[1] **Raad Sa'dy Abdulradi**

[2] **Mohsin Noori Hamzah**

[3] **Imad Abdul-Hussain Andul-Sahib**

A Review of the Materials' Characteristics and Prosthetic Foot Models

Abstract: - Products are created by prosthetic limb manufacturers to replace lost limbs and partially restore the abilities of amputees. Although the person's efficiency is improved, these prosthetic feet are not as versatile as the genuine foot. In particular, when it comes to prosthetic feet, choosing a prosthesis depends on how well it mimics the features of a human foot. Prosthetic feet are made to be flexible, long-lasting, corrosion-resistant, tensile strength, rust-resistant, shear-resistant, and cost-effective. The aforementioned factors depend on the characteristics of the material utilized, the layout of the feet, and the production process employed. When the composite is modified in terms of fiber selection, system, kind of combination, mass capacity, and prosthetic architecture, the efficiency of the foot changes. In this paper, a thorough review of the biomechanics, elements, and ideas of the artificial foot has been conducted.

Keywords: lower limb amputation, lower limb prosthesis, Prosthetic limbs, Feet, Biomechanics, Materials, Models.

I. INTRODUCTION

Prosthetics are man-made devices that serve the same purposes as a missing body part. Artificial limbs, often known as prosthetic limbs, are manufactured items that give amputees a replacement for their lost limb and partially restore their function. If lower limb prosthetic devices are to be functional, they must restore walking ability. [1]. Various artificial components, such as foot parts, prosthetic sockets, knee parts, hip joint applications, removable dental dentures, hand and finger pieces, and other biomechanical applications, have been manufactured in past years [2]. The prosthetic foot's longevity reflects the prosthesis' overall performance. Many prosthetic feet and legs have been created to meet the needs of amputees. Many research studies describe the efficacy and biomechanical features of trans prostheses and artificial feet and legs utilized, while few research studies discuss the efficiency and biomechanical features of trans prostheses and prosthetic feet and legs used. These gadgets are useful and mimic the normal biomechanics of the ankles. Recent research has revealed that an electromechanical passive device can replace the foot mechanics at lower speeds than previously thought, albeit this would necessitate a more robust active power source. At a normal walking pace, the stance phase of a typical ankle moment-angle curve shows a brief hysteresis loop, as shown by Hansen et al. The healthy ankle-foot configuration recommended by Takahashi and Stanhope has a work ratio of no more than 1.0 when walking normally. As a result, at slow to standard walking rates, an adjustable spring-damper system may be advantageous. Figure (1B) depicts the levels and categories of below-the-knee amputees. Figure 1A shows the four major elements of BK prostheses: socket, pylon, foot prostheses, and coupling [3-5].

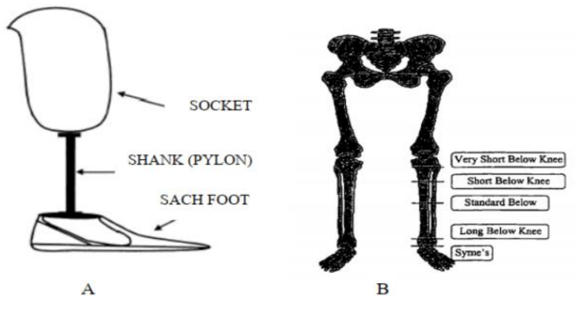

Fig. 1. A) Prosthetic bk constituent, B) Prosthetic limb levels [5].

II. PROSTHETIC FOOT BIOMECHANICS

Durability is among the most significant biomechanical characteristics of a Solid Ankle Cushion Heel (SACH) foot. Commonly manufactured feet would be put through rigorous yet controlled testing to expose how materials and design affect longevity and to find any flaws or errors. In order to assess how long a foot design would endure before failing, Daher [6] investigated nine different SACH foot versions using cyclic analysis. Replacement feet

[1]Mechanical Engineering Department, University of Technology, Baghdad, Iraq. me.19.21@grad.uotechnology.edu.iq
[2]Mechanical Engineering Department, University of Technology, Baghdad, Iraq. 20066@uotechnology.edu.iq
[3]Mechanical Engineering Department, University of Technology, Baghdad, Iraq. 20018@uotechnology.edu.iq

were loaded up to the equivalent of 100 kg (approximately 220 lb.) in 500,000 tests. He also discovered that changes in stiffness and distortion occur at a frequency of one per 5,000 cycles. R. Deval [7] evaluated the Seattle foot's load-deflection characteristics and the durability of thermoplastic and thermosetting with reinforcing material in prosthetic feet. Wevers and Duranc [8] assumed dynamic simulation on SACH artificial feet, however they loaded the complete trans-tibial prosthesis instead of simply the foot. Even with low wear and fewer than 100,000 cycles, the outcomes were on par with Daher's.

T Van Jaarsveld H. [9] investigated the hysteresis and rigidity of nine different types of prosthetic foot. He discovered that shoes have an impact on the hysteresis of the foot. When wearing athletic shoes, Hysteresis loss for all verified feet grows, but variances in hysteresis between the two feet disappear. S. Kabra and R. Narayanan [10] constructed a dynamic loading system that measures cyclic knee flexion to examine the prototype, including the artificial Jaipur ankle-foot, during long-term loading conditions, intending to evaluate these machines at the same time. Based on the findings of the 26 Jaipur foot, he discovered that the prosthesis foot has good efficiency and tremendous movement in three axes. This research by Toh H. [11] investigated the fatigue strength of four artificial feet. A straightforward fatigue measurement device was constructed, and different normal loads were put on the forefoot's heel for 500,000 cycles. The endurance of the Lambda and (SACH) feet was successfully studied using a basic fatigue device. The Lambda ankle displayed strong fatigue properties, according to the study.

The biomechanical features of the prosthetic foot have an impact on how it reacts after an amputation. Additionally, kinetics, kinematics, and energy restoration are the most investigated characteristics; a gait analysis is typically performed utilizing physical aspects to give this biomechanical investigation. However, models are rarely available for use in actual situations [12]. Therefore, in research, Arya A.P [13] looked into the differences and similarities of the prosthetic feet used in Jaipur, Seattle, and SACH. The study aimed to assess shock absorption and its effect on gait pattern. The research indicates that the Jaipur foot is more efficient and realistic in its simulation of the human foot than the Seattle foot and the SACH foot. When compared to feet from Jaipur and Seattle, the SACH foot scored better in terms of impact resistance. The heel region of prosthetic feet was studied by Glenn K., and he looked at the shoes' qualities. Klute et al. [14]. For the purpose of calculating and simulating the heel's ability to absorb impact shocks when walking, a pendulum was constructed to mechanically mimic the conditions occurred soon after the initial heel ground touch [14]. The study by Sam et al. [15] examined 11 varieties of prosthetic foot used in developing nations, zeroing in on their resonance frequencies and damping ratios. We analyzed the dynamic features that manifested themselves when the prosthesis oscillated with a mass analogous to that of the body. Functional rollover morphologies comparable to those of a typical SACH foot were observed in the vast majority of the prosthetic feet evaluated in this investigation. IOS 10328 was utilized to assess heel and toe flexibility characteristics at a rate of 5mm/min as part of Anne Schmitz's [16] quantitative analysis of the biomechanical parameters of the Nigra foot model. A pressure plate on the heel and toe that is tilted at 15 and 20 degrees, respectively, disperses 1600N of force.

Steen [17] examined and studied the mechanical features of 21 prosthetic feet used in underdeveloped nations. All feet that measured more than 5mm underwent tests for UV exposure, humidity, cycle foot testing, static proofing testing, static strength experimentation, deformation, and fracture in the forefoot prosthesis area. This research will aid in building a new foot model for patients in underdeveloped countries. Mohammadniay [18] used slope walking to investigate the effects of slope on the biomechanical parameters of three different prosthetic feet on the lower limb kinetics and kinematics in a transtibial and transfemoral amputee. The first peak of the vertical ground reaction power on the prosthetic side is lowered by expanding the slope, which has an impact on walking characteristics. Due to the difficult coordination between the replacement knee and the patient's motor control, the transfemoral amputee could not have been able to keep an eye on this behavior. The mechanical properties of two prosthetic foot specimens that were subjected to impact while jogging were assessed by Hamzah, M.N., et al. [19]. They created two samples, A and B, by weaving layers of fiberglass in various directions and bonding them together with unsaturated polyester resin, utilizing the hand arrangement of the fiber layers. The mechanical characteristics of the composite materials utilized in the production of the feet were then calculated using a theoretical analysis. They discovered from the deviation load test findings that foot sample B provides a peak load of 128.7 kg in 0.06 seconds, while foot sample A provides a peak load of 125.32 kg in 0.069 seconds. Andrea [20] improved the ability of designers and prostheses to recognize the mechanical parameters of the artificial foot. Testing procedures that individually assess the elastic properties were improved in this study. Three different SACH foot types—two energy recovery athletic feet and a prosthetic foot that simulated energy return—were studied. Stable feet have lower heel stiffnesses and higher toe stiffnesses, whereas dynamic, energy-returning feet have larger heel bending stiffness and fewer toe stiffnesses. Before selecting a prosthesis, Adalarasu [21] took the patient, cost, material attributes, compatibility, and comfort into account. By analyzing the material properties of the typical materials utilized in various feet and simultaneously validating these findings through subjective input, a comparison of multiple inexpensive non-articulating stiff ankle prosthetic feet was established. Bryce et al. [22] studied the elite athletic prosthesis foot. These initial results show that load capacity testing is not approved to foresee, specify, or control such technologies. Inaccuracies in performance and unfair performance thresholds are developed as a result of the endeavor. The energy return prosthesis's vulnerability to mechanical stiffness effects as a result of ground contact deviation or variations in the functional artificial blade's length due to gait has been confirmed.

Nooranida Arifin et al. [23] researched how different prosthetic feet would affect transtibial amputees' balance when standing on various surfaces. Ten amputees with different types of prosthetic feet were tested to see how well they maintained their balance and posture. The three types of feet tested were the solid ankle cushion heel (SACH), single axis (SA), and energy saving and return (ESAR) feet. The results focus on how the shape of the prosthetic foot affected the stability of below-knee amputees, and how this was most noticeable while the patients were standing on a cushioned surface. Doctors need to keep this in mind when recommending lower artificial limbs for amputees who plan to perform most of their walking on carpets or other soft surfaces.

The results can be implemented to increase patient involvement in rehabilitation using various support surfaces that may help patients with prosthetic feet maintain their balance and reduce their chance of falling. Steen et al. [24] conducted a clinical trial on vulcanized rubber footwear for trans-tibial amputees in underdeveloped nations. They made use of 186 different models of rubber prosthetic feet designed especially for trans-tibial prosthetic amputees. After 12 months, a 20% failure rate was reached, however due to logistical challenges, half of the patients were monitored for more than 15 months, and the PP-rubber foot's functionality was exceptional. After 18 months, the failure rate rose to 62 percent as a result.

Elizabeth [25] tested 14 users with unilateral transtibial prostheses for the effects of forefoot flexibility on their gaits. In the study, researchers found that late stance and through-loading transfer between the prosthetic and ipsilateral limbs can "drop-off" with some solid-ankle prosthesis foot designs due to the increased flexibility of the forefoot components. Feet with Dynamic Energy Return (DER) can store and get more energy while you move. Haberman [26] to make it simpler for developers and prostheses to modify the mechanical properties of prosthetic feet to fit the walking needs of individual patients, we have refined an experimental method named "Mechanical properties of dynamic energy return prosthetic feet." Prosthetics professionals and designers can use this method to study how the mechanical properties of prosthetic feet change over time. Trost [27], who tested many materials that gained power when squeezed by body weight during the stance phase, says that the energy-storing foot could be a useful addition to the arsenal of prosthetics. Nicholas et al. [28] made revolutionary prosthetic feet that can store and return energy while keeping their weight.They accomplished this by employing topological optimization techniques. A less-material-intensive prosthetic foot that aimed to replicate the stiffness characteristics of a commercially available foot was constructed using the framework. The groundbreaking foot design that is appropriate for SLS manufacturing and flexible in the future was created using this basis.

Zahra [29] developed a novel technique for creating and enhancing a visco-elastic ankle-foot synthetic by repeatedly walking through the full ankle moment-angle loop. The full ankle's moment-angle loop was divided into quarters, and appropriate models were applied to two viscoelastic units to replicate passive motion of the ankle. The upgraded model was put through its paces on a healthy subject using an amputee gait simulator. The prosthetic ankle's moment-angle loops were found to be identical to those of the integrated ankle after four times the amount of attention was paid to each. The findings demonstrate the accuracy with which the model represented the severe ankle's behavior. Quesada et al. [30–32] found that sound limb contact work was less when the prosthetic foot produced less heel energy than natural levels, but this benefit decreased until there was no difference in contact work when ankle power was at or above biological levels. The prosthetic foot may have an effect on dynamic gait systems that help lessen the load on the healthy limbs because it puts out so much energy. The initial maximum of the EKAM in the sound limb and the peak of the vertical GRF are both reduced when the power output of a passive prosthetic foot is increased beyond that of a typical push-off (but below that of a biological foot or ankle). Hamzah, M.N., et al. [33] looked into a new design for a prosthetic made of carbon fiber. They divided the design idea into parts based on what each part was supposed to do. Some thought has been given to the idea of a rolling form. The carbon fiber-epoxy composite was looked at to see if it could be used to make a strong and light prosthetic foot. They noticed that the way the keel and heel are made works like a non-prismatic cantilever, so they proposed a thorough analysis to figure out the best thickness for the keel and heel based on the material.

III. Types of Lower Limb Prosthesis

Artificial prostheses are artificial limb replacements for amputees. It is crucial to incorporate the needs of the patient into the design process. A passive prosthesis (which lacks the ability to generate energy) requires the amputee to use their own body weight to propel the artificial limb. Fully powered semi-active prostheses get their power from the user's regular energy during the stance phase and from the swing phase, when the prosthesis is actively used. However, active prostheses rely entirely on an external power source. [34].

The SACH was the original prosthetic foot (Solid Ankle Cushioned Heel). In order to generate foot action, the prosthetic shank is connected directly to the heel and toe, which are elastic. During production, the angle between the foot and the shank is adjusted to give each shoe its desired heel height [34].

Seid et al[35] . focused on semi-active knee prostheses, and created the MR (magneto-rheological) damper valve to regulate the transfemoral prosthesis' swinging motion. It was determined that the three most important parameters for regulating damping force and damper motion were the force acting, damping factors, and force offset. The simulation demonstrated a 71% reduction in weight compared to the existing MR damper. Tommaso Lenzi created

a semi-active, hybrid, transfemoral knee prosthesis for use on stairs [36]. The active variable transmission system and electric motor were combined with the spring-damper mechanism. When compared to powered prostheses, the prototype's small weight of D1.7 Kg is significant, according to the authors. For walking and stair ambulation, it operates in both passive and active modes. Sup et al. [37] create and construct a powered transfemoral prosthesis using a pneumatically operated powered tethered device. In order to track forces and moments on a three-axis socket, they developed a load cell. In order to achieve a more natural walk, the design was examined to make sure that the required torque was supplied to the joints. A motorized transtibial prosthetic was introduced by Lukas et al. [38] for amputees who climb stairs and use a treadmill. The lightweight multipolar design model was able to provide physiological energy with a small amount of socket torque while accommodating the anatomic foot contour. By adjusting the necessary velocity and torque at the motor's output, it was advantageous to increase efficiency while easing the load on the primary transmission line. The proposed prosthesis was 40.9 percent lighter and had a construction height that was 36.8 percent shorter than Ottobock's (12 cm) (1.32 Kg). Dong et al. [39] described a geared five-bar pneumatic actuator that might be used to power a motorized transtibial prosthesis based on the SEA (Series Elastic Actuator). Reducing the motor's maximum output and providing a specific 70 kg subject with net positive power, it simulates the biomechanical action of the human foot. Normal walking speed on a treadmill activated 35.3% of the motor. saves power by decreasing maximum motor output from 150W to 132W.
When considering price, ease of use, and weight, among the three main categories of prostheses discussed above, a semi-active prosthesis looks to be the best option for the amputee in this situation.

IV. Solid Ankle Cushion Heel

In recent years, the Solid Ankle Cushion Heel (SACH) foot has been increasingly popular because to its dependability, effectiveness, and affordability, leading to the development of a few novel feet with dynamic elastic response properties. These new designs were inspired by the development of advanced materials that can "store and transmit energy" to facilitate running and walking. Many new commercially available prosthetic feet have emerged. Although each design has strong clinical advocates, the attributes of these designs are unknown. These feet's demands lower walking energy consumption and improve mobility. New materials that have the capacity to "store and release energy" allowing for controlled mobility, are now posing a threat to the SACH foot design. The dynamic elastic response foot is the functional classification [40-42]. Figure 2 shows the innovative SACH foot created by Morgan C. [43] for the Center for International Rehabilitation (CIR). The Shape and Roll (SR) foot from Northwestern University and the SACH foot from the International Committee of the Red Cross were two prosthetic feet that CIR was requested to examine the effects of pairing with its monolimb. The results of the finite element (FE) modeling of the monolimb and artificial feet were compared to the results of practical tests of the artificial foot under various conditions and loading changes. Major loading scenarios demonstrate that the rigid Shape and Roll assembly stresses the monolimb more but cannot reach its yield strength, and that the SR foot is inferior to the prosthetic SACH foot. R. Figueroa and C.K. Muller [12] performed computational analyses on a novel design for a prosthetic foot that provides dynamic power return, and followed up by examining its mechanical properties, in particular the elasticity of its keel for energy storage. Numerical research performed with FEM shows that a unique design may effectively store and release energy.

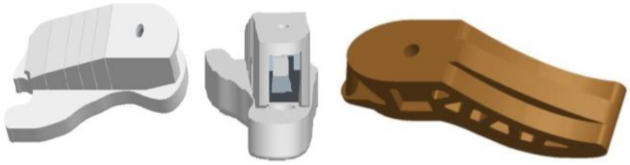

Fig. 2. Morgan created the Prosthetic Foot [43].

Polymers are the primary component of prosthetic foot. Many orthoses and rigid artificial limb sockets are made from low-density polyethylene because it is lightweight, flexible, and easy to mold. However, PP polymer is among the best polymeric materials for producing these applications because it has great mechanical strength, toughness, and high stiffness, providing greater stability to orthoses or prostheses in response to changing clinical demands [44].

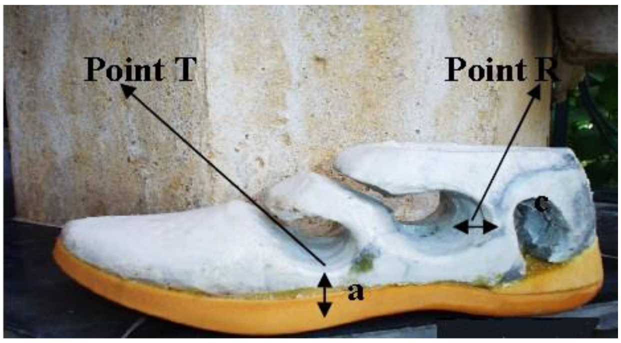

Fig. 3. Kadhim designed the foot [45].

Yadan Z. [46] developed an innovative ABS polymer prosthetic ankle. The unique prosthesis design was put through its mechanical paces. The CAD program was used to design and model the prosthetic ankle, which was then tested in both mechanical and clinical settings. Results from the tests show that the manufactured ankle prosthesis successfully met the specifications for the bulk properties.

V. Metabolic energy expenditure and artificial feet

Individuals with lower-limb amputations frequently struggle to move from one location to another efficiently. Even the most advanced prosthetic technology cannot perfectly replicate the movements and functionality of a real limb, but providing a prosthesis can help someone with a transtibial (below-the-knee) amputation regain some of their independence in their daily lives. Therefore, using a prosthesis to get about isn't always as efficient, and things like running and walking take more work. [47] The cost of energy (i.e., gait efficiency), for instance, is between 12 and 33 percent higher in transtibial prosthetic patients than in non-amputees at a self-selected or acceptable walking pace [47-50]. 1-4 In a similar vein, runners using transtibial prostheses expend 8 to 38 percent more energy [51, 52].

As design, materials, and technology for artificial things have improved, many different kinds of feet have been made [53, 54]. Even though many studies have been done over the past few years [51, 52, 54–58] to see if different types of prosthetic feet can reduce the amount of energy needed to walk or run, there hasn't been a recent systematic review of all the evidence as a whole. Hofstad and colleagues [59] did a Cochrane study that found that different foot designs didn't change how much energy transtibial prosthetic patients used when walking on flat ground at their desired walking speeds. They saw that there wasn't much evidence. The findings also demonstrated that highly active participants expended less energy when they switched to a dynamic reaction foot from a solid ankle-foot whether traveling uphill, downhill, or at a quicker speed.

VI. Conclusion

1- Because of its flexibility, simplicity of molding, superior mechanical properties, and lightweight nature, Prosthetic lower limbs made from polyethylene (PE) of varied densities have become increasingly common in recent years.

2- The SACH foot's forefoot is very durable compared to other types because it has a rubber sole and the materials used to make it have excellent mechanical properties. A fatigue test can be used to measure how long something lasts.

3- The Seattle and Jaipur feet are less capable of absorbing trauma than the SACH foot. The Jaipur foot functions more normally and is more anatomically accurate to the human foot than the SACH foot and the Seattle foot.

4- Important elastic foot properties including a high tensile strength to relative density, ability to withstand stress, and smooth rollover capability are offered by composites, which are frequently utilized for prosthetic foot applications.

5- The kind of fibers, the quantity of layer reinforcing, and the kind of matrix resin can all affect how effective a composite polymer artificial foot is.

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