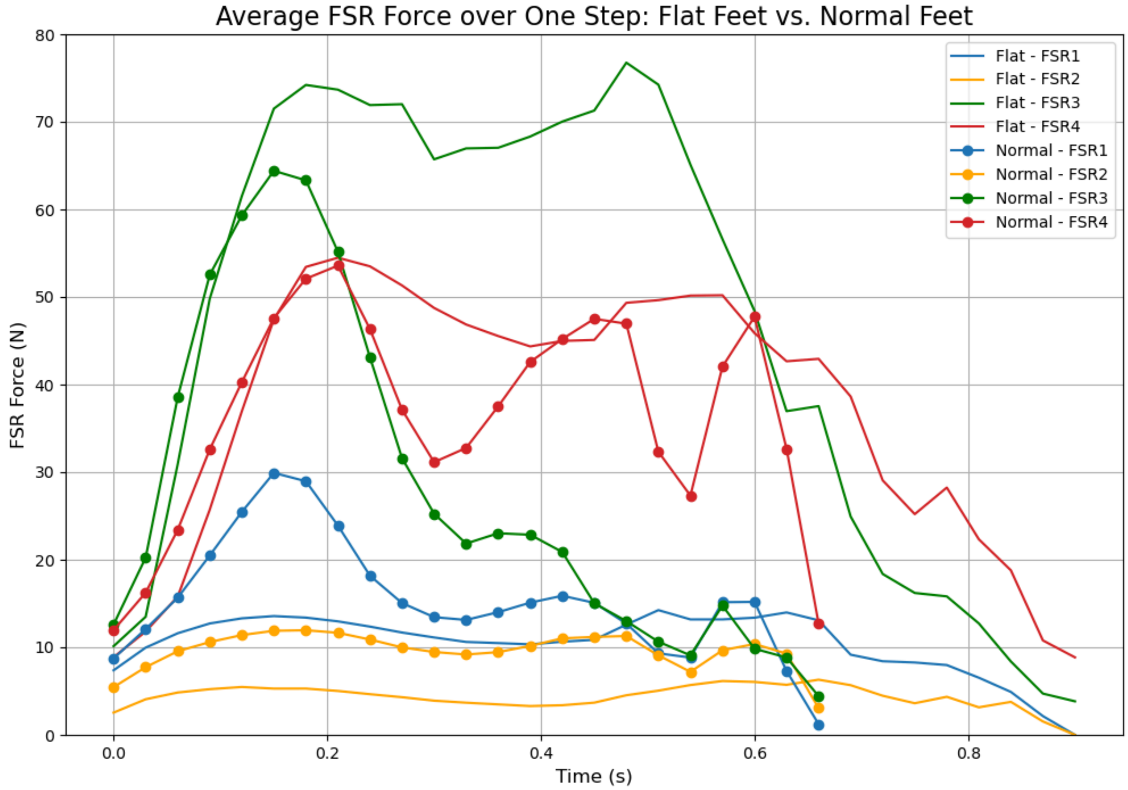

Figure 14: The comparison of the average step of the flat and normal feet participants.

The average pressure for each FSR for normal and flat feet participants was calculated for each step (Table 1). Then, the means for each FSR between normal and flat feet participants were compared using an independent *t*-test. The independent t-test was chosen for its ability to compare the means of two independent groups—flat feet and normal feet individuals—thus determining if differences in pressure distribution were statistically significant. The results indicate that for FSR 1, 2, and 3, the *p*-values obtained were less than the accepted threshold of 0.05 ($p < 0.05$), suggesting that the differences in the mean pressure in the normal and flat foot groups are statistically significant. Consequently, the null hypothesis can be rejected, as the foot pressure distributions in normal and flat feet differ significantly.

Visually and numerically, FSRs 1 and 2, placed along the medial longitudinal arch, demonstrate lower mean pressure values for flat feet individuals than normal feet individuals. FSR 3, placed along the lateral longitudinal arch, demonstrates higher mean pressure values for flat feet individuals than normal feet individuals. FSR 4, placed along the lateral longitudinal arch, more distal to the ankle than FSR 3, revealed pressure values that were not significantly different between flat and normal feet individuals.

Table 1: The mean pressure per step in Newtons for each FSR in flat and normal feet participants. The *t*-statistic and the corresponding *p*-value are also depicted. A *p*-value between 0.05 and 0.01 is indicated by *; a *p*-value of less than 0.01 is indicated by **.

	Statistic	Normal (N)	Flat (N)	T-statistic	P-value
0	FSR1 Mean	16.971170 N	11.760464 N	2.745957	2.11e-02*
1	FSR2 Mean	9.908329 N	4.591756 N	9.873294	4.33e-07**
2	FSR3 Mean	32.412446 N	56.526911 N	-5.333147	4.54e-05**
3	FSR4 Mean	38.736389 N	37.087499 N	0.371639	7.15e-01

DISCUSSION

Logically, one would expect that the collapsing of the medial longitudinal arch in flat feet individuals would lead to more pressure being exerted on their arch, as the heel and forefoot turning outward would direct the force towards the medial longitudinal arch area. However, the data rejects this hypothesis, instead supporting that flat feet individuals have higher pressure along the lateral longitudinal arch and lower pressure along the medial longitudinal arch when compared to normal feet individuals. This result is consistent with a study performed by Bates et. al., which found that healthy individuals tend to exhibit higher pressure along the medial longitudinal arch [9].

Contrary to the initial hypothesis, the redistribution of pressure toward the lateral longitudinal arch in flat feet individuals indicates a compensatory biomechanical tendency. Instead of concentrating pressure medially, the pronation and inward rolling of the foot observed in flat feet may shift the load outward. This shift in pressure may occur as a way for the foot to maintain balance and stability despite the reduced arch support. The increased lateral pressure may be due to greater reliance on the lateral side of the foot to absorb impact, especially when sufficient medial arch activation is absent.

These findings have significant implications for clinical practice, particularly in physical therapy and orthotic design. The observed lateral pressure imbalance suggests that therapeutic methods should focus on strengthening the medial longitudinal arch to improve overall foot stability and redistribute pressure more evenly. Exercises aimed at strengthening the intrinsic foot muscles could potentially alleviate some of the excessive loading seen in flat feet individuals [10]. Furthermore, the use of orthotic devices that provide customized medial arch support may help reduce the lateral pressure imbalance and improve gait biomechanics [11].

Incorporating pressure mapping into physical therapy practice could also lead to more personalized treatment plans. Patients with flat feet could benefit from real-time feedback on their foot pressure distributions, allowing therapists to tailor treatments to specific pressure imbalances. Over time, this could improve treatment outcomes by enabling continuous monitoring of changes in foot pressure distribution during rehabilitation.

As a pilot study, this research was constrained by a small sample size and technological limitations. The variability between participants, as well as the use of low-fidelity FSRs, may have introduced variability in the data. Future research would benefit from a larger and more diverse sample population to better capture the different foot types and gait patterns present in the population. Additionally, utilizing more advanced pressure-sensing technologies, such as pedobarographs or sensor-embedded insoles, could provide more precise data and capture more minute variations in pressure distribution.

The findings of this study may pave the way for innovations in both diagnostic and therapeutic strategies. Integrating pressure mapping into routine physical assessments could help detect early signs of abnormal pressure distribution, allowing for earlier intervention and better outcomes. In the future, real-time pressure mapping feedback could be used to create customized orthotics or footwear modifications tailored to individual needs. Additionally, pressure mapping technologies could be integrated into physical therapy programs, allowing patients to monitor their progress and receive personalized feedback during their rehabilitation.

CONCLUSION

The study investigated pressure distribution differences between individuals with flat feet and those with normal feet during stair climbing, using force-sensitive resistors (FSRs) to measure midfoot pressure. The results showed that flat feet individuals experienced higher pressure along the lateral longitudinal arch and lower pressure on the medial arch, contrary to the hypothesis that the medial arch would experience increased pressure due to collapse. These findings suggest a compensatory shift in pressure for flat feet individuals, where the foot may adjust by directing more force toward the lateral side to maintain balance and stability due to the reduced support from the collapsed medial arch. This outward shift in pressure may serve as a biomechanical response to compensate for the lack of structural integrity in the arch, which could contribute to the altered gait patterns and discomfort associated with flat feet. The study highlights the need for targeted physical therapy and custom orthotics to improve medial arch support. Furthermore, this study emphasizes the potential of pressure mapping in personalizing treatment and improving outcomes in flat foot management.

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