

BIOMECHANICAL CHARACTERIZATION OF FOOT ASYMMETRY IN STAIR ASCENT AND DESCENT: A CASE STUDY IN A HEALTHY ADULT USING PLANTAR PRESSURE METRICS

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ABSTRACT

Stair ascent and descent creates unique biomechanical demands which affect gait symmetry even in healthy people. The occurrences of differences in stair ascent and descent can lead to an increased risk of joint injuries. This case study explored the differences in vertical forces derived from plantar pressure and induced loads under each foot during stair ascent and descent using a pressure-sensitive platform. Within the research objectives, several parameters were observed such as peak force, time to peak force, force impulse, root mean square error, correlation coefficients, and the foot asymmetry index. Those parameters indicated that gait became noticeably more asymmetric during stair descent, particularly at the heel. This appeared linked to limited ankle mobility, which delayed force transfer and increased local peak forces, suggesting the body was compensating to maintain balance or momentum. These compensations could lead to excess stress higher up the kinetic chain, possibly raising the risk of joint wear in the knees or hips over time. Our findings emphasize how even subtle mobility issues can affect whole-body mechanics and highlight the value of ankle-focused rehab and personalized prosthetic design. While the single, subject design limits broader conclusions, this work offers a useful starting point for future research into joint loading patterns, neuromyofascial coordination, and strategies to support more balanced movement.

KEY WORDS

plantar pressure, stair gait, asymmetry, ankle mobility, biomechanics

CLASSIFICATION

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INTRODUCTION

Gait is a complex motor process that depends on joint mobility, muscle coordination, and proper force distribution through the lower limbs. It is commonly analysed through spatial and kinetic parameters like stride length, cadence, joint angles, and ground reaction forces [1, 2]. Although level walking is widely studied, stair ambulation creates additional biomechanical challenges. It requires more joint range of motion, greater postural control, and increased force at the ankle and knee joints [3]. Understanding how the body adapts to those demands means looking beyond just the joints and muscles. The neuromyofascial system, described by Sušić et al. [4], offers a more connected view. It explains how muscles, fascia, and neural structures work together to maintain movement efficiency and stability. According to the aforementioned interpretation of the human locomotor system, when there are neuromyofascial restrictions in one area of the body, such as reduced ankle mobility, the force can be transferred elsewhere. This can lead to imbalances or compensatory patterns that show up as left–right asymmetries. One of the most reliable ways to track these changes is through plantar pressure analysis, which looks at how force is distributed across the foot. This study used Tekscan’s MobileMat, a pressure-sensing platform that records real-time data as a person walks or climbs stairs [5, 6]. While some asymmetry is expected in healthy individuals [7], larger differences in timing or pressure can indicate mobility restrictions or muscular imbalances [8, 9]. Although gait asymmetry is well documented on flat ground, there is limited research on how it appears during stair ascent and descent. Most studies rely on force plates at stair landings, which only capture isolated steps. More recent research shows that symmetry can vary depending on fatigue [10], external load [11], and walking direction [12]. These factors suggest that asymmetry is context-dependent and that more focused research on stair use is needed. This study looked at plantar pressure asymmetry during stair ascent and descent in a healthy adult, using the MobileMat system. Forces were tracked under the heel and forefoot, and left-right comparisons were made. To assess asymmetry, we extracted several parameters, including peak force, time to peak force (TTPF), force impulse (FI), root mean square error (RMSE), correlation coefficients, and the foot asymmetry index (FAI). The goal of this research is to better understand how asymmetry appears in stair gait and how that information could help guide rehabilitation strategies and personalized prosthetic designs that support more balanced movement.

METHODS

A case study approach was chosen to demonstrate that measurable foot asymmetries can exist even in healthy, non-symptomatic individuals and can be effectively quantified during stair gait. The focus was not on individual variability, but on illustrating the presence and biomechanical relevance of asymmetry within a single subject. It is correct to approach this issue in an individualized manner, because the measurement findings are individually specific, and therefore cannot be unambiguously generalized, but an approach can be established to analyse the occurrence of differences in the symmetry of people’s movements.

PARTICIPANTS

One female respondent participated in this study. A 23-year-old student 158 cm tall, weighing 56 kg. She self-reports maintaining an active lifestyle, engaging in weekly training activities. The student’s anthropometric measurements of lower extremities are provided in Figure 1. The respondent has no prior history of lower extremity injury or other conditions that could influence gait mechanics and has provided written informed consent to use the data for this research.

EXPERIMENTAL SETUP

The research was conducted at the Department of Biomechanics and Ergonomics, Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb. The primary measuring device used in this study consists of a mobile pedobarography platform MobileMat manufactured by Tekscan™. The platform's dimensions provided by the manufacturer are $63,6 \times 55,9 \times 4,2 \text{ cm}^3$, and sensed area of 1 sensor per cm^2 . The capture frequency rate of the platform is 100 Hz. Manufacturer documentation indicates a maximum pressure range of 50-125 psi which corresponds to 345-862 kPa. In lieu of explicit uncertainty data, calibration performance from independent evaluation indicates a root mean square (RMS) error of approximately 2,7% when using the default power calibration algorithm, and as low as 0,6% with a user-defined cubic calibration curve [13]. The platforms primarily used to capture and analyse plantar pressure which is done using bundled software Tekscan Research.

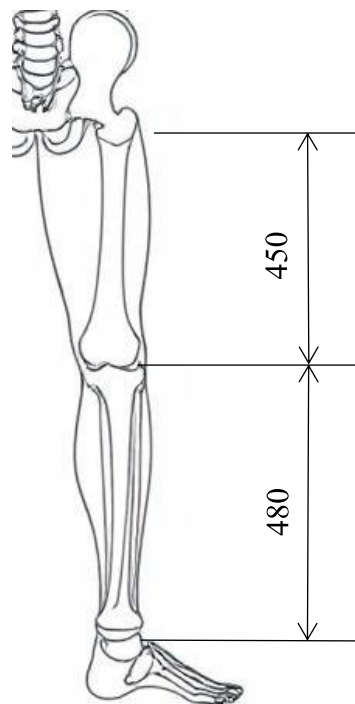


Figure 1. Anthropometric measurements of participant's lower extremities.

MEASURING PROCEDURE

The measuring procedure consists of four different gait profiles: a) walking on level ground (LW), b) ascending onto a stair (AOS), c) ascending from a stair (AFS), and d) descending onto a stair (DOS), as illustrated in Figure 2. The vertical distance between two successive stairs, referred to as the “raiser” is measured to be 19,5 cm, while the depth of each stair, known as the “thread” is 30 cm.

For the purposes of this study, both left and right foot were measured for comparison of asymmetry during stair-related gait. The participant was instructed to walk at a comfortable pace during the trials. The plantar pressure, measured using a pressure platform at foot contact, was converted into vertical force measurements for specific regions, primarily under the forefoot (F) and heel (H).

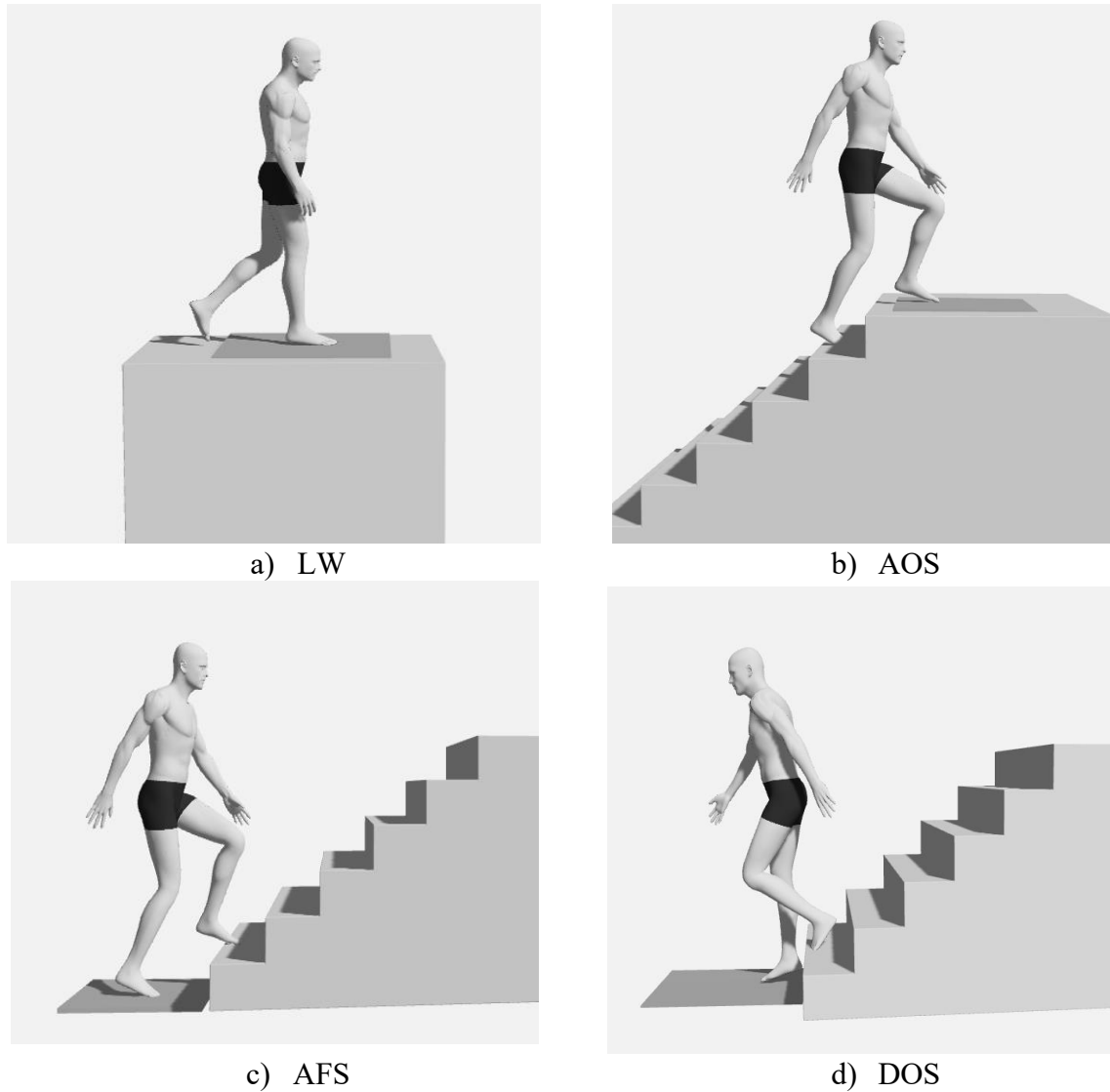


Figure 2. Four distinct gait profiles assessed during the measuring procedure: (a) level ground walking (LW), (b) ascending onto a stair (AOS), (c) ascending from a stair (AFS), and (d) descending onto a stair (DOS). Blue (rectangle) area represents position of measuring pedobarography platform. The sketches were made qualitatively using the free online platform Magic Poser Web [14].

Data processing was carried out using GNU Octave to extract key parameters, including RMSE, FAI, TTPF and FI.

FAI [9] is calculated as:

$$FAI = \frac{|avgRight - avgLeft|}{\frac{(avgRight + avgLeft)}{2}} \cdot 100, \quad (1)$$

where *avgRight*, and *avgLeft*, denote the average force values of the right and left foot, respectively, computed separately for all gait profiles.

FI was calculated as the numerical integral of the vertical ground reaction force-time curve over the contact phase (F_k), using the trapezoidal rule with a sampling interval based on sampling rate of 100 Hz, which equates to 0,01 s (Δ_t):

$$FI = \sum_{k=1}^N F_k \cdot \Delta_t. \quad (2)$$

RESULTS

A case study approach was chosen to demonstrate that measurable foot asymmetries can exist even in non-symptomatic individuals, with healthy lifestyle.

OVERVIEW OF DATA

The data for this study were collected across four distinct gait profiles, each representing a different phase of movement: LW, AOS, AFS, and DOS. These profiles were chosen to capture a comprehensive range of biomechanical dynamics during daily activities involving both level and stair-based locomotion. Each gait profile (LW, AOS, AFS, DOS) was recorded once per foot. Given the case study design, the aim was not to establish intra-subject variability but to demonstrate that foot asymmetries can be detected and quantified under distinct locomotor tasks. The data collection included measurements of force-time curves under both heel and forefoot contact phases for each gait cycle, providing insight into how forces are distributed across the left and right feet. Vertical force was recorded during each gait profile, from which parameters such as peak force and TTPF were extracted. Other parameters such as average force, RMSE, correlation coefficients, FI and the FAI were calculated. These parameters were chosen to assess both the magnitude and the temporal dynamics of the forces involved in each movement phase and are shown in Table 1. The goal was to identify relationships between the left and right foot force profiles across different gait phases, particularly in terms of their symmetry and the timing of force application. To present the results clearly, data was visualized using force-time plots and bar graphs, facilitating a comprehensive comparison of all parameters across the different gait profiles.

Peak Force Analysis

Peak forces were analysed to get insight in the distribution of forces during the gait profiles. Peak force values under left foot spanned from 369,85 to 589,11 N, while peak forces under right foot ranged from 368,07 N to 620,7 N. Mean value of forces under left foot is 475,65 N. A slightly bigger mean value of 486,63 N is under right foot. Even though peak forces for both feet are similar in magnitude, the variation in force values was prominent and was observed across different gait cycles. During ascent onto a stair, the right foot (forefoot) generated its highest peak force when compared to other gait profiles. When compared to the left forefoot, there was with a substantial difference of 112 N. In contrast, the left foot (forefoot) demonstrated the highest peak forces during descent onto a stair, which, when compared to right foot in the same gait profile showed a difference of 89 N. These findings suggest that the left foot generates greater force during descent, while the right foot plays a more dominant role during ascent. Peak force comparison and difference are shown in Figures 3 and 4.

Root Mean Square Error Analysis

RMSE was extracted from the force-time curves shown on Figure 5. To resolve the time discrepancy between measurements, the force-time data were standardized by interpolating the time frame to 1000 frames. This approach preserved the structure of the curves, making the force measurements beneath the left and right feet suitable for RMSE comparison. The results indicate that walking on level ground exhibited the lowest RMSE values for both the heel and forefoot comparisons, suggesting a symmetric force profile. Ascent onto the stairs resulted in higher RMSE values, followed by ascent from the stairs. The highest RMSE values were observed during the descent onto the stairs, particularly at the forefoot contact, which suggests that descending stairs introduces the greatest asymmetry in gait.

Table 1. Table showcase of the collected/processed data.

Gait profile	Peak Force (N)		Average Force (N)		RMSE	Correlation (L - R)	FAI (%)	TTPF (s)			Force Impulse (Ns)		F/ Difference (Ns)
	Right	Left	Right	Left				Left	Right	Diff.	Right	Left	
Level Walking	409,37	447,9	245,75	263,4	37,7926	0,96509	6,94	0,22	0,17	0,05	78,64	100,102	21,4619
	493,2	589,1	295,89	307,7	50,2533	0,97284	3,9	0,41	0,26	0,15	195,29	193,828	1,4593
Ascent onto a stair	378,81	369,9	243,80	272,5	49,6152	0,95212	11,12	0,19	0,17	0,02	70,703	84,4787	13,776
	620,7	508,6	339,86	267	114,584	0,88954	24,01	0,44	0,24	0,2	197,12	154,872	42,2477
Ascent from a stair	377,86	408,8	244,51	254,8	68,2234	0,88357	4,1	0,22	0,2	0,02	97,803	99,3543	1,551
	521,74	461,9	239,89	273,4	86,9013	0,89183	13,06	0,57	0,5	0,07	189,52	224,207	34,6918
Descent onto a stair	368,07	449	243,75	248,4	94,6865	0,7402	1,89	0,03	0,03	-	39	74,5228	35,523
	488,58	578,3	293,58	308	154,215	0,44631	4,8	0,42	0,22	0,2	187,89	221,781	33,8896

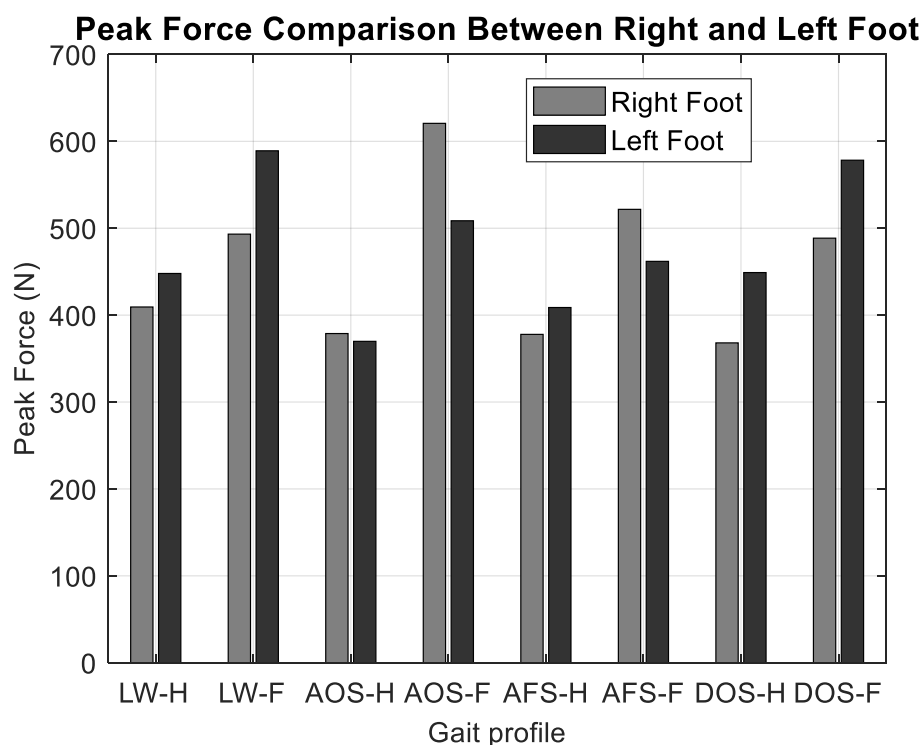


Figure 3. Bar graph comparison of peak force between gait profiles.

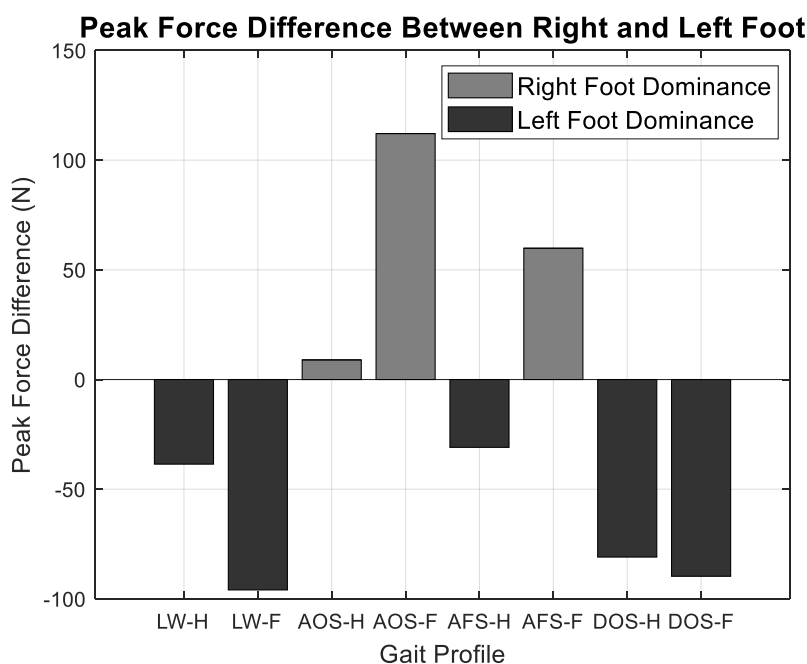
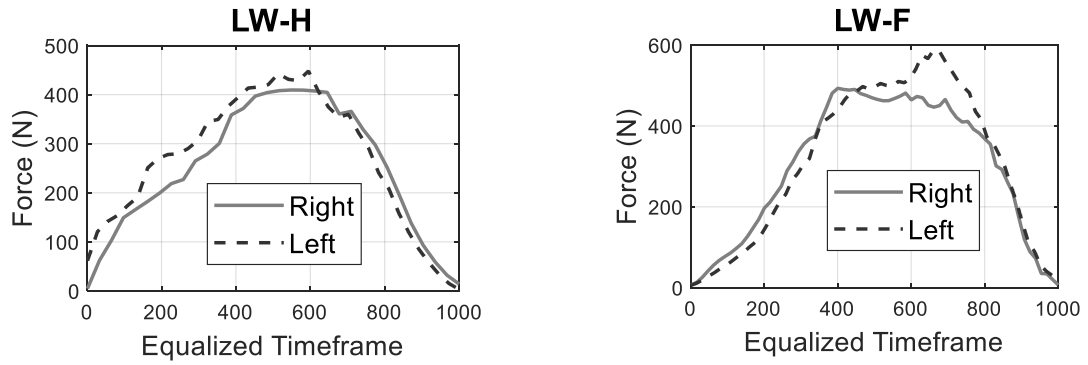


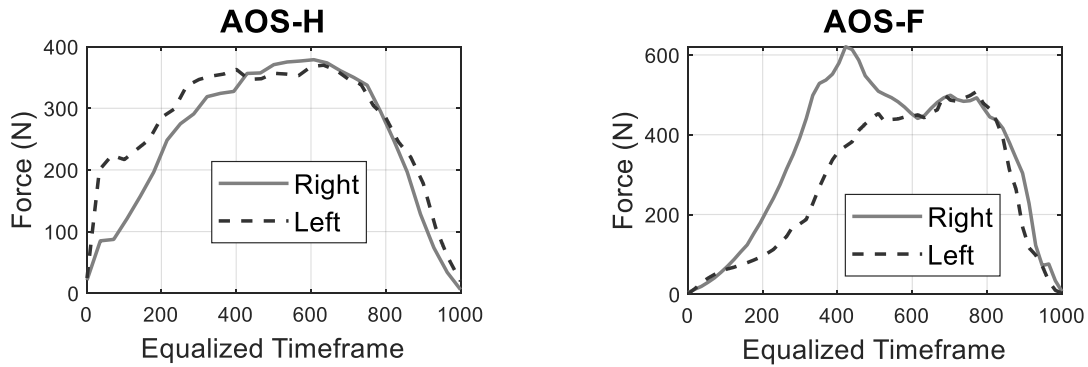
Figure 4. Bar graph representation of foot force dominance between gait profiles.

Correlation Analysis

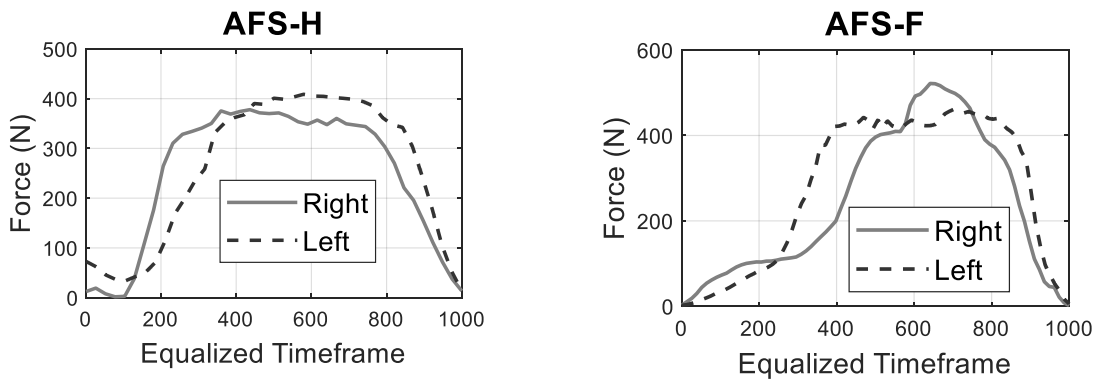
Correlation coefficients were calculated for the gait profiles to assess the relationship between the standardized force-over-time curves of left and right foot. The results show a high correlation during level walking and ascending onto a stair. A slightly lower, yet still significant correlation was observed during ascending from a stair. However, the correlation during descent onto stairs drastically decreased, particularly at forefoot contact, suggesting a substantial asymmetry in the forces applied by the left and right foot during these more complex movements.



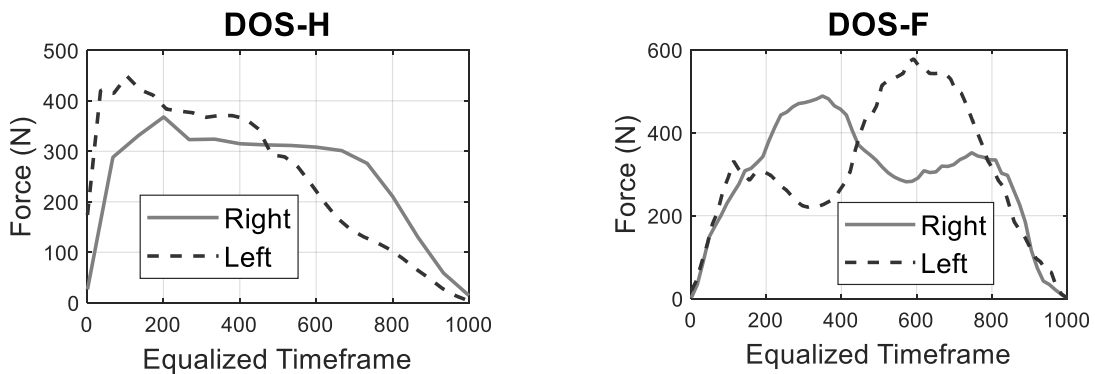
a) Level walking,



b) ascent onto a stair,



c) ascent from a stair,



d) descent onto a stair.

Figure 5. Force-time curves for measurements under the left and right feet during different gait conditions. Left side corresponds to heel (H) measurements, while right side showcases forefoot (F) measurements.

Foot Asymmetry Index

The FAI values for the gait profiles varied across the different gait profiles, Figure 6. Propulsion during level walking exhibited low asymmetry in both the heel and the forefoot region, with a slightly higher value under the heel. Ascent onto a stair showed the highest FAI value under the forefoot, implying that there are substantial differences in push-off between left and right foot, while the heel region showcases moderate asymmetries. The FAI values for descent show relatively low values for asymmetries which is inconsistent with the trend seen in correlation, however, this is due to the fact that FAI only takes average force values into account, indicating there are major temporal or peak differences which cause low correlation.

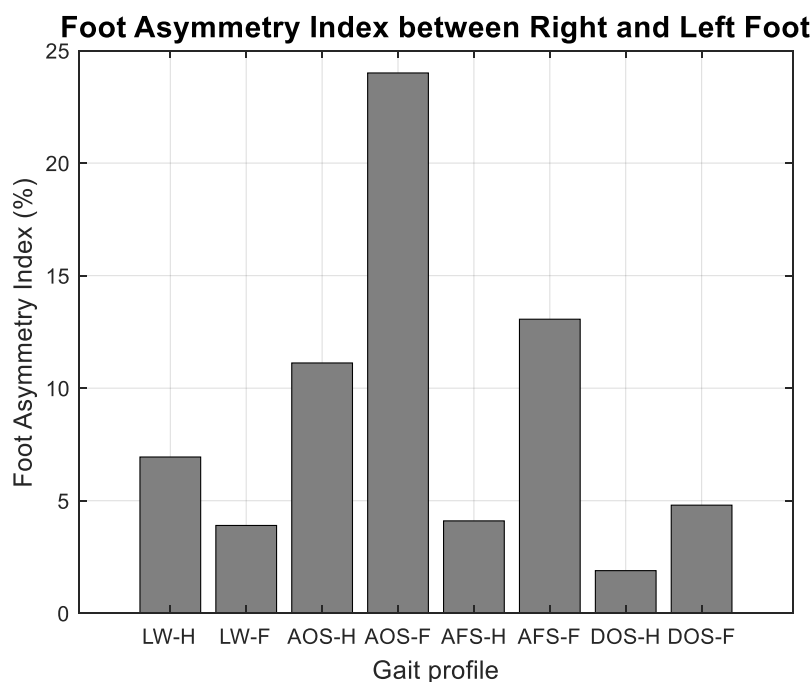


Figure 6. Bar graph comparison of FAI for each gait profile.

Time to Peak Force

TTPF values for both the left and right foot, whose comparison and differences are shown in Figures 7 and 8, were analysed to assess temporal differences in force application. Left foot measured TTPF values move in the range from 0,03 s to 0,57 s. Right foot values exhibited a similar temporal range, with values spanning from 0,03 s to 0,5 s. To better present asymmetry, the time difference between the feet was calculated as absolute difference in TTPF. The difference values ranged from 0 s to 0,2 s across the different gait profiles. The smallest TTPF difference occurred during the descent onto a stair at heel strike, indicating a synchronous peak force application, which contrasts with previous results, where a difference was observed between feet. The largest TTPF difference of 0,2 s was observed during ascent onto a stair at the forefoot, where the left foot required significantly more time to reach its peak force.

Time-to-Peak Force Comparison Between Right and Left Foot

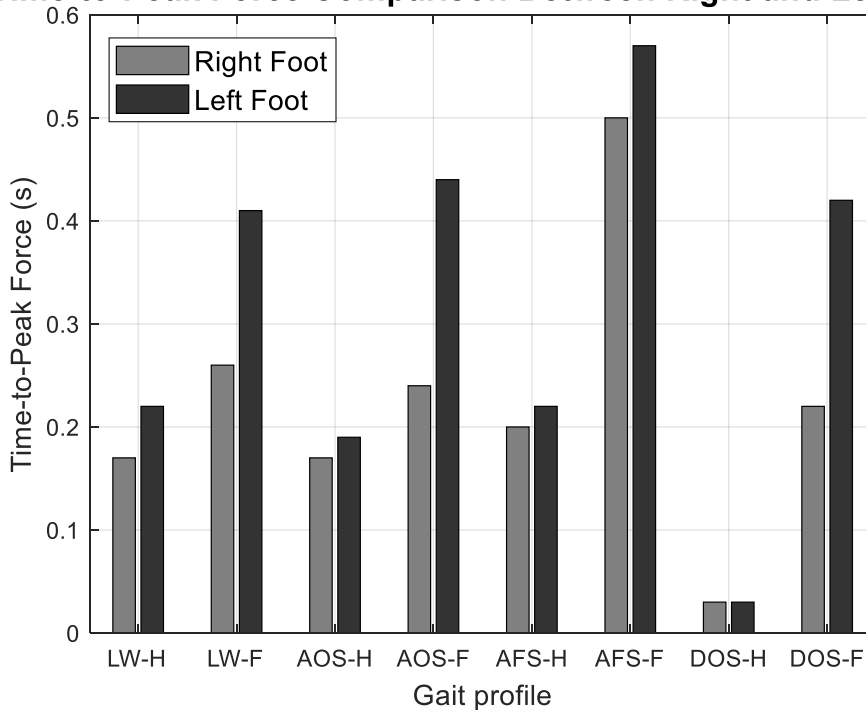


Figure 7. Bar graph comparison of TTPF between gait profiles.

Time-to-Peak Force Difference Between Right and Left Foot

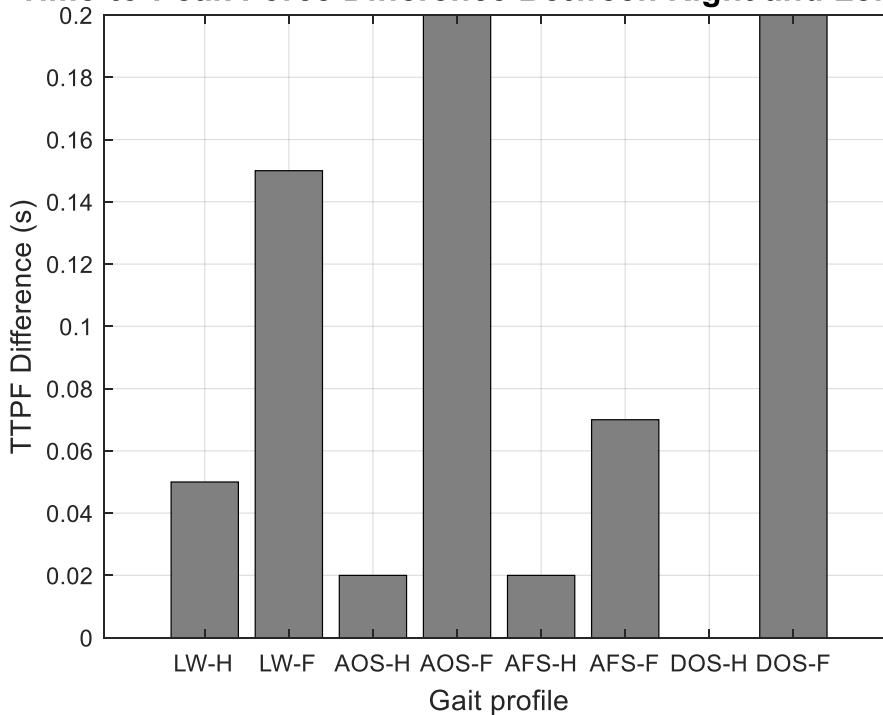


Figure 8. Bar graph representation of TTPF differences between gait profiles.

Force Impulse Analysis

FI values were analysed to assess the cumulative force applied over time during the gait profiles. The FI differences between the left and right feet were calculated to evaluate asymmetries in load distribution across the different gait phases. The force impulse developed for left foot moves in the range from 7 452,28 to 22 420,69 Ns, while right foot FI values varied between 3 899,98 Ns to 19 711,97 Ns. The FI differences between left and right foot had

significant fluctuations in value across the gait profiles, with the highest FI difference observed during the ascent onto a stair (forefoot contact), which suggests that the right foot generates a notably higher load during the ascent phase. The lowest *FI* difference was observed during level walking with forefoot contact, where the FI difference was minimal, implying relatively balanced load distribution between the left and right feet during this phase. The second-highest FI difference occurs during the descent onto a stair (heel contact), with a difference of 3 552,30 Ns. This indicates that the left foot bears a significantly higher load during the descent phase compared to the right foot. These results indicate that substantial asymmetries in force distribution exist during the ascent and descent of stairs. Force impulse comparison and difference are shown in Figures 9 and 10.

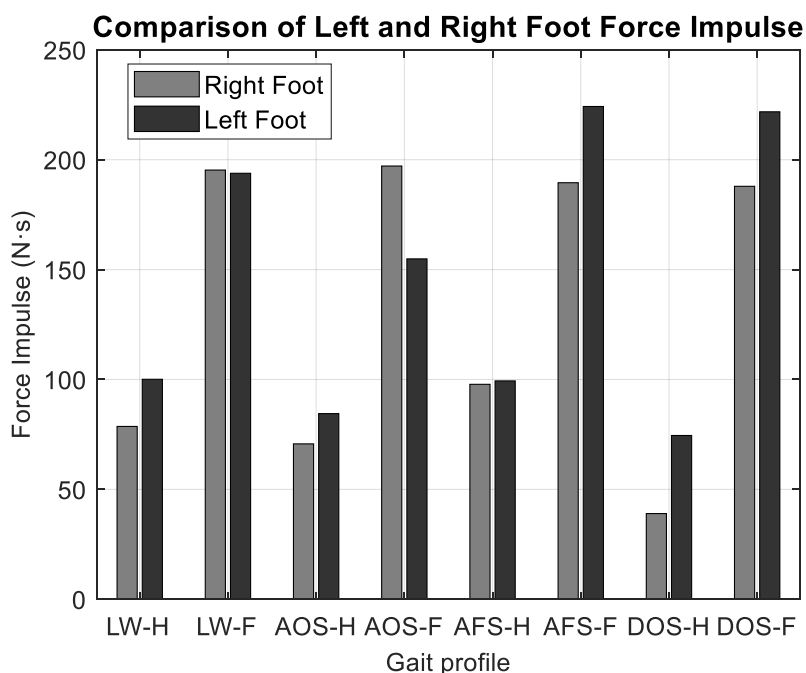


Figure 9. Bar graph comparison of *FI* between gait profiles.

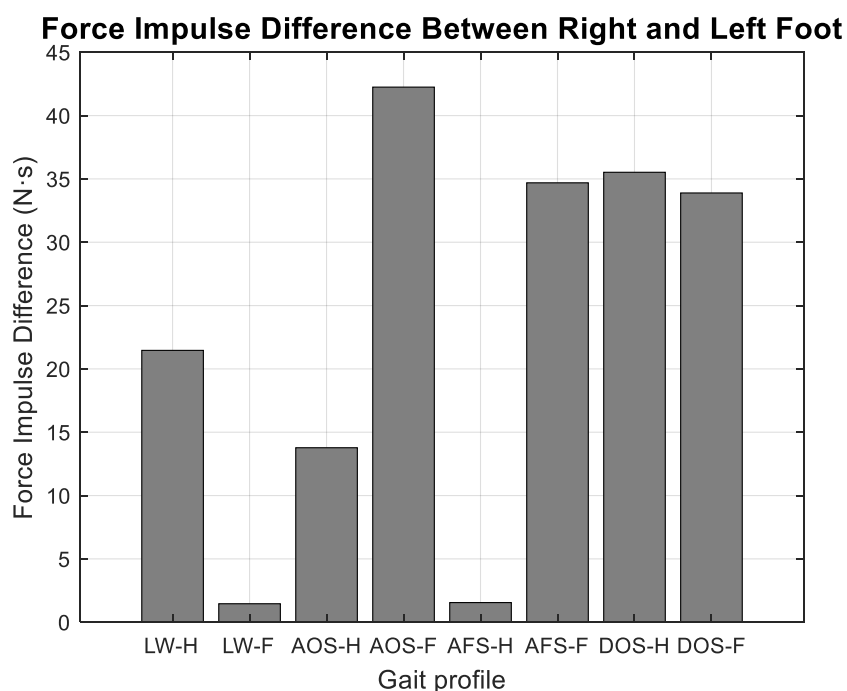


Figure 10. Bar graph representation of *FI* differences between gait profiles.

DISCUSSION

During stair descent, the average force asymmetry between left and right heel was relatively low, however, temporal differences in the force-time profiles, including delayed time to peak force and higher peak forces, indicate functional asymmetries that can affect joint loading. Considering descent is only revolved around heel movement, the asymmetry is not a byproduct of active gait of the entire lower extremities, which is the case during ascent or level walking. Those findings were found by Wafai, L. et al. [9], who also observed increased asymmetry due to increase in pressure under left heel in pathological population. Measuring under both the heel as well as forefoot provides a more detailed insight into the underlying factors contributing to this asymmetry. The collected data could be a result of a reduction of range of motion in the left foot, specifically the ankle. This reduction can be a product of several causes such as muscle limitations, tendon stiffness, or even neuromyofascial imbalances [4]. These mobility restrictions caused the delayed TTPF, and an increased peak force observed during the descent phase under the left heel. When the ankle has limited mobility, it may struggle to effectively absorb impact and control load during stair descent, resulting in compensatory increases in peak force to maintain stability [15, 16]. During ascent, the peak force was higher in the right foot, likely due to the greater load borne by the right leg as the body propels upward. This finding aligns with previous literature, which reports increased force application on the leading foot during ascension, particularly during the initial push-off phase [3]. In contrast, during descent, the left foot exhibited delayed TTPF and higher peak forces under the left heel, and notable temporal differences under the forefoot, further suggesting biomechanical disruptions likely caused by reduced ankle mobility. Furthermore, the abnormal loading of the left heel during stair descent has significant implications for the entire kinetic chain. As peak force is transmitted through the lower extremities, excessive stress is placed on the knee, as well as the hip. Excessive stress leads to joint wear and tear, faster degradation, fractures and other injuries. For example, heightened forces, which are a product of limited ankle motion, could lead to an increase in cartilage wear in the knee [17]. Going further up the kinetic chain, different loads on the hip could increase the risk of labral tears [18]. With that in mind, it's important to address asymmetries and imbalances through exercise and rehabilitation to reduce excessive stress on the knees and hip joint, mitigating long-term injuries. The asymmetry observed during the descent also raises important considerations for prosthetic design, especially for individuals with partial amputations. The data shown suggests that using the non-amputated foot as reference in prosthetics may not be an effective solution for individuals who retained ankle and heel function but lost part of the forefoot. Reduced ankle mobility and altered force distribution in the remaining foot led to significant asymmetries as shown in this study, and that may not be addressed by conventional prosthetic designs [19, 20]. Prosthetics that do not account for these biomechanical differences may result in inadequate force absorption, which lead to an increased risk of joint stress and injury. A more personalized approach to prosthetic design which incorporates personalized biomechanical assessments would be better to support the functional needs of individuals with partial amputations. Such designs should not only replicate the healthy foot, but also consider the mobility and force distribution of the wearer, thus improving gait function and reducing the risk of injury [21, 22].

CONCLUSION

This study gives valuable insights into the asymmetry of locomotion during stair climbing and descending the stairs. Reduced ankle mobility under left foot is concluded to be the primary cause for asymmetry, which leads to increase in peak force during stair related gait. That increase, which can be caused by muscle limitations, tendon stiffness, or imbalances in the neuromyofascial system, can lead to increased stress on the knee and hip joints. Those increases

possess a risk of long-term musculoskeletal injuries like joint degeneration and fractures. Ankle rehabilitation and strength training could be seen as a form of intervention to help minimize the risks by improving ankle mobility and overall force distribution. The findings also correlate the need for personalized prosthetic designs for individuals with partial amputations. Such individuals retain ankle and heel function but have lost part of the forefoot. A prosthetic that mirrors the non-amputated foot might fail to address the specific biomechanical inefficiencies seen in the remaining foot. With that in mind, a need for personalized prosthetic solutions that account for these biomechanical challenges could significantly improve gait symmetry and reduce the risk of injury due to excessive joint stress. A limitation of this study is the fact that it is a case study, and one participant is not enough to get enough insight to the findings. Future research with larger sample sizes would enrich, as well as validate these results. Further investigation would also lead to more knowledge on the impact of reduced ankle mobility on overall joint health. Studies could explore the specific causes of reduced ankle mobility based on the cause (muscle, tendon, or neuromyofascial) as well as the effectiveness of rehabilitation in preventing these biomechanical inefficiencies. Another direction of future research could be based upon the neuromyofascial system, primarily its description of muscle tone which could lead to imbalances in the body as a whole. Such imbalances could also be the reason for the asymmetry in the entire body, including locomotion based tasks, which is a planned step further.

The study was conducted in accordance with ethical principles for research involving human participant. Data used was fully anonymized. The procedure was entirely non-invasive and did not require any additional preparations or interventions beyond the participant's normal activity. The participant was fully informed about the nature and purpose of the study and provided and signed a voluntary, informed consent prior to participation.

The authors have no conflicts of interest related to this work.

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