A Study of the Effect of the Difference in Energy Stored in Two Prosthetic Feet Made of Carbon Fiber Amputated Below the Knee on the Efficiency of Walking

Noor B. Mohammed[1], Yassr Y. Kahtan [2*]

Authors affiliations:
1) Department of Prosthetics and Orthotics Engineering, Al-Nahrain University, Baghdad, Iraq.
madehope1998@gmail.com

2*) Department of Prosthetics and Orthotics Engineering, Al-Nahrain University, Baghdad, Iraq.
yasir.yaarb@nahrainuniv.edu.iq

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Abstract

ESAR feet are prosthetic feet with carbon fiber parts that store mechanical energy while standing and release it during propulsion. It is believed to reduce the metabolic energy needed for walking, and to promote the economy of walking. However, there is little scientific evidence to support this claim. This study aimed to compare the energy storage properties of two prosthetic feet made of carbon fiber using the P-Walk, G-Walk, and Podium devices developed for gait analysis, which is a systematic examination of human movement, enabling phasing, estimation of musculoskeletal performance, and determination of kinematic and motor parameters. The amount of energy was calculated for each of the feet using the load deflection test, and the results showed that the new artificial foot with an energy of 6.186 joules showed a great improvement in the results of the tests compared to the old artificial foot with an energy of 3.403 joules. The Podium device tests showed a significant improvement in walking patterns and pressure distribution after using a new foot. The pressure distribution became almost equal on both sides, and the angular deviation of COP decreased from -7 to 1.3 degrees. Ground reaction force vector tilt results also improved, with a body angle of 0 degrees and inclination varying slightly depending on the tibiofemoral angle for males. P-Walk results reveal left-sided static test pressure distribution, exposing amputees to osteoarthritis risk and revealing lack of confidence in prosthetic foot. After use the new prosthetic foot, amputees press more on right foot, indicating balance restoration. The G-Walk device shows the effectiveness of both healthy left and prosthetic foot when walking on an amputated right leg when use the new prosthetic foot. The amputated side's performance is similar to a healthy limb, with minimal difference and within normal limits. Walking cadence and speed values are within normal ranges, while stride length and step length are outside normal ranges for both sides. Obliquity results show a small difference in pelvic angles due to weak pelvic muscles, but these are close to standard values for prosthetic foot use. The amputee's opinions about the evaluation of the new prosthetic foot were good when using the T-score by 61.0 with a rate of 86.4%. It was a significant improvement compared to the old foot with an evaluation of 53.6 by 63.9%.

Keywords: Prosthetic foot, Energy storing, Podium, G-Walk, P-Walk.

دراسة تأثير خاصية تخزين الطاقة للقدم الاصطناعية للبتر تحت الركبة على كفاءة المشي

نور باسم محمد، ياسر يعرب قحطان

الخلاصة:

أقدام **ESAR** هي أقدام صناعية بأجزاء من ألياف الكربون تخزن الطاقة الميكانيكية أثناء الوقوف وتحررها أثناء الدفع. يُعتقد أنها تقلل من الطاقة الأيضية اللازمة للمشي، وتعزز اقتصاد المشي. ومع ذلك، هناك القليل من الأدلة العلمية لدعم هذا الادعاء. هدفت هذه الدراسة إلى مقارنة خواص تخزين الطاقة لقدمين صناعيتين مصنوعتين من ألياف الكربون باستخدام أجهزة **P-Walk** و**G-Walk** و **Podium**المطورة لتحليل المشي، ويعتبرن فحص منهجي لحركة الإنسان، وتمكين المراحل، وتقدير الأداء العضلي الهيكلي، وتحديد المعلمات الحركية والحركية. تم حساب كمية الطاقة لكلا القدمين باستخدام اختبار انحراف الحمل، وأظهرت النتائج أن القدم الاصطناعية الجديدة بطاقة ٦,١٨٦ جول أظهرت تحسنًا كبيرًا في نتائج الاختبارات مقارنة بالقدم الصناعية القديمة بطاقة ٣,٤٠٣ جول، وأظهرت اختبارات جهاز **PODIUM** تحسنًا كبيرًا في أنماط المشي وتوزيع الضغط بعد استخدام قدم جديدة. أصبح توزيع الضغط متساويًا تقريبًا على كلا الجانبين، وانخفض الانحراف الزاوي لـ **COP** من -٧ إلى ١,٣ درجة. تحسنت أيضًا نتائج إمالة ناقل قوة رد الفعل الأرضي، بزاوية جسم تبلغ ٠ درجة وميل يختلف قليلاً اعتمادًا على زاوية الفخذ الظنبوبي للذكور. تكشف نتائج **P-Walk** عن توزيع ضغط الاختبار الثابت على الجانب الأيسر عند استخدام القدم الاصطناعية القديمة، مما يعرض مبتوري الأطراف لخطر الإصابة بهشاشة العظام ويكشف عن عدم الثقة في القدم الاصطناعية. بعد استخدام القدم الجديدة يضغط مبتورو الأطراف أكثر على القدم اليمنى، مما يشير إلى استعادة التوازن. يُظهر جهاز **G-Walk** فعالية كل من القدم اليسرى والاصطناعية السليمة عند المشي على الساق اليمنى المبتورة باستخدام القدم الاصطناعية الجديدة. أداء الجانب المبتور مشابه لطرف سليم، مع حد أدنى من الاختلاف وضمن الحدود الطبيعية. تقع قيم سرعة وإيقاع المشي ضمن النطاقات العادية، بينما يقع طول الخطوة وطول الخطوة خارج النطاق الطبيعي لكلا الجانبين. تظهر نتائج الانحراف اختلافًا بسيطًا في زوايا الحوض بسبب ضعف عضلات الحوض، لكنها قريبة من القيم القياسية لاستخدام القدم الاصطناعية، وكانت آراء مبتوري الأطراف حول تقييم القدم الاصطناعية الجديدة جيدة عند استخدام **T-Score** بنسبة ٦١,٠ بمعدل ٨٦,٤٪.كان تحسنا ملحوظا مقارنة بالقدم القديمة بتقييم بلغ ٥٣,٦ بنسبة ٦٣,٩٪.

1. Introduction

Energy storing and return prosthesis (ESAR) feet have been available for many years. These artificial feet feature carbon fiber parts or other materials that act like springs, storing mechanical energy during stance and releasing it during push-off [1]. Long assumed to reduce the amount of metabolic energy needed for walking, this characteristic enhances walking economy. However, there is very little scientific evidence to back up this claim [2]. When compared to standard rigid feet, biomechanical studies have shown that using ESAR feet resulted in greater mechanical energy storage during early stance and a considerable increase in positive power during push-off [3]. Additionally, studies have demonstrated that the reduced push-off power experienced when walking on ESAR feet leads to an increase in external mechanical work during prosthetic walking [4]. However, these enhancements in mechanical energy transfers during walking do not necessarily have a positive impact on metabolic energy expenditure and gait economy. The positive effects of greater mechanical ankle push-off power have been hypothesized to be counteracted by increased muscle activity required for body support or for controlling power transmission across the remaining joints in the prosthetic leg [5]. The majority of patients who utilize lower limb prostheses continue to favor ESAR feet despite the apparent absence of improved walking economy. This suggests that there may be more practical benefits in addition to financial gains. It has been demonstrated in the past that ESAR feet reduce mechanical stress, potentially preventing overload injuries in natural or prosthetic legs. The greater ankle push-off force with an ESAR foot, on the other hand, may improve gait stability and symmetry, according to recent research on the gait patterns of individuals who have had lower limb amputations [6]. The aim of this study is to study the effect of increasing the energy storage property of the prosthetic feet of the amputee below the knee on the walking cycle and its efficiency. Two different artificial feet were compared in the energy storage property. The purpose was to prove that the energy-storing feet have a significant impact on the human walking cycle. The comparison was made using upgraded P-Walk, G-Walk and Podium devices. The systematic examination of human locomotion is called gait analysis. This type of analysis includes the measurement, description, and evaluation of the factors that constitute human locomotion [٧]. Gait analysis enables the identification of the gait phase, the quantification of musculoskeletal functioning, and the determination of the kinematic and kinetic parameters of human gait events, all of which are necessary for spotting the emergence of disorders that affect motor behavior [8]. Thus, gait analysis has been applied to sports, therapy, and medical diagnosis [9].

2. Experimental Work

The aspect of this study includes testing a Velocity foot made of carbon fiber for College Park Company once (an old prosthetic) and testing the foot that was manufactured in this study using twill woven 2X2 carbon fiber and Ottobock (617H55) Orthocryle C resin (methyl methacrylate) (a new prosthetic) to evaluate the effect of the prosthetic foot on walking efficiency, as shown in Figure (1).

Figure (1): The carbon fiber prosthetic foot.

2.1 Loading-deflection test

In order to perform the test, a vertical compression load is applied on the top of the adapter and fox the forefoot and the heel (static). The load is gradually increased from (0 N) to (960 N), which is equal to (1.2) of the body weight(80kg) that the shank expressed when walking [10]. The test was carried out by the Al-Nahrain University's Mechanical Engineering Department's testometric machine laboratory, as shown in Figure (2). Equation (1) is used to calculate the energy stored in the prosthetic foot. When making a curve fitting of the curve obtained from the test, it accounts for the stiffness k, which represents the slope value at x, as well as the maximum deformation that occurs in the foot when forces are applied by x [11].

$$U = 1/2k \times x^2 \quad \text{.....(1)}$$

(a) (b)

Figure (2): Loading-deflection test for the a) new prosthetic foot, b) old prosthetic foot.

2.2 Podium Test

A medical system called Podium employs augmented reality techniques to offer clinical and/or sports evaluations according to certain motor tasks carried out by diseased and sports subjects. PODIUM is a technology that uses two digital platforms and two video cameras to offer objective data on the ground response force, which is otherwise hard to measure with the human eye. PODIUM's meticulous construction ensures the prestige of the medical or athletic facility where it is housed and quickens the evaluation and rehabilitation process by assisting the therapist or personal trainer in performing exercises meant to restore impaired functions or boost performance. The technique is specifically recommended for the motor evaluation of pathological or athletic individuals of any age with the goal of assessing their performance or enhancing their motor ability [12]. The test was performed by selecting the protocol to be used: the static protocol (standing for 30 seconds) and the dynamic protocol (walking in place for 60 seconds) were used. Three BTS VIXTA50 cameras photograph and analyze the movement with a platform consisting of a large network of sensors. Testing was done at the Biotech Center for rehab once using his old prosthesis foot and once using the carbon fiber prosthetic foot that was manufactured in this study, as shown in Figure (3).

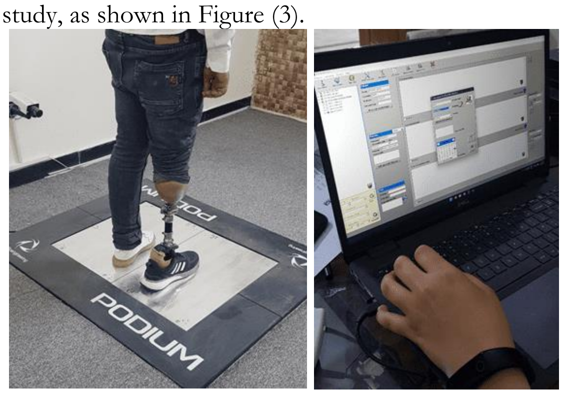


Figure (3): The amputee stands on the platform to begin testing protocols which include standing and walking in place.

2.3 P-Walk Test

The patient is tested to measure the strength of the ground reaction using the p-walk platform at the Biotech Center. The results are extracted using standing protocol and the test performed once using his old prosthesis foot and once using the carbon fiber prosthetic foot that was manufactured in this study, and the steps of the foot are recorded, as shown in Figure (4).

Figure (4): The amputee stands on the platform to begin testing protocols which include standing and walking in place.

2.4 G-Walk Test

For a quick and accurate evaluation of the parameters for walking, running, and leaping, G-WALK is the best option. It comprises of the inertial sensor G-SENSOR, the G-Studio software, and a collection of protocols for the analysis of particular movements. The Sensor includes a Tri-axial Accelerometer with Multiple Sensitivity, a Tri-axial Magnetometer, and a Tri-axial Gyroscope with Multiple Sensitivity. The sensor collects the data and sends it to the PC via Bluetooth so that it may be processed and the report is generated automatically. The individual will start the test by standing motionless in an orthostatic position. Until the stabilization phase is over, this position will be held for a few seconds. The patient should move at its natural pace along a completely straight path once the operator gives the signal to begin so that at least five full gait cycles (more than 7 meters) can be executed before changing directions, as shown in Figure (5). It is required to place the sensor on the test subject in the manner depicted in order to get accurate and reproducible data throughout the execution of the tests. The sensor was positioned for the Walk+ protocol below the lumbosacral channel, which corresponds to the S1-S2 vertebrae, as shown in the following Figure (6). The sensor was centered on the predetermined location of the column within the belt, flat side towards the rear of the pocket. The belt was securely tightened in order to make it as supportive as possible for the body and prevent it from moving while the test was being conducted.

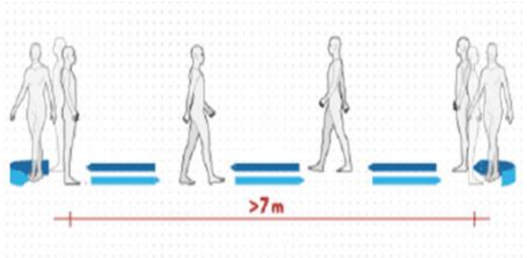


Figure (5): The path of walking [13].

Figure (6): The amputee wears the G-Walk sensor and start the test.

2.5 Prosthesis Evaluation Questionnaire

Using PLUS-MTM instruments, the amputee's perspective is used to assess his experiences both before and after using the prosthetic foot. The questions gauge the respondents' perceptions of their ability to perform particular tasks that call for the use of both lower limbs. The final evaluation depends on the arithmetic results specified in the questionnaire by collecting and recording the opinions of the amputee, and each question contains a set of questions, and each question has certain numerical values. After collecting them, their values are searched for in the T-sore table out of 100 [14].

3. Result and Discussion

3.1 Load Deflection Result

Results revealed that when a force of 960 Newtons was applied, the manufactured foot in this study distorted by 16.5 mm whereas the old foot deformed by 6.7 mm, as illustrated in Figure (7). According to the test, the created foot had energy stored in it of 6.186 joules compared to the previous foot's 3.403 joules.

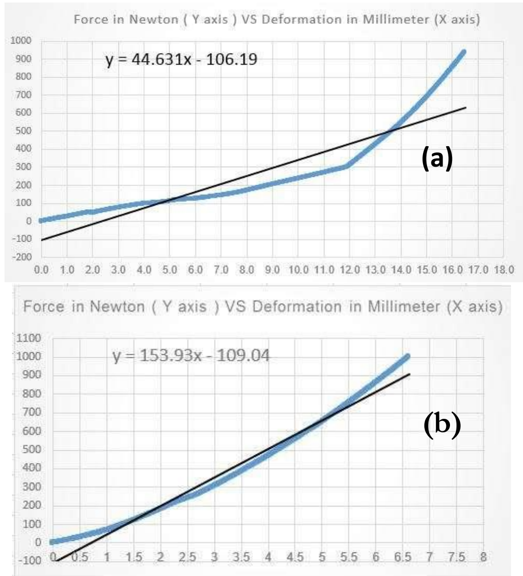


Figure (7): Force deformation curve for a) the new prosthetic foot was manufactured in this study, b) the old prosthetic foot.

3.2 Podium Result

All tests were performed on a below-the-knee amputee to calculate the statistical results with specialized devices. The platform shows the temporal parameters of the protocol's outcomes for walking in place. The result of the cycle duration shows the amputated right leg increased from 0.8 to 1.1 seconds when the study's custom-made prosthetic foot was used. Additionally, the left leg's score dropped from 1.75 to 1.3 seconds, and both legs' values fell within acceptable ranges. It demonstrated an improvement in the stance phase period, becoming 59.5% to the right and 61.9% to the left, and the swing phase became 40.5% to the right and 38.1% to the left. The results are normal, according to earlier studies [15,16], and it demonstrated single support and first double support results that were within the normal range, as shown in Figure (8).

The pressure distribution after using the manufactured foot became equal between the amputated right foot (which was represented in green) and the healthy left foot (which was represented in red), where each of them falls on 50% of the weight of the amputee, and the pressure distribution sensors in the podium device show us the pressure distribution accurately because it contains a large network of sensors. As shown in Figure (9) and (10), the results of the static test while standing on the pallet reveal that when using the old limb foot, the pressure distribution on the left foot (red) was greater than the right foot (green), and after using the manufactured foot, the pressure distribution between the right and left foot was roughly equal [17].

TEMPORAL PARAMETERS	RIGHT	LEFT
Cycle Duration (s):	0.80	1.75
Stance (%):	53.7	70.3
Swing (%):	46.3	29.7
Single supp (%):	33.8	49.2
1 st Double supp (%):	8.3	13.1

(a)

TEMPORAL PARAMETERS	RIGHT	LEFT
Cycle Duration (s):	1.1	1.3
Stance (%):	59.5	61.9
Swing (%):	40.5	38.1
Single supp (%):	39.3	41.97
1 st Double supp (%):	9.63	11.13

(b)

Figure (8): The result of walk-in place protocol of the a) old prosthetic foot, b) new prosthetic foot.

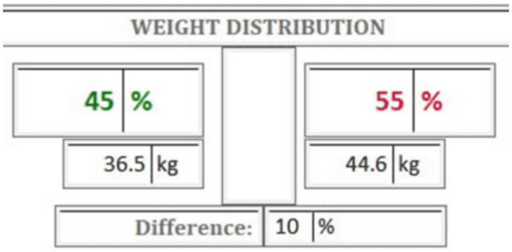


Figure (9): The weight distribution of the old prosthetic foot (The right amputated side is represented in green and the intact side in green).

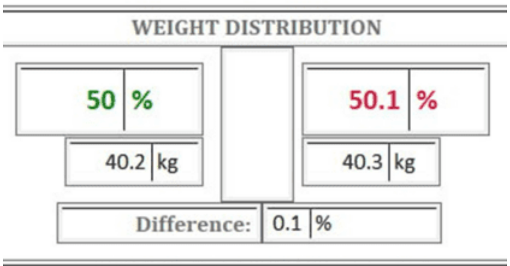
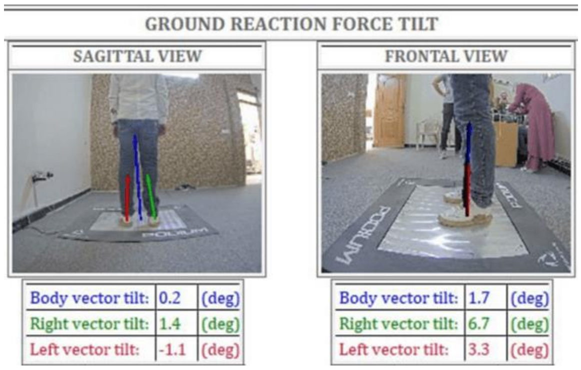


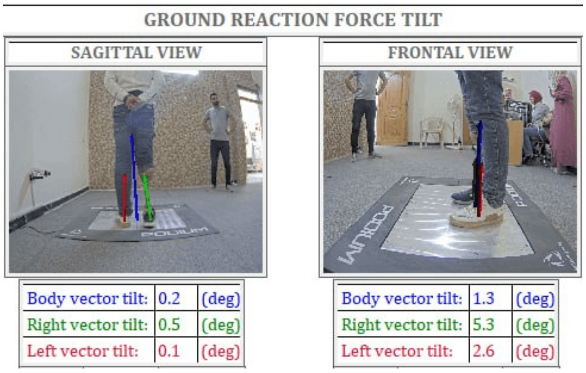
Figure (10): The weight distribution of the new prosthetic foot.

The static protocol demonstrates that the ground reaction force vector tilt results have improved from the ideal values. In the sagittal view, the body vector tilt appears to be about 0.2 degrees for both the old and new prosthetic foot, while the right vector tilt has improved from 1.4 degrees to 0.5 degrees and the left vector tilt has improved from -1.1 to 0.1%. In frontal view, the left vector tilt shifts from 3.3 to 2. 6 degrees, the right vector tilt shifts from 6.7 to 5. 3 degrees, and the body vector tilt improves somewhat from 1.7 to 1. 3 degrees. The evaluation of the results is understood to mean that the body's angle is 0 degrees. The vector gets closer to the healthy body whenever it near zero. Regarding the right and left tilt vectors, the inclination varies slightly depending on the tibiofemoral angle for males, ranging from 3 to 6 degrees [18,19]. However, the program interprets the normal value of degrees as the zero axis, so if the inclination vector's value is (3-6), it is read as zero, or the ideal value. The value is excellent if it is as near to zero as possible. In a sagittal view, a positive value for the right and left body vectors indicates a force that is directed forward, whereas a negative value indicates a force that is directed backward. In frontal view, a positive body vector value indicates a force that is left-oriented, whereas a negative value indicates the opposite. According to Figure (11) and Table1, it refers to right-directed force, and the positive values of the right and left vectors indicate laterally oriented force while the negative value denotes medially oriented force.

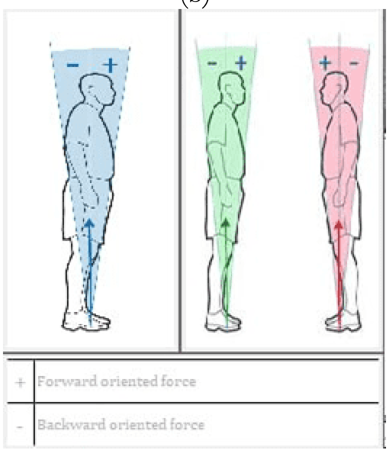
The center of pressure (COP) in static analysis reveals that the distance between the feet has increased from 236.5 mm to 261.9 mm (the usual distance between the feet is around 30–80 mm), and that the angular deviation has decreased from -7 to 1.3 degree, as shown in Figures (12) and (13).



(a)



(b)



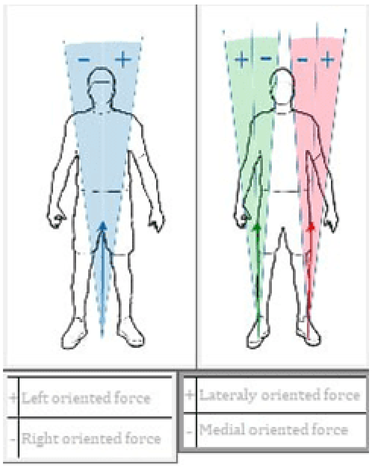


Figure (11): The result of walk-in place protocol of the a) old prosthetic foot, b) new prosthetic foot.

Table (1): The ground reaction force tilt.

Ground reaction force	Body vector tilt (deg)	Right vector tilt (deg)	Left vector tilt (deg)
Sagittal view for old prosthetic foot	0.2	1.4	-1.1
Frontal view for old prosthetic foot	1.7	6.7	3.3
Sagittal view for old prosthetic foot	0.2	0.5	0.1
Frontal view for old prosthetic foot	1.3	5.3	2.6

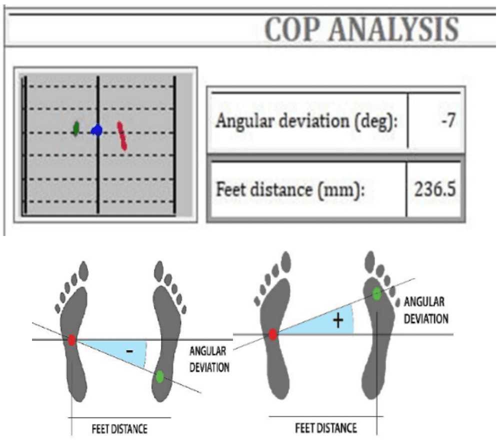


Figure (12): The center of pressure of old prosthetic foot.

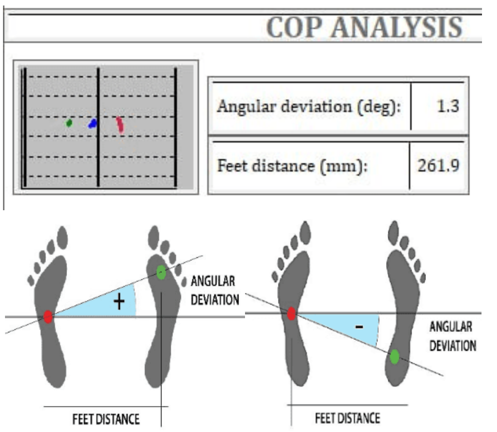


Figure (13): The center of pressure of new prosthetic foot.

After using the new prosthetic foot, the oscillation ranges for the left foot decreased from 60.9mm to 35.7mm, the COP oscillation of the body also decreased from 59mm to 39.6mm, and the oscillation for the right foot decreased significantly from 137.6mm to 40.8mm, according to the center of pressure displacement for antero-posterior.

The average speed data likewise reflect an improvement, with the left foot's COP oscillation speed dropping from 10.5 m/s to 9.3 m/s, the body from 10.4 m/s to 9.1 m/s, and the right foot from 10.2 m/s to 8.7 m/s. As seen in Figure (14), a decrease in oscillation range and average speed denotes an improvement in bodily balance.

COP DISPLACEMENT:	ANTERO-POSTERIOR			MEDIO-LATERAL		
	LEFT	BODY	RIGHT	LEFT	BODY	RIGHT
Oscillation range (mm):	60.9	59	137.6	29.9	303.1	81.5
Average speed (mm/s):	10.5	10.4	10.2	7.3	11	16.2

(a)

COP DISPLACEMENT:	ANTERO-POSTERIOR			MEDIO-LATERAL		
	LEFT	BODY	RIGHT	LEFT	BODY	RIGHT
Oscillation range (mm):	35.7	39.6	40.8	7.1	8.1	8.3
Average speed (mm/s):	9.3	9.1	8.7	10.5	12.1	15.2

(b)

Figure (14): The center of pressure displacement of a) old prosthetic foot, b) new prosthetic foot.

3.3 P-Walk Result

The P-Walk results demonstrate that the pressure distribution in the static test is more on the left, sound side than on the amputated side, exposing the amputee to the risk of osteoarthritis in the knee on the sound side and also demonstrating the amputee's lack of confidence in the prosthetic foot [20]. The pressure distribution results in this study demonstrate that the amputee started to press more on the right foot after switching to the artificial foot, and this suggests a restoration of balance with time, as shown in Figures (15) and (16).

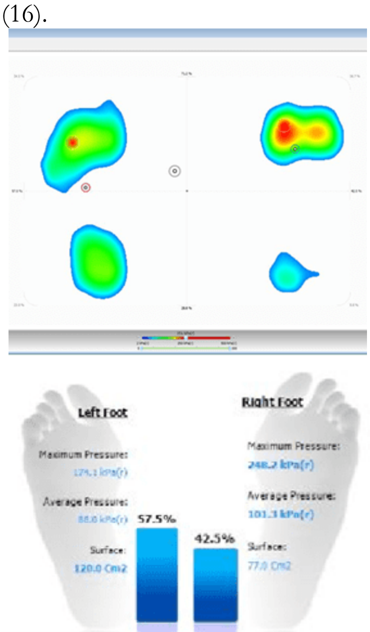


Figure (15): Static P-Walk test before use the prosthetic foot (the old prosthetic foot).

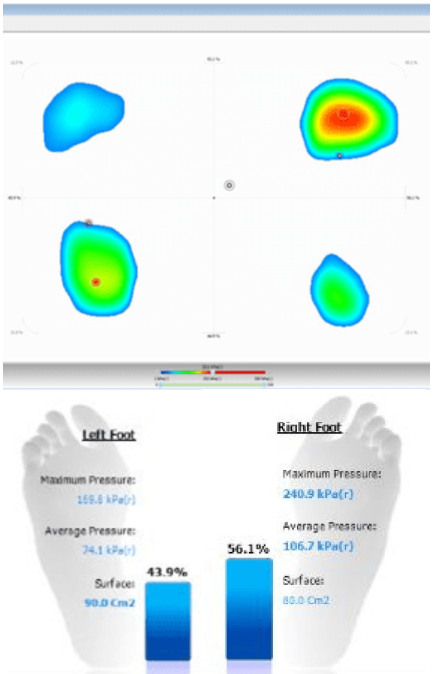


Figure (16): Static P-Walk test after use the prosthetic foot (the new prosthetic foot).

3.4 G-Walk Result

The outcomes demonstrate the effectiveness of the healthy left foot and the prosthetic carbon fiber foot when walking on the amputated right leg. As can be seen in Figure (17), the performance of the severed side is quite similar to that of the healthy limb, indicating that the difference is very slight. During walking, it was concluded that the gait cycle of the healthy left leg is within the normal limits, and that the right leg shows less results than the healthy one, but also results appear within the normal limits. The stance phase is about 58.03% while the normal limits range between (58.98±1.97) %, the swing phase is about 41.97% while the normal limits range between (40.03± 3.56) %, the first double support phase and the single support phase of the gait cycle are about (8.78±0.74) % and (38.90±2.04) %, sequentially, within normal limits (10.27±3.09) % and (38.87±2.57) %, sequentially, as shown in Table (2).

The results show that walking cadence and walking speed show results as follows: (113.40±8.73) step/min and (1,13±0.05) m/s, respectively, within the normal ranges, which appear as (118.8±7.80) step/min and (1.23±0.11) m/s, respectively. The stride length of the intact left leg is within the normal limits [21], and that the amputated right leg appears within the natural limits with the use of a carbon fiber prosthetic, where the values are (1.07 ± 0.03) m and the stander values are (1.12 ± 0.15) m, however the height of stride length and the step length showing values outside the normal range for both side and this is fairly normal for an amputee patient [22], as shown in the Table (3) and Table (4).

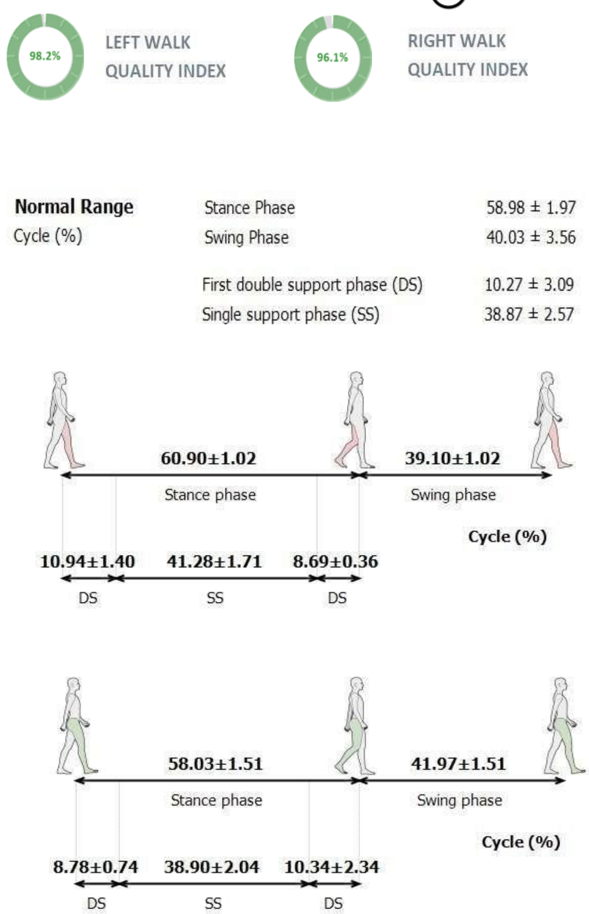


Figure (17): Result of gait cycle analysis

Table (2): The gait cycle analysis by walk+ protocol using G-Walk device.

Cycle (%)	The left side(normal side)	The right side (amputated side)	Normal range
Walk quality index	98.2	96.1	100
Stance phase	60.90±1.02	58.03±1.51	58.98±1.97
Swing phase	39.10±1.02	41.97±1.51	40.03±3.56
First double support phase	10.94±1.40	8.78±0.74	10.27±3.09
Single support phase	41.28±1.71	38.90±2.04	38.87±2.57

Table (3): The first spatio-temporal parameters.

Spatio-Temporal parameters	Value (Mean $\pm$ ***Std Dev***)	Normal Value (Mean $\pm$ ***Std Dev***)
Analysis duration (s)	27.9	
Cadence (steps/min)	113.40 ± 8.73	118.80 ± 7.80
Speed (m/s)	1.13 ± 0.05	1.23 ± 0.11

Jacobian gives the relationship between the joints velocities and the corresponding end effector linear and angular velocities. The end effector linear and angular velocities can be defined as:

$$\begin{bmatrix} v_e \\ \omega_e \end{bmatrix}_{(6x1)} = \begin{bmatrix} J_p \\ J_o \end{bmatrix}_{(6xn)} \begin{Bmatrix} \dot{q} \end{Bmatrix}_{(nx1)} \quad ...(1)$$

Where:

v_e : (3x1) matrix represents the end effector linear velocity in cartesian space.

ω_e : (3x1) matrix represents the end effector angular velocity in cartesian space.

J_p : (3xn) jacobian matrix relates the end effector linear velocity to joints velocities.

J_o : (3xn) jacobian matrix relates the end effector angular velocity to joints velocities.

The geometry i[th] column of jacobian matrix for revolute joint is: [13]

$$\begin{bmatrix} J_{p_i} \\ J_{o_i} \end{bmatrix} = \begin{bmatrix} z_{i-1} \times (p_e - p_{i-1}) \\ z_{i-1} \end{bmatrix} \quad ...(2)$$

Where:

z_{i-1} : unit vector in z-direction is given by third column of the rotation matrix ${}^{0}R_{i-1}$.

p_e : end effector position vector is given by the first three elements of fourth column of transformation matrix ${}^{0}T_e$.

p_{i-1} : is given by the first three elements of the fourth column of transformation matrix ${}^{i-1}T_i$.

Table (4): The second spatio-temporal parameters

Spatio-Temporal parameters	Left Value (Mean $\pm$ ***Std Dev***)	Right Value (Mean $\pm$ ***Std Dev***)	Normal Value (Mean $\pm$ ***Std Dev***)
Gait cycle duration (s)	1.06 ± 0.05	1.07 ± 0.03	1.12 ± 0.15
Stride length (m)	1.19 ± 0.03	1.21 ± 0.02	1.23 ± 0.07
% Stride length (% height)	65.88 ± 1.43	66.98 ± 1.01	84.70 ± 6.10
Step length (% str length)	47.59 ± 2.87	52.41 ± 1.60	50.00 ± 0.70
Elaborated steps	6	6	

In the sound limb, the first stage includes the double support phase, which begins at zero and lasts for about ten percent of the gait cycle. During this phase, there will be a deceleration as the other foot prepares to enter the swing phase, and stability training will also begin because the body has become dependent only on the sound limb. While in this stage we notice a slight change in deceleration in acceleration, and this occurs when the trunk is moved forward in stance phase of the sound limb, the green dashed line that is found in the Figure (18) represents the point at which the amputated limb will begin to swing and the beginning of the stage of single support. The heel strike location of the amputated limb is indicated by the solid green line. Following this line, the sound limb experiences a sharp reduction in acceleration as it enters the double support phase once more, however this time the support will be more pronounced on the severed foot. The swing phase for the sound limb starts when the load is totally severed from it at the dashed red line.

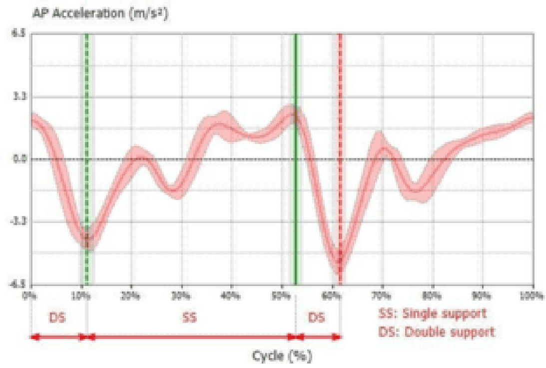


Figure (18): The acceleration of the old prosthetic foot.

In the amputated limb, the first stage includes the double support phase, which starts from the zero point to about ten percent of the gait cycle, in which there will be also a deceleration but it is more fast than the sound limb deceleration with a much lower value as a result of the high shock absorb of the carbon fiber foot which is much better for the patient comfort , after that the red dashed line indicates the toe off of the sound limb so the body has become based on the amputated limb only , just like the sound limb in this stage we notice a slight change in deceleration in acceleration, and this occurs when the trunk is moved forward in stance phase of the amputated limb but the curve of the acceleration value is smoother and easy forward progression of the trunk. The heel strike location of the sound limb is indicated by the solid red line. After this point, the amputated limb experiences a sharp reduction in acceleration as it enters the double support phase once more, but this time with a new kind of support provided by the sound foot. At the green dashed line, where the load is totally removed from the amputated leg, the swing phase for that limb begins, as shown in Figure (19).

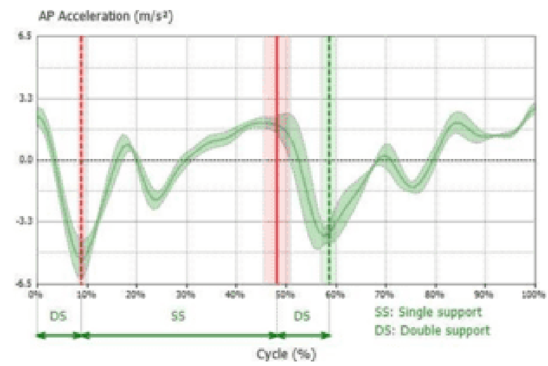


Figure (19): The acceleration of the new prosthetic foot.

The hip's anterior and posterior tilt angles show that the amputee is within the normal range (the green curve mean the amputated right side and the red curve mean the left side and both of them within the gray shadow region, which represents the normal range in the drawing). Any discrepancy in angles between the amputee's side and the intact side during the walking cycle falls within the acceptable tilting range, as shown in Figure (20).

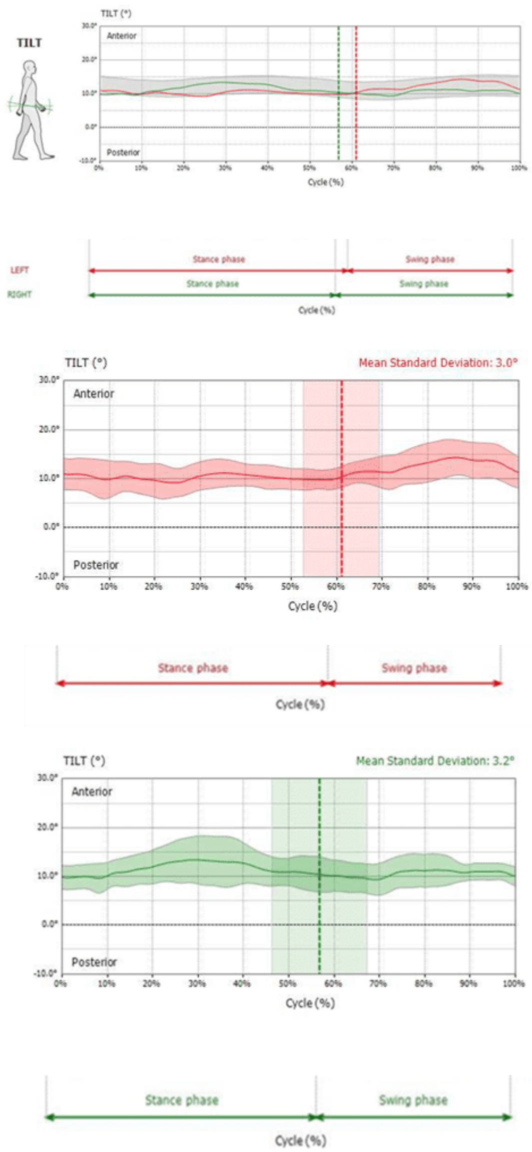


Figure (20): The tilt angel of pelvic when using the new prosthetic foot.

The obliquity result showed that there is a small difference between the right limb and the left limb pelvic angles, and this is because the patient used to walk diagonally because of little weakness of pelvic muscles (the green curve mean the right side and the red curve mean the left side). Despite this, the results are close to the standard values, as shown of Figure (21).

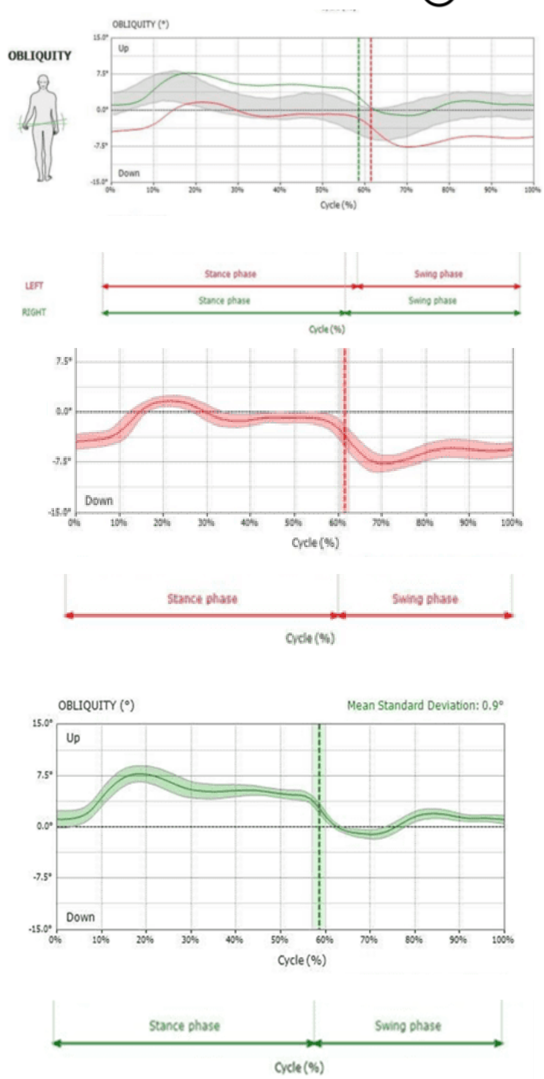


Figure (21): The obliquity angel of pelvic when using the new prosthetic foot.

The rotation angle results demonstrated that the patient did not experience any variation in the pelvic rotation angle during the walking cycle because the results on the right and left sides are very similar in shape and value to the standard values (the green curve mean the right side and the red curve mean the left side). as shown in Figure (22).

Figure (22). The rotation angel analysis for right and left leg .

4. Evaluation Questionnaire Result

The questions were answered by the amputee once when using the old prosthetic foot (O) and again when using the new prosthetic foot (N) as shown in the Table (5) [14]. The patient's scores are then summed up for each aspect separately. At the completion of the collection process, an option is made to T-score of the proceeds of collection for the old prosthetic foot once, and for the new prosthetic foot again:
For old prosthetic foot:

$$5+5+4+3+5+4+4+5+4+4+3+3 = 49$$

The T-Score is equal to 53.6 and the percentile equal to 63.9%.
For new prosthetic foot:

$$5+5+5+4+5+5+5+5+5+4+4+4 = 56$$

The T-Score is equal to 61.0 and the percentile equal 86.4%.

Table (5): Amputee answers for old prosthetic foot (O) and new prosthetic foot (N).

Question	**Without any difficulty [5]**	**With a little difficulty [4]**	**With some difficulty [3]**
1.Are you able to walk a short distance in your home?	N/O		
2.Are you able to step up and down curbs?	N/O		
3.Are you able to walk across a parking lot?	N	O	
4.Are you able to walk over gravel surfaces?		N	O
5.Are you able to move a chair from one room to another?	N/O		
6.Are you able to walk while carrying a shopping basket in one hand?	N	O	
7.Are you able to keep walking when people bump into you?	N	O	
8.Are you able to walk on an unlit street or sidewalk?	N/O		
9.Are you able to keep up with others when walking?	N	O	
10.Are you able to walk across a slippery floor?		N/O	
11.Are you able to walk down a steep gravel driveway?		N	O
12.Are you able to hike about 2 miles on uneven surfaces, including hills?		N	O

5. Conclusion

The aim of this paper is to study the effect of the energy conservation property of the prosthetic foot on the gait of the amputee and to compare two artificial feet with different energy storage and also to compare it with the healthy one. The results of the tests using the Podium device showed a significant improvement in the walking pattern and pressure distribution, as the weight was concentrated more on the healthy leg, but after using the new foot, the pressure distribution improved and became almost equal on both sides, and the angular deviation of COP has decreased from -7 to 1.3 degrees when using the new foot, which preserved energy by 6.186 joules compared to the old foot, which was 3.403 joules to conserve energy, and this indicates the significant improvement shown by amputees while walking when their feet are Capable of storing energy. The static protocol shows that ground reaction force vector tilt results have improved from ideal values. In the sagittal view, the body vector tilt is about 0.2 degrees, while the right vector tilt has improved from

1.4 degrees to 0.5 degrees and the left vector tilt from -1.1 to 0.1%. In the frontal view, the left vector tilt shifts from 3.3 to 2.6 degrees, while the right vector tilt shifts from 6.7 to 5.3 degrees. The evaluation indicates that the body's angle is 0 degrees, and the vector gets closer to the healthy body when nearing zero. The inclination varies slightly depending on the tibiofemoral angle for males, ranging from 3 to 6 degrees. The program interprets the normal value of degrees as the zero axis, so a positive value indicates a force directed forward, while a negative value indicates a force directed backward. Positive values indicate right-directed force, while negative values indicate laterally oriented force. The P-Walk results show that static test pressure distribution is more on the left, sound side, exposing amputees to osteoarthritis risk and revealing their lack of confidence in the prosthetic foot. After switching to the artificial foot, amputees began pressing more on the right foot, suggesting a restoration of balance over time. The G-Walk device demonstrates the effectiveness of both healthy left and prosthetic carbon fiber feet when walking on an amputated right leg. The severed side's performance is similar to that of a healthy limb, with minimal difference. The goal cycle of the healthy left leg is within normal limits, while the right leg shows less results than the healthy one but also appears within normal limits. The stance phase and swing phase are within normal limits, while the first double support phase and single support phase are within normal limits. The study reveals walking cadence and speed values of 113.40 ± 8.73 step/min and 1,13 ± 0.05 m/s, respectively, within normal ranges. The stride length of the intact left leg is within normal limits, while the amputated right leg is within normal limits with a carbon fiber prosthetic. However, the height of stride length and step length are outside the normal range for both sides, which is fairly normal for an amputee patient. The amputee's hip tilt angles indicate normal range, with the amputee right side and left side within the gray shadow region. Any discrepancy between the amputee's and intact side during walking falls within the acceptable tilting range. The obliquity results showed a small difference in pelvic angles between the right and left limbs due to the patient's diagonal walking due to weak pelvic muscles. However, these results are close to standard values for the obliquity of the angel of the pelvic when using a new prosthetic foot. The rotation angle results showed no variation in pelvic angle rotation during walking, as the right and left sides are similar in shape and value to the standard values. The patient's evaluation of the prosthetic foot using T-score 61 was 86.4%, which was a significant improvement compared to the old foot, with an evaluation of 53.6, or 63.9%. It's fascinating to think about the potential of this technology, because it will give doctors access to trustworthy, quick diagnostic tools to help them in their work.

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