Basrah Journal for Engineering Sciences, Vol. 25, No. 1, (2025), 1-6

Original Article

Journal homepage: www.bjes.edu.iq
ISSN (Online): 23118385, ISSN (Print): 18146120

Comfort Ability of a Transtibial Amputee According to a Biomechanical Comparison Between SACH, Single-Axis and Multi-Axis Feet Using GRF and Interface Pressure Tests

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Article Info

Article history:
Received: 18 September 2024
Revised: 24 November 2024
Accepted: 29 December 2024
Published: 16 August 2025

Keywords:
Below knee prosthetic feet,
Interface pressure,
GRF,
Socket.

https://doi.org/10.33971/bjes.25.1.1

Abstract

Individuals with special needs who use lower limb prostheses (artificial devices designed to replace missing body parts) have specific sociocultural requirements that have driven the development of prosthetic feet. This study conducted a biomechanical analysis of three types of prosthetic feet (SACH, single-axis, and multi-axis) by comparing their biomechanical properties using ground reaction forces and an F-socket. The goal is to enhance prosthetic technology and improve the user experience for below-knee amputees by examining how different foot types affect stresses in below-knee prosthetic limbs during daily activities. The patient case study involves a 28-year-old man weighing 71 kg, who underwent a below-knee amputation of his left limb due to injuries sustained during battles with ISIS. Ground reaction force (GRF) testing is crucial for determining the forces exerted on a patient's feet while walking. Additionally, the Interface Pressure test was performed to measure the pressure between the remaining lower limb and the below-knee prosthetic socket using a pressure sensor. The healthy foot (right leg) served as the reference for comparison. The results of this study on GRF and knee force for various prosthetic feet provide valuable insights into their performance during gait analysis. The multi-axis foot demonstrated superior capabilities, potentially enhancing user mobility and quality of life. Furthermore, the F-socket test indicated that the multi-axis foot offers the best balance of pressure distribution, dynamic performance, and comfort, making it well-suited for adapting to different surfaces necessary for an active lifestyle.

1. Introduction

In the past ten years, the field of lower limb prosthetics has seen a complete transformation as a result of major technological and material breakthroughs. Some of these advances have been achieved by a deeper understanding of biomechanics and the introduction of innovative composite materials. Tahir et al. (2022) proved that despite of the passive ankle joint simplicity in construction and components, it is close to the biological function of the ankle, especially in terms of angles [1].

Jeryo et al. (2021) discovered that the utilization of advanced composite materials (10 Perlon and 0.75 Wt of MWCNTs) in the manufacturing of ankle-foot orthoses (AFOs) and prosthesis leads to increased durability and reduced costs. Additionally, these materials were found to minimize the variation in data obtained from gait tests between the patient's legs [2]. Moreover, one of the advancements in recent years has been the increased desire for recreational physical activity from amputees with higher hopes and anticipations; as a result, many innovative ankle-foot parts have been designed. However, despite the growing popularity of these designs, the SACH foot continues to be widely used around the world due to their exceptional functionality and performance.

The missing or losing parts of the body for several causes such as trauma, disease, congenital disease, or other causes commonly replaced by prostheses. Among these, the ankle-foot prostheses are mainly purpose which is assisting in locomotion [3]. Figure 1 representing the resection of the leg Below Knee (BK), which is the most often types of limb amputation.

The socket, which is pivotal interface between the patient's leg and the prosthetic, as shown in Fig. 2. This part must supply stability, durability, and comfort which gives it notable importance. Failure in providing these requirements could lead to one of two outcomes: the patient refusing to wear the prosthetic or undergo dissatisfaction about it [4]. Comparison study conducted by Arya et al. (1995) included SACH, Seattle and Jaipur feet. The researchers of it were successfully evaluate the shock absorption characteristics of these prostheses' feet and their influence on the walking style of the individual's by using the GRF data. The study revealed that the SACH foot exhibited superior shock absorption capacity compared to the Seattle and Jaipur feet. However, the Jaipur foot demonstrated a more natural performance, closely resembling that of a normal foot [5]. The design of the socket and the suspension system employed can be affected the distribution of pressure inside the socket. Utilizing a total surface bearing socket along with a Velcro suspension system can potentially enhance the ease of donning the prosthesis and decrease pulling at the end of the remaining limb during the swing phase of gait, Gholizadeh et al. (1995) [6]. Miao-Ju, et al. study with eight men with unilateral transtibial amputation as a case study, the utilization of energy storing-releasing feet showed some indications of enhanced gait performance when compared to the SACH foot. However, the observed differences in foot types were not statistically significant. It is recommended to conduct further studies with a larger sample size to gain more conclusive insights [7]. The socket's shape does not precisely replicate the residual limb, but it incorporates modifications or corrections that enable a substantial transfer of load between the prosthesis and the remaining limb [8]. Bearing loads play a crucial role in the functionality of a prosthetic socket for transtibial amputees. Consequently, the structure of the socket is of great significance as it directly impacts the comfort and performance of the prosthesis, particularly through the mechanical interaction between the amputated limb's skin and the socket [9]. The lifespan of a prosthetic socket, indicating when it becomes uncomfortable and requires replacement, is determined by subjecting it to cyclic loading and unloading. During this process, a phenomenon called hysteresis may occur, affecting the numerical value associated with the socket's life cycle [10].

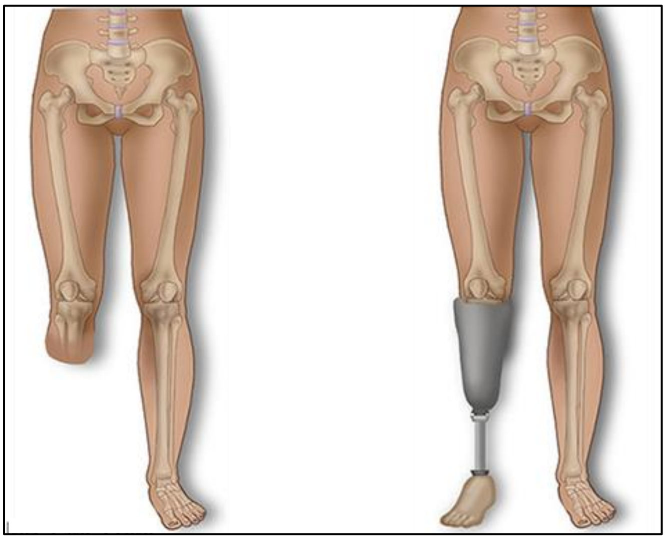

Fig. 1 Below- knee amputation.

Fig. 2 The socket.

2. The ground reaction force

The Tekscan device is an advanced tool for measuring pressure distribution and force analysis across various applications. It features a thin, flexible sensor that integrates easily into different surfaces and uses an array of sensors to capture real-time data for accurate pressure mapping. Its user-friendly software offers valuable insights into biomechanics, gait analysis, and pressure distribution, making it essential in medical research, sports science, and prosthetics.

The device captures real-time pressure applied to its surface, with each sensing element recording the exerted force. This data is processed and visualized through specialized software, providing detailed insights into pressure distribution changes over time.

During the gait cycle, at the moment the foot contacts the ground, forces are applied to the ground, generating ground reaction forces (GRF) as a result. These forces represent the interaction between the foot and the ground and are closely related to the acceleration of the center of mass (COM). According to Newton's law, the equation describing the relationship between GRF and the variables involved is as follows:

$$GRF = M\,(g + a) \tag{1}$$

Here, *GRF* represents the ground reaction force, g is the acceleration due to gravity, a is the vertical acceleration of the center of mass (COM), and M represents the mass of the person's body. As the mass (M) and acceleration due to gravity (g) are constant values, any alteration in the value of *GRF* depend solely on variations in the vertical acceleration (a) [11].

3. Experimental work

3.1. The test of interface pressure

The distribution of interface stresses between the residual limb and the prosthetic socket of a transtibial amputee is regarded as a direct indicator of the socket's fit and comfort. Consequently, researchers have shown considerable interest in quantifying these interface stresses to assess the potential damage the socket may cause to the tissues of the residual limb [14]. The sensor of F-Socket was utilized to the pressure measurement between different zones of the limb. During the stance phase, the sensor was connected and its response was measured, providing information about the pressure exerted. The F-Socket sensor was interfaced with recording equipment and a computer to facilitate data collection and analysis. The pressure measurements were obtained from different regions of the leg, specifically from four locations: front, back, left, and right. The positions of the F-Socket sensor for measuring pressures are illustrated in Fig. 3. The case study data for this work are presented in Tables 1. This test procedure was conducted repeatedly for each of the three types of feet: SACH, single-axis, and multi-axis, Fig. 4 respectively.

The device records both minimum and maximum magnitude of pressure and tracks changes in these values over time. It captures the highest pressure value achieved during the measurement period [12].

Table 1. Case study data.

Gender	Male
Age	28
weight	71 kg
Length	180 cm
Side amputation	Left leg
Type of amputation	Below knee
The length of amputation	18 cm

Fig. 3 Pressure sensor position.

Fig. 4 SACH, single-axis, and multi-axis respectively.

3.2. *The ground reaction force (GRF)*

The Ground Reaction Force (GRF) is the primary force influencing the body during walking, acting in a vertical direction [13]. These vertical forces are generated and measured while the patient walks on a force plate. The GRF results from the biomechanical interactions that occur during stance and gait. Figure 5 shows the force plate used to measure these forces in this test.

In this study, the patient with a below-knee amputation in the left leg subjected to this test three separate time while wearing three different types of prosthetic feet: SACH, single-axis, and multi-axis. The force plate was using in this test, a device with sensors to measure GRF and center pressure.

This experiment was managed at AL-Nahrain University/ Biomedical Engineering Department.

4. Result and discussion

4.1. *Gait cycle test results*

The results from the ground reaction force (GRF) test are shown in the figures and tables below. Figures 6, 7, and 8, created using Walkway software, display GRF curves with two peaks: the first peak during right foot contact and the second during left (prosthetic) foot contact. Figures 9, 10, and 11 illustrate the forces over time for both the left and right feet. The minimum GRF recorded was 663.116 N for the SACH foot, 674.182 N for the single-axis foot, and a maximum of 703.024 N for the multi-axis foot. These GRF results were used to estimate the forces experienced by the feet.

Fig. 5 GRF tests.

The step table illustrated in Table 2 is for a man with below-knee prosthesis in his left leg while wearing three different types of prosthetic feet separately: SACH, single-axis, and multi-axis. The patient's weight is 71 kg and height is 180 cm, and the healthy leg (right leg) was used as reference to compare the results. The results that illustrated in the Table 2 show that the percentage difference between the affected leg and the healthy leg is close in both the single-axis and multi-axis feet, which mean that they perform better than the SACH foot.

Additionally, the percentage differences between the single-axis and multi-axis feet are also close to each other. Table 3 provides the gait cycle parameters, comparing the healthy right leg with the affected left leg. The results demonstrate that all types of prosthetic feet yield acceptable results in terms of the gait cycle parameters. The discrepancies in Table 3 between the single-axis and multi-axis feet compared to the SACH foot suggest that the design and functionality of the single-axis and multi-axis feet have a more substantial impact on gait cycle parameters compared to the SACH foot. These differences may be attributed to the increased flexibility, improved shock absorption, and enhanced biomechanical alignment provided by the single-axis and multi-axis feet. Additionally, the large differences observed in the gait cycle parameters may have implications for the user's overall gait quality and efficiency. For instance, a longer step length and stride length can contribute to a more natural walking pattern, while an appropriate cadence is crucial for maintaining a balanced and efficient gait.

Table 4 presents the maximum force measurements, comparing the healthy right leg with the affected left leg. The results indicate that the single-axis foot is the closest to the healthy foot in terms of force measurements.

The results presented in the figures and tables indicate significant findings regarding the performance and mechanics of each foot type during gait analysis. The ground reaction force GRF curves revealed two peaks: the first during right foot contact and the second during left (prosthetic) foot contact, highlighting the dynamic loading of the prosthetic. The SACH foot recorded the lowest minimum GRF value 663.116 N, while the multi-axis foot had the highest maximum GRF 703.024 N, suggesting better energy absorption and stability for the multi-axis design.

Pressure measurements showed variations in load distribution between the prosthetic and healthy foot, crucial for assessing prosthetic effectiveness. Comparative analysis in Table 4 indicated the multi-axis foot exerted the highest lift force 585.85 N, while gait analysis Tables 2 and 3 demonstrated that the single-axis foot had a slightly higher cadence and velocity than the SACH foot. Finally, stance and step dynamics revealed that the multi-axis foot closely mimicked natural gait patterns, suggesting it offers enhanced performance characteristics that could improve user mobility and quality of life.

Table 2. The step stride table.

Step-Stride Table	Sach foot			Single axis			Multi axis		
	Left (Infected)	Right (Healthy)	Percentage of Difference %	Left (Infected)	Right (Healthy)	Percentage of Difference %	Left (Infected)	Right (Healthy)	Percentage of Difference %
Step time (sec)	0.8	0.68	-17	0.72	0.64	-12	0.73	0.66	-10
Step length (cm)	42.5	37.7	-12	40.2	41.2	2	41.6	41.1	-1
Step velocity (cm/sec)	53.1	55.7	4	55.9	64.5	13	57	62.1	8
Step width (cm)	7	7.1	1	10.2	10	-3	9.4	8.9	-5

Table 3. Gait cycle test result.

Gait Cycle Table	Sach foot			Single axis			Multi axis		
	Left	Right	Difference	Left	Right	Difference	Left	Right	Difference
Stance Time	0.92	0.91	-0.01	0.88	0.84	-0.04	0.92	0.88	-0.03
Initial Double Support Time	0.15	0.25	0.1	0.15	0.24	0.09	0.15	0.26	0.1
Terminal Double Support Time	0.25	0.15	-0.1	0.24	0.15	-0.09	0.26	0.15	-0.1
Total Double Support Time	0.39	0.39	0	0.39	0.39	0	0.41	0.41	0
Heel Contact Time	0.79	0.62	-0.18	0.77	0.69	-0.08	0.81	0.5	-0.31
Foot Flat Time	0.37	0.1	-0.27	0.5	0.23	-0.27	0.46	0.08	-0.38
Midstance Time	0.76	0.62	-0.14	0.72	0.53	-0.19	0.74	0.62	-0.12

Table 4. Maximum force (N).

Type of foot	Left foot	Right foot	different
Sach foot	552.6	463.82	-19
Single axis	561.82	523.46	-7
Multi axis	585.85	479.12	-22

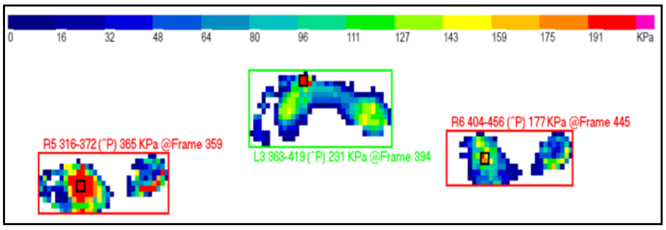

Fig. 6 Pressure measurement for left and right foot in SACH foot.

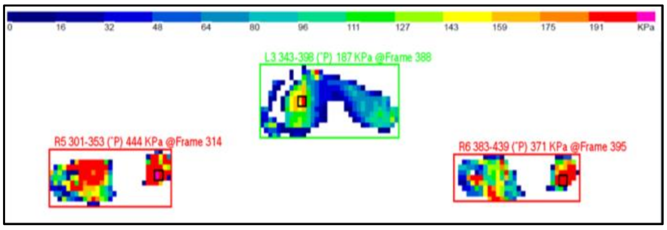

Fig. 7 Pressure measurement for left and right foot in single axis foot.

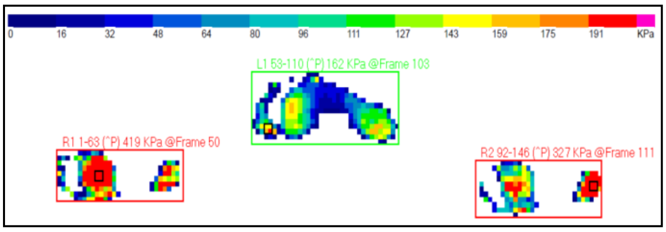

Fig. 8 pressure measurement for left and right foot in multi axis foot.

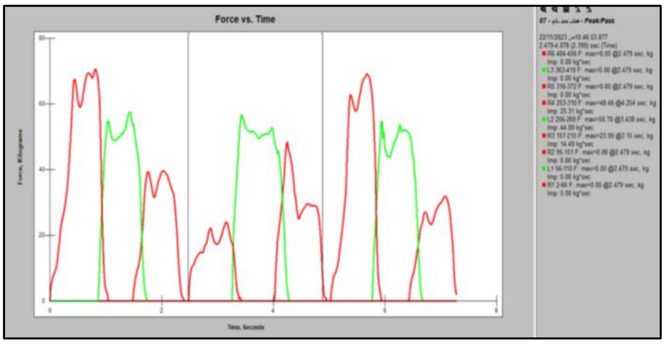

Fig. 9 force with time for left and right foot in SACH foot.

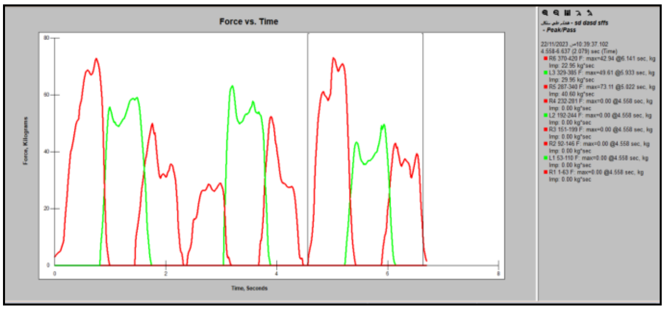

Fig. 10 force with time for left and right foot in single axis foot.

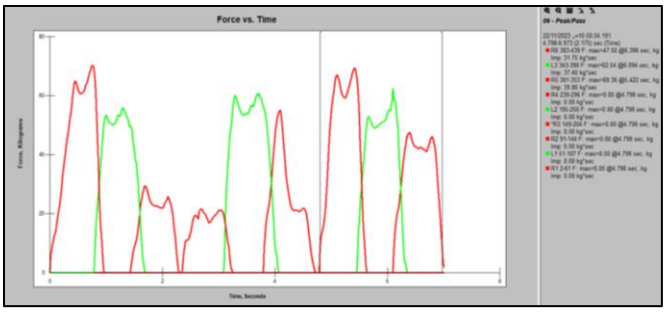

Fig. 11 force with time for left and right foot in multi axis foot.

4.2. *Interface pressure test result*

The F-socket test was conducted to determine the maximum concentrated pressure on the socket. During the test, sensors were strategically placed in four locations: front, back, left, and right. Notably, the left side of the socket exhibited the highest-pressure readings. The test was performed while the patient walked on the floor, and the results were recorded accordingly.

Furthermore, separate figures were presented to depict the pressure versus percentage data curve for each type of prosthetic foot. Figures 12, 13, and 14 specifically showcase these curves. The recorded peak pressure for the SACH foot was 33 psi (227.53 kPa), for the single-axis foot it was 40 psi (275.79 kPa), and for the multi-axis foot it was 35 psi (241.3 kPa).

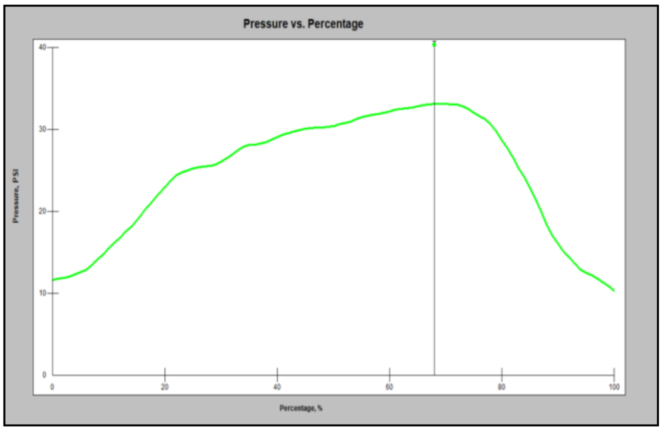

Fig. 12 the pressure vs. percentage for SACH foot.

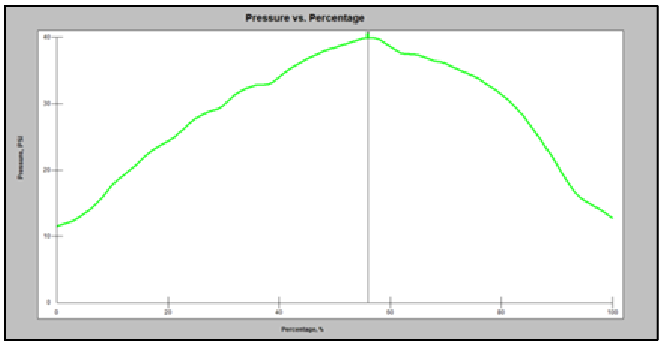

Fig. 13 the pressure vs. percentage for single axis foot.

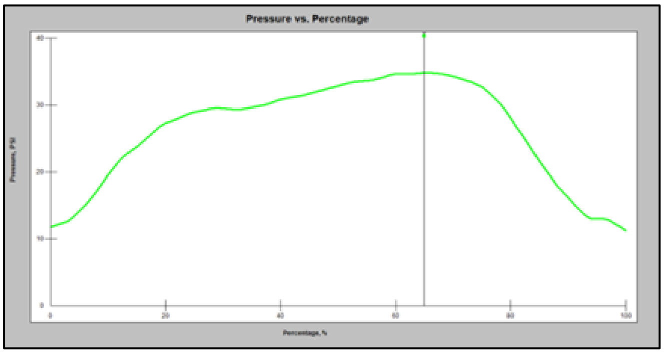

Fig. 14 the pressure vs. percentage for multi axis foot.

The comparison of peak pressure recorded for the three types of prosthetic feet revealed the following: the SACH foot exhibits moderate pressure distribution, suggesting decent comfort. In contrast, the single-axis foot shows the highest peak pressure, indicating a potential for discomfort and increased risk of skin issues. The multi-axis foot demonstrates slightly better pressure distribution than the single-axis foot, striking a balance between performance and comfort.

While the SACH foot provides stability, its lack of adaptive characteristics may limit performance on varied terrains. The single-axis foot offers a more natural gait but concentrates loads more, as reflected in its highest peak pressure. On the other hand, the multi-axis foot is designed to adapt to different surfaces, providing superior shock absorption and load distribution, enhancing the user's walking experience.

Overall, the multi-axis foot stands out as the best option among the three due to its effective pressure distribution, dynamic performance, and user comfort, making it well-suited for an active lifestyle.

5. Conclusions

This study conducted a biomechanical analysis of three types of prosthetic feet SACH, single-axis, and multi-axis focusing on their performance during daily activities for below-knee amputees. The findings indicate that the multi-axis foot offers superior pressure distribution, dynamic performance, and enhanced user comfort compared to the other types. While the SACH foot provides stability, it lacks adaptability to varied terrains. The single-axis foot, although it offers a more natural gait, tends to concentrate loads, leading to higher peak pressures and potential discomfort.

Overall, the multi-axis foot stands out as the optimal choice for enhancing mobility and quality of life for users, making it well-suited for active lifestyles. Future research should continue to explore advancements in prosthetic technology to further improve the user experience and address the specific needs of amputees.

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