Properties of Materials and Models of Prosthetic Feet: A Review

Jawad K Oleiwi¹ and Ahmed Namah Hadi²

¹ Department of Materials Engineering, University of Technology, Iraq
² Department of Biomedical Engineering, College of Engineering, University of Babylon, Iraq

E-mail: 130041@uotechnology.edu.iq

Abstract. Prosthetic limbs fabricate devices that provide amputees with a replacement for their missing limbs, restoring some function. These artificial feet are not as multifunctional as natural feet, but they improve the patient's performance level. Considering prosthetic feet, in particular, selecting a device is based on how favorably a device matches the human foot's characteristics. Prosthetic feet are designed to meet required values for tensile strength, density, corrosion resistance, shear strength, flexibility, durability, and cost-efficiency. The above considerations depend on the properties of the material used, the foot's design, and the manufacturing process applied. In the manufacture of the prosthetic foot, polymers composite reinforced with fibers have been used. Their characteristics confirm a constant and low weight structure that makes it possible for agglomeration, distribution, and energy storage through walking, making a certain rise in gait effectiveness. Depending on the composite's adjustment in terms of fiber choice, their system, type of mixture and mass content, and the prosthesis design, the foot gets change effectiveness as the ratio of energy unconfined to energy assembled. In this paper, the biomechanics, materials, and models of the prosthetic foot have been reviewed.

Keywords. Prosthetic limbs, Feet, Biomechanics, Materials, Models.

1. Introduction

A prosthetic device is an artificial device that mimics the function of a missing body part. Prosthetic limbs, or artificial limbs, are fabricated devices that provide amputees with a replacement for their missing limb, restoring some function. Lower limb prosthetic devices must restore walking capacity if they are effective [1-2]. In recent years, different artificial parts were manufactured, such as foot part, [3-5], prosthetic sockets, [6-12], knee parts, [13-17], hip joint application, [18-22], removable partial denture [23-26], hand and fingers parts, [27-31], and other biomechanics application, [32-35]. So, the prosthesis application required improvement for composite materials used to manufacture the prosthesis by different techniques. Therefore, in the last years, multi researchers investigated different techniques as reinforcement by different types to increase the mechanical properties and behavior for structure, [36-47], reinforcement by different types of powder materials, [48-53], reinforcement by various nanomaterials types additives, [54-63], and other reinforcement effects [64-69]. In developing countries, especially rural amputees, the production and improvement of the prosthetic foot are important. Furthermore, the durability of the prosthetic foot indicates the strength of the whole prosthesis. Several prosthetic feet have been developed to achieve rural amputees requirements in
developing countries; some of these feet are made in developed countries and exported to low-income countries to be used, such as the Snelson foot and the feet made in Geneva by the International Committee of the Red Cross. Many papers explain the benefits of particular methods and techniques, manufacturing prosthetic foot, while few studies described the performance and biomechanics characteristics of trans prostheses and prosthetic feet used in developing countries. While these devices are beneficial and replicate the natural ankles' biomechanics, they are currently not widespread. This may be because of the complexities of the mechanisms, energy consumption demands, and rising prices. Nevertheless, recent experiments have shown that a simplified mechanical passive device will replace the ankle biomechanics at slow-moving at normal speeds, and a more rapidly active source of energy is required. Hansen et al. found a natural ankle moment-angle curve in the stance phase shows a narrow hysteresis loop at normal walking speed. Takahashi and Stanhope also recommended a natural ankle-foot system that exhibited a work ratio not better than 1.0 in the normal walking speed. Therefore, it is advised that a variable spring-damper mechanism may be useful at slow to normal walking speeds. Levels and classification of below the knee amputations are shown in Figure (1B). BK prostheses, Figure (1A), comprise four significant components: Socket, Pylon, Foot prosthetic, and Couplings [70-72]. In this review, the prosthetic foot's biomedical properties have been discussed, and use polymer and composite materials within this field. The research's further objective offers a brief outline numerical analysis of SACH and sport feet' new design with common materials used in this application.

![Figure 1. A) Component of prosthetic bk, B) Prostheses levels[72].](image)

### 2. Biomechanics properties of prosthetic feet

Durability is one of the vital biomechanics features of a SACH (Solid Ankle Cushion Heel) foot. The subjection of commercially available feet to controlled but vigorous testing would indicate the effects of design and materials on durability, identify weaknesses or faults, and hopefully lead to an improved design. Daher [73] assumed cyclic analysis testing of nine types of SACH feet to measure the durable of the foot design until failure happened; the prosthetic foot was stressed for 500,000 cycles at a load which artificial an active amputee weighing nearly 100 Kg. Furthermore, he found out that the change in strength and deformation happens within only 5,000 cycles. R. Deval [74] investigated the durability of the Seattle's foot and the reported load-deflection features that obtain as a part of the framework investigation to improve mixture suitable of thermoplastic, thermoset polymers with reinforcement material of prosthetic feet. Wevers and Duranc [75] also assumed dynamic analysis on SACH prosthetic feet, but they loaded the whole trans-tibial prostheses, not the foot alone. Their results were like to Daher's with fast wear and the feet lower than 100,000 cycles. Van Jaarsveld H. [76] considered the hysteresis and stiffness for nine types of prosthetic feet. He found that shoes affect the hysteresis of the feet. However, with sports shoes, the differences in hysteresis between the feet disappear, and hysteresis loss for all confirmed feet increases when applies leather shoes. Kabra S. and Narayanan R develop a cyclic loading system measuring cyclic dorsiflexion [77] to consider the functional parameters of the prosthetic Jaipur ankle-foot before and after longtime cyclic loading, with the simultaneous aim of assessing these machines. He found from the results on the 26 Jaipur foot
that prosthetic foot good efficiency and significant mobility in three planes. Toh H. [78] tested fatigue strength for four prosthetic feet was described in this study. A simple fatigue testing machine was designed, and various normal loads were used to the heel and forefoot for 500,000 cycles. The simple fatigue tester was used successfully to study the durability of the Lambda foot and (SACH) foot. The study finds out that the Lambda foot had high fatigue characteristics. Muhsin J. Jweeg et al. [79] analyzed for improving the fatigue behavior (safety factor of fatigue) of the non-articular prosthetic foot (SACH) in the region (Bolt Adapter). The mechanical properties and fatigue behavior tests were carried for material that the bolt manufacture from it, a region where the failure occurred and inserted these properties in the engineering analysis program (Ansys) to calculate fatigue's safety factor. The results showed that the safety factor after hardening by laser is increased by 42.8%.

Biomechanical properties of the artificial foot affect its behavior in an amputation. Furthermore, usually research properties are kinematics, kinetics, and energy return; to get this biomechanical analysis, a gait analysis is typically achieved using physical characteristics. However, in practice, prototypes are not always available [80]. Arya A.P [81] compared between Jaipur, Seattle, and SACH prosthetic foot was performed in this study. The study was devised to compare both the shock absorption capacity and the influence on gait style. The conclusions indicated that the Jaipur foot's performance is further normal and closer to the human foot than the Seattle and SACH feet. The SACH foot had a superior impact resistance than Jaipur and Seattle's feet. Glenn K. KLute et al.[82] considered the heel region of artificial feet and shoe properties. In the direction of estimation and model the heel ability to impact shocks, a pendulum was constructed to mechanically simulate the conditions immediately following initial heel ground contact during walking [82]. Sam et al.[83] investigated the mechanical dynamics, including damping ratios and resonant frequency characteristics of 11 prosthetic feet types used in low-income countries. The study determined the dynamic properties that arose when the prosthesis has fluctuated with a mass similar to that of the human body. Most of the prosthetic feet tested in this study portrayed functional rollover shapes similar to that of a typical SACH foot. Anne Schmitz [84] analyzed the biomechanical properties of the Nigra foot model numerically; hell and toe stiffness responses were evaluated by IOS 10328 using a rate of 5mm/min. Displacement via a loading plate angled at 15° and 20° on the heel and toe, respectively, with force 1600N. Steen [85] investigated the mechanical properties of 21 artificial feet used in developing countries. The deformation and failure in the forefoot prosthetic region for all feet that exceed 5mm, the static proof test, the static strength test, the cyclic foot test, UV exposure, and humidity were also studied. This study would help the release of a new foot design for patients in developing countries. Mohammadniay [86] contrasted the influence of slope on the biomechanical properties of three different prosthetic feet on lower limb kinematics and kinetics through slope walking, between a transfemoral and a transfibular amputee. The gait characteristics are affected by the slope, expanding the slope reductions the first peak of the vertical ground reaction force on the prosthetic side, whereas for the transfemoral amputee, this conduct may not be watched because of the difficult collaboration of the artificial knee and the subject’s motor control. Andrea [87] enhanced designers and prosthetics' capability to identify the mechanical properties of artificial feet. In this research, testing methodologies were improved that separately estimated the elastic characteristics. Three types of SACH feet were investigated, two energy return feet for active users and a new prosthetic foot designed to offer a partial energy return. Stable feet tend to display lower heel stiffnesses and higher toe stiffnesses, while dynamics, energy return feet tend to show higher heel stiffnesses and lower toe stiffnesses. Adalarasu [88] considered many parameters for selecting prostheses such as patient, cost, material characteristics, compatibility, and comfort. Comparison and analysis of different low-cost non-articulating solid ankle artificial feet were prepared by estimating the appreciation of the material characteristic investigations of the popular materials utilized in different feet and at the same time confirming these results through subjective feedback. Bryce et al. [89] considered properties of the elite sport prosthetic foot. These initial investigations determined that static load testing is not approved to predict, specify, or regulate such technology. The results of the work produce inaccurate performance and unfair thresholds in performance being estimated. It was confirmed the energy return prosthesis is subject to alterations in mechanical stiffness due to ground contact deflection or gait induced changes in effective prosthetic blade length. Nooranida Arifin et al.
[90] studied the influence of prosthetic foot types on the postural stabilization among transtibial amputees when stand-up on various support surfaces. The postural stabilization of 10 transtibial amputees wearing solid ankle cushion heel (SACH) foot, single-axis (SA) foot, and energy-saving and return (ESAR) foot was appraised. The results refer to the stabilization of below-knee amputees influenced by prosthetic foot design, mostly when subjects were standing on a compliant surface. This factor must be considered by clinicians when prosthetic lower limbs are prescribed to amputees who ambulate mostly on soft surfaces. The results can also be used to improve involvement during rehabilitation using different support surfaces, which may lead to postural stabilization and decrease the risk of falls in a person with an artificial foot. Clinical investigation studied vulcanized rubber feet for transtibial amputees in developing countries by Steen et al. [91-92]. They used 186 rubber prosthetic feet of various designs adapted to amputees with transtibial prostheses. A failure rate of 20% was satisfied after 12 months, but little feet were followed for more than one year, and the performance of PP-rubber foot was excellent, so that half of the subjects were followed for more than 15 months due to logistic reasons, and the failure rate increased to 62% at 18 months. The same researchers conducted a clinical investigation of 172 polyurethane. The failure rate decreased by 20% after 18 months for feet-tibial amputees in tropical developing countries with the spring-blade foot was meaningfully better than others. Elizabeth [93] conducted the influence of the flexibility forefoot on the gait of 14 unilateral transtibial prosthetic users. The results of this work recommend solid-ankle prosthetic foot designs with more flexible forefoot sections can cause a “drop-off” influence in the late stance phase and through the transmission of loading between prosthetic and contralateral limbs. Dynamic Energy Return (DER) feet are those capable of storing and returning energy during the gait cycle. Haberman[94] improved an experimental technique “Mechanical properties of dynamic energy return prosthetic feet” by which time variable with dependent mechanical characteristics of the prosthetic feet can be determined to develop the capability of designers and prosthetics to conform the mechanical of prosthetic feet characteristics to the patient-specific locomotion requirements, as well as stability, smooth rollover, and efficient propulsion. Trost [95] used different materials that returned energy when compressed by body mass during the stance phase and concluded the energy-storing feet could be a valuable addition to the prosthetic armamentarium while Nicholas et al.[96] provide energy storage and return with reducing weight by using topology optimization methods to develop new prosthetic feet. The framework was used to generate a prosthetic foot that minimized material usage and attempted to replicate a commercially available foot's stiffness characteristics. This framework produced a novel foot design, well-suited for SLS fabrication, which with future design modifications. Zahra at el. [97] used a new technique to design and improve a visco-elastic ankle-foot artificial by repeating the entire ankle moment–angle loop in the natural walking speed. The moment–angle loop of the intact ankle was distributed into four portions, and the appropriate models, including two visco-elastic units, were measured to duplicate the passive ankle dynamics. The improved model was then tested on a healthy person with the amputee gait simulant. The results display that the prosthetic ankle moment–angle loop was like that of the integral ankle with the worthiness of notice four times. The results commend that the model wonderfully presented the dynamics of the negative human ankle. Quesada et al. [98-101] demonstrated a decrease in sound limb collision work while the prosthetic foot delivered lower than biological levels of ankle power, but this benefit tapered to no change in collision work for ankle power at or beyond biological levels. Providing high energy from the prosthetic foot may influence dynamic walking devices to support decrease sound limb loading. Growing the energy return from a passive prosthetic foot to higher than conventional push-off levels (but lower than a biological foot/ankle) decreases the first peak of the vertical GRF and the first peak of the EKAM in the sound limb.

3. Solid ankle cushion heel (SACH) foot

Resulting years of accepting the Solid Ankle Cushion Heel (SACH) foot to accommodate durability and efficiency and being of acceptable cost, few new feet with dynamic elastic response characteristics have been designed. The stimulus for these new designs is the modern improvement of materials that can "store and release energy" to assist walking and running. Many new prosthetic feet have become available commercially. The qualities of these designs are not known, though each has its strong
clinical advocates. The requirement from these feet reduce the energy for walking and increase mobility. Today, the SACH foot design is being confronted by new materials that offer controlled mobility by their capacity to "store and release energy" Functionally, they are being classed as dynamic elastic response feet [102-105]. Morgan C.[106] designed new SACH foot by Center for International Rehabilitation (CIR) can be seen in figure 2. CIR was asked to analyze the influence of pair their monolimb with two having been designed prosthetic feet; the International Committee of the Red Cross’s SACH foot and Northwestern’s Shape and Roll (SR) prosthetic foot. Monolimb and prosthetic feet were modeled have been studied and analyzed by using finite element (FE), then the results are compared with physical tests of the prosthetic foot under condition and loading change. These results recommend that the SR foot does not achieve prosthetic SACH foot, according to significant loading situations and the inflexible Shape and Roll assembly manufactured higher strains on the monolimb but did not pass the yield strength of the monolimb. Numerical tests were conducted by R. Figueroa and Muller C.K. [107] on a new design prosthetic foot with dynamic energy return, then studied the mechanical properties includes the flexibility keel prosthetic foot's ability to store energy. The numerical analysis is applied using the FEM and proves that a novel design can store and return energy.

![Figure 2. Prosthetic Foot is designed by Morgan [106].](image)

Polymers, materials in prosthetic feet. It is apparent that one of the most usually used polymers for the production of orthoses and rigid prosthetic sockets are low-density polyethylene, due to lightweight, flexibility, and easy to mold, as well as PP polymer as one of the best polymers for manufactured this type of applications for good tensile strength, hardness, and rigidity, which offer to orthoses or prostheses greater stability as clinical requests [108]. The application development division has developed various resins and other products for making artificial limbs and orthotic appliances based on Polyurethanes, Silicones, Epoxies, and other Synthetic Rubbers. Karunakaran [109] developed lightweight polyurethane PU foam at the Vikram Sarabhai Space Centre for the Jaipur prosthetic foot to improve both appearance and comfort; studies showed PU foot was considered comfortable and accepted by the amputee population. Many tasks were devoted to ensuring both the quality of the prosthesis and its adherence to high standards. The PU foot needed to be produced at a reasonable cost, specifically for developing countries. Kadhim [110] designed and manufactured a new prosthetic foot, made from PE polymer, then compare with the SACH foot to conclude if there were variances in the pattern gait while wearing the foot designed and whether these modifications would be problematical. Prosthetics design combines modern prosthetic design elements, such as components and materials. The analysis results by (Finite Element method FEM) and experimental methods were carried out on the new design foot, as shown in Figure 3A. Emdad [111] designed a new prosthetic foot manufactured from (PTFE) polymer and compared it with the SACH foot, as shown in Figure 3B. The dorsiflexion, energy returned, impact, and fatigue foot was studied, with the numerical technique the finite element was used by applying ANSYS to find out the stress distribution with gait cycle and Von Mises stresses. The modified foot is compared with the SACH foot in cost and weight. The cost of designed foot compares with other types was lower by about 80%, while weight was lighter than by 25%. Also, the modified prosthetic foot has perfect properties paralleled with the SACH foot. Muslim [112] designed a prosthetic foot by PE polymer and compare it with SACH prosthetic foot, as shown...
in Figure 3C. Dorsiflexion, impact absorption, and fatigue foot tests were carried out on the new design prosthetic foot and compared to the SACH foot. The results of the static and fatigue analysis were carried out using (Finite Element Model FEM), and experimental methods show adequate dorsiflexion (7.8-6.4°), the force transferred at impact heel (9.82-9.50N), and fatigue of foot (2, 103,445-896, 213) cycles respectively. Yadan Z. [113] designed a new prosthetic ankle from ABS polymer. The mechanical properties were carried out on the new prosthetic design. The prosthetic ankle was designed and modeled by CAD software and tested on both a robot and a human subject. The test results exhibit that the designed ankle prosthesis verified its ability to satisfy the bulk property requirements. Matt [114] designed a new prosthetic foot by CMA center and manufactured from (PE+PP) copolymer. A new design was manufactured by basing on static models and the historical performance of other models based on past prosthetic research with the CMA center's experience. The design is composed of a forefoot with equally spaced transverse slots to facilitate bending. This is currently used on the Shape and Roll foot at the CMA and was achieved well in the field. Second, the ‘C’ ankle will be put on the ankle to increase ankle flexure and relieve stress on the toe. Muhsin J. Jweeg et al.[115] designed a new prosthetic foot from polymer HDPE, and the influence of temperature on the characterization of a novel design has been studied and compared with (SACH) Solid Ankle Cushioned Heel foot based on the numerical and investigational analysis. The new design's failure properties at room temperature and 600C were conducted using the test of fatigue foot tester, so the angle of dorsiflexion was measured. The safety factor of polymer prosthetic design determined by numerical analysis and the results in this work, the maximum dorsiflexion angle at toe-off for the SACH and the new prosthetic foot is 4.7° and 6.3°, respectively. Failure of the new design occurs at 1,1047,321 and 1,089,463 cycles for tests achieved at room temperature (23 °C) and 60 °C, respectively.

![Figure 3](image)

**Figure 3.** (a) The foot is designed by Kadhim [109], (b) The foot is designed by Emad [110], and (c) The foot is designed by Muslim [111].

More developments were associated with the outline of sphere-shaped joints, ankle changing, but then the foot keeps on weighty and inflexible. Composite materials have proven to be a development in the history of prosthetics foot, as it has allowed the preservation and distribution of energy through work. The launch of the Seattle Foot in 1981 (the United States.Pat.4547913) has taken place as the indication of ESPF. Prosthetic foot mobility and stability were developed with an improvement in resilient properties [116,117]. Composite materials that are commonly used in manufacturing prosthetic foot consist of two parts: matrix resin and reinforcement material as fiber or particle, so that most of the load applied to the structure of composite material was carried out by fiber reinforcement material, as well as good strength with low specific gravity is the main characteristic of composite materials, with dependent on the requirements, we can change the composites with an alteration of the reinforced system, obtaining the conforming properties of composite materials can be achieved by the type of resin and reinforcement system [116-120]. Hassan S. M. and Majid Habeeb Faidhi-Allah [121] improved two composite materials of HDPE and LLDPE filled with date palm wood (DPW) used in the manufacture of a prosthetic foot. The impact of energy and tensile strength have been studied. The Young’s modulus of HDPE40:60 DPW meaningfully improved to 80% parallel with the values...
obtained for pure HDPE. On the other hand, he noticed that adding 10% of (LLDPE) to 90% HDPE increased the elongation at break to 27% compared with the values obtained for pure HDPE, while the ultimate yield stress and impact all reduced. Carbon fibers(CF) are described by exceptionally high durability, i.e., strength to weightiness ratio, good impact, and wear strength [119]. These are the most significant specialty for prosthetics, and the lower artificial foot needs to be lower weight than a normal foot that reduces the energy requirement needed to move the foot[122-123].

Shekhar et al. [124] investigated the mechanical properties of carbon composite materials for lower limb prostheses. The tensile, hardness, and SEM analysis tests were carried out on these materials analyses. The tensile and hardness results indicate that Carbon-Carbon fibers have the highest tensile strength and hardness; Carbon-Carbon composite is still the best material of choice for this application. Hamzah M. and Gatta A. [125] used Carbon Fiber-Epoxy composite material to manufacture a new design prosthetic foot. The model was made less complicated by segregating the model into portions in agreement with the purpose, and the roll-over shape concept considers the design. The roll-over shape offers high-quality energy coming back in ankle-foot prosthetics, with the keel and heel design performing as a non-prismatic cantilever beam. The deformation of the heel and the keel was analyzed by FEM, although insufficient deformation was illustrated in the vertical loading test. Rasaq Olawale Medupin et al. [126] used multi-walled carbon nanotube (WMCnt) reinforced natural rubber (NR) polymer nanocomposite (pink) for prosthetic foot application. Mechanical investigation revealed that NR/MWCNT-3 exhibited the highest capacity to withstand tensile and dynamic loading (449.79 MPa).

It also showed the superior filler distribution and hence improved crystallinity and cross-link. The water absorption test indicated that NR/MWCNT-3 offers optimum dimensional stability at ambient conditions. Better wear resistance ability can also be reported of the newly developed than existing prosthetic material. It can be deduced that the formulated nanocomposite from MWcnts for reinforced natural rubber is suitable for the development of the anthropomorphic prosthetic foot. Oleiwi J.K. and Hadi A.N. [127-130] designed a new prosthetic SACH foot from polymer composite material reinforced by carbon fiber, as shown in Figure 4A. The mechanical properties, including tensile, flexural, and impact strength, were carried out for prepared specimens, and the results were analyzed with the numerical method. The finite element was employed by employing the ANSYS package to determine the stress distribution with the gait cycle and Von Mises stresses. Hasan S. Mohammed and Salman [131] developed a composite material from (HDPE) high-density polyethylene polymer reinforced with Date Palm Wood (DPW), which can be used as suitable material in producing prosthetic feet with low cost and good mechanical characteristics as shown in figure 4B. The characteristics showed by prosthetics compared to those of a human foot were considered. The analytical section presents the static analysis results by numerical systems (Finite Element method FEM) investigation systems. Therefore, the dorsiflexion angle was determined for the novel foot design.

![Figure 4](image_url)

*Figure 4.* (a) A foot designed by Hadi and Jawad [126], (b) A foot designed by Hasan [130].
4. Sport foot design with numerical analysis

Partnership amputees have been shown in sports to support amputees develop their dynamic condition and general well-being. Amputees use technology supports, such as prostheses, wheelchairs, or crutches, to compete in sports. In running and other sports that need a high-dynamic position, lower-limb prostheses are needed. Standard prostheses can do any sport, whereas other sports require special prostheses. Improved prosthesis sections and prostheses used for sports have grown in recent years, leading to an increasing number of sports prostheses and modifications that can be used in sports by amputations [132-133]. By developing carbon fiber reinforced polymer (CFRP) as a common suitable material for manufacturing prosthetic foot, the amputee’s abilities were revolutionized by developing prosthetic foot that supported sports activity requirements with good mechanical properties and energy return, and lightweight [134-135]. The prosthetic foot structure was developed, and it was first introduced in the Swattle foot in 1981 due to advances in gait analysis and biomechanics for prosthetic lower limbs [136]. Energy returns are produced with compressive loads due to the bodyweight being converted into CFRP structure, and thus the material returns to its original form; thus, the energy is recovered, considering the normal steadiness of the device in the configuration of an electrical store and return (ESAR) foot is required. The CFRP foot can be used as a perfect spring; the rule of Hooke can apply. Moreover, this basic sports foot model does not involve energy leakage inside the system. The flex foot is the first sports prostheses made from CFRP, was developed by Philips in 1985 [137-138]. It is first seen in elite sport at the 1988 Paralympic Games. The new prostheses sport no include longer heels, while elite runners can use the long keel design on their toes [139-140]. Work with Nolan [118] recommends that the spot CFRP sports prostheses design be improved by a scientific manifestation for the run speed of foot style and toughness. Although various advanced models, today’s sports prostheses are nearly prepared from CFRP, specifically those used in jumping and running games [118]. In 2008, Olympic and Paralympic Games, when Oscar Pistorius, a bilateral lower limb amputee, need to play by new prosthetic foot design, the International Association of Athletics Federation initially saw that new prostheses offer an unfair improvement [136], for that advising that new composite prostheses designs may even be able to outperform the human limb. However, despite the development of composite materials in the lower limb industry, their presence and applications are not restricted to this marketplace. To illustrate, Riel et al. [141] improved a prosthetic arm kit for racing cyclists, manufactured from nylon and fiberglass, which was magnificently used by a Canadian athlete at the 2008 Paralympic Games. Many materials with energy-storing when compacted by the body during the early stance phase have been investigated by Francis J. Trost [142]. Analysis results include determining factors of gait and oxygen consumption. Fifty-two young amputees, including Flex-feet, Seattle feet, Carbon Copy feet, and Sten's feet, were analyzed, and the energy storing foot was provided. Most amputees responded that it was easier, with energy return feet for running, jumping, climbing stairs. Salee H. Abood and Majid Habeeb [143] tested two models of Flex-Foot Cheetah fabricated from materials (carbon, glass) materials with the PE polymer matrix and compared them to the foot with the perfect in the running on the level of a professional athlete as shown in figure 5A. The maximum principal elastic strain and maximum stress, the strain of energy; finally, the total blade deformation was calculated for both feet by numerical analysis. The deflection -load test was prepared for the foot to estimate the bending. The results were very close to the numerical results, and the curve of the carbon foot sample was lower than that for the glass foot sample that indicates the strength of carbon fiber. Muhsin J. Jweeg et al. [144] manufactured a new Athletic prosthetic foot and designed an impact foot tester shown in Figure 5B. The foot was manufactured using Carbon: Glass Fibers, and Epoxy, which gives a good mechanical response. For the same dropped level, the samples' impact response with glass fiber and carbon fiber has the same peak load for different drop angles. It is also clear that the responses of the sample manufactured with carbon fiber were smoother than the sample manufactured with the glass fiber. Hamza, M. et al.[145] evaluated the differences in mechanical properties of two athletic prosthetic feet samples made of fiberglass reinforced epoxy, as shown in Figure 5C. The sample's layers were fabricated with the hand laying method, and an investigation of the mechanical properties of the composite used was performed. The work in this study has been carried out analytically using ANSYS, and experimentally
to conclude the influence of prosthetic foot design on their mechanical properties, and experimentally
to determine the effect of prosthetic foot design on their mechanical characteristics [146-158].

![Figure 5](image)

**Figure 5.** A- The Flex-Foot designed by Saleel [142], B- Athletic Prosthetic Foot designed by Muhsin [143], C- Athletic Prosthetic Foot designed by Hamza[144]

5. **Concluding**

The conclusions of the literature review are as follows:

1. Stiffness characteristic can only be described by improving the mechanical properties of materials used in the manufacture of prosthetic feet, as well as the fact that shock absorption can be improved by using sports shoes compared to leather shoes, so professionals recommend amputees to use sports shoes during walking better than hard leather shoes to improve this property.
2. Durability can be described by fatigue test and the forefoot region of the SACH foot, highly durable compared with other types due to the rubber sole and good mechanical properties of materials used in producing SACH foot.
3. According to the prosthetic feet' biomechanics properties, the SACH foot has a better shock absorption capacity than the Seattle and Jaipur feet. The Jaipur foot's performance is more natural and nearer to the normal foot than the SACH and Seattle's feet. There are no other significant differences in gait style produced by the SACH, Seattle, or Jaipur feet.
4. It is apparent in recent years that one of the most widely used polymers for fabricating prosthetic lower limbs are polyethylene (PE) with high or low density and polypropylene (PP) polymer, due to flexibility, easy to mold, good mechanical properties, and lightweight, which in turn is useful for the manufacture of prostheses with clinical requirements of superior stability.
5. Composite materials reinforced with fibers commonly used for prosthetic foot application offer important elastic foot characteristics such as large strength to density ratio, ability of shock resistance, and smooth rollover capability. The type of fibers can control the prosthetic foot's efficiency made by a composite polymer, the number of layer reinforcement, and the type of matrix resin. Carbon, glass, and Kevlar fibers are the most reinforcement fibers that can be used for manufacturing prosthetic feet. Carbon and glass fibers combined with epoxy resin matrix will offer medium efficiency deal with durable, lightweight, and energy return for the amputee patient while carbon combined within an epoxy resin matrix will increase the activity of prosthetic feet.
6. References

[1] Childress D, Andrew H 2001 *The Shape & Roll Prosthetic Foot for Use in Low-Income Countries* (Northwestern University Feinberg School of Medicine)

[2] Cochrane H, Orsi K 2001 *Lower Limb Amputation* (Prosthetics and Orthotics International)

[3] Saif M Abbas, Kadhim K Resan, Ahmed K Muhammad, Muhannd Al-Waily 2018 *Mechanical and Fatigue Behaviors of Prosthetic for Partial Foot Amputation with Various Composite Materials Types Effect* (International Journal of Mechanical Engineering and Technology) vol 09 no 09 pp 383–394

[4] Ayad M Takhakh, Saif M Abbas 2018 *Manufacturing and Analysis of Carbon Fiber Knee Ankle Foot Orthosis* (International Journal of Engineering & Technology) vol 07 no 04

[5] Lara E Yousif, Kadhim K Resan, Raad M Fenjan 2018 *Temperature Effect on Mechanical Characteristics of A New Design Prosthetic Foot* (International Journal of Mechanical Engineering and Technology) vol 09 no 13 pp 1431–1447

[6] Mohsin Abdullah Al-Shammar, Emad Q Hussein, Ameer Alaa Oleiwi 2017 *Material Characterization and Stress Analysis of a Through Knee Prosthesis Sockets* (International Journal of Mechanical & Mechatronics Engineering) vol 17 no 06

[7] Muhsin J Jweeg, Zaid S Hammoudi, Bassam A Alwan 2018 *Optimised Analysis, Design and Fabrication of Trans-Tibial Prosthetic Sockets* (IOP Conference Series: Materials Science and Engineering) vol 433, 2nd International Conference on Engineering Sciences

[8] Ayad M Takhakh, Saif M Abbas, AseelK Ahmed 2018 *A Study of the Mechanical Properties and Gait Cycle Parameter for a Below-Knee Prosthetic Socket* (IOP Conference Series: Materials Science and Engineering) vol 433, 2nd International Conference on Engineering Sciences

[9] Saif M Abbas, Ayad M Takhakh, Mohsin Abdullah Al-Shammar, Muhannd Al-Waily 2018 *Manufacturing and Analysis of Ankle Disarticulation Prosthetic Socket (SYMES)* (International Journal of Mechanical Engineering and Technology) vol 09 no 07 pp 560–569

[10] Ahmed Khaleel Abdulameer, Mohsin Abdullah Al-Shammar 2018 *Fatigue Analysis of Syme’s Prothesis* (International Review of Mechanical Engineering) vol 12 no 03

[11] Fahad M Kadhim, Ayad M Takhakh, Asmaa M Abdullah 2019 *Mechanical Properties of Polymer with Different Reinforcement Material Composite That used for Fabricates Prosthetic Socket* (Journal of Mechanical Engineering Research and Developments) vol 42 no 4

[12] Ehab N Abbas, Muhsin J Jweeg, Muhannd Al-Waily 2020 *Fatigue Characterization of Laminated Composites used in Prosthetic Sockets Manufacturing* (Journal of Mechanical Engineering Research and Developments) vol 43 no 5 pp 384–399

[13] Bashar A Bedawi, Jumaa S Chiad 2012 *Vibration Analysis and Measurement In the Below Knee Prosthetic Limb Part I: Experimental Work* (ASME 2012 International Mechanical Engineering Congress and Exposition, Proceedings (IMECE))

[14] Noor Dhia Yaseen, Jumaa S Chiad, Firas Mohammed Abdul Ghani 2018 *the Study and Analysis of Stress Distribution Subjected on the Replacement Knee Joint Components using Photo-Elasticity and Numerical Methods* (International Journal of Mechanical and Production Engineering Research and Development) vol 08 no 06 pp 449–464

[15] Fahad M Kadhim, Jumaa S Chiad, Ayad M Takakh 2018 *Design and Manufacturing Knee Joint for Smart Transfemoral Prosthetic* (IOP Conference Series: Materials Science and Engineering) vol 545, International Conference on Materials Engineering and Science

[16] Muhsin J Jweeg, Abdulkareem Abdulrazzaq Ahumdayn, Ali Faik Mohammed Jawad 2019 *Dynamic Stresses and Deformations Investigation of the Below Knee Prosthesis using CT-Scan Modeling* (International Journal of Mechanical & Mechatronics Engineering) vol 19 no 01

[17] Fahad M Kadhim, Jumaa S Chiad, Maryam Abdul Salam Enad 2020 *Evaluation and Analysis of Different Types of Prosthetic Knee Joint Used by above Knee Amputee (Defect and Diffusion Forum Journal)* vol 398 pp 34–40
[18] Jawad K Oleiwi, Rana Afif Majed Anaee, Safaa Hashim Radhi 2018 *Tensile Properties of UHMWPE Nanocomposites Reinforced by CNTs and nHA for Acetabular Cup in Hip Joint Replacement* (Journal of Engineering and Applied Sciences) vol 13 no 13

[19] Jawad Kadhim Oleiwi, Rana Afif Anaee, Safaa Hashim Radhi 2018 *Roughness, Wear and thermal Analysis of UHMWPE Nanocomposites Asacetabular Cup In Hip Joint Replacement* (International Journal of Mechanical and Production Engineering Research and Development) vol 8 no 6 pp 855–864

[20] Jawad Kadhim Oleiwi, Rana Afif Anaee, Safaa Hashim Radhi 2018 *CNTS AND NHA as Reinforcement to Improve Flexural and Impact Properties of Uhmwpe Nanocomposites for Hip Joint Applications* (International Journal of Mechanical Engineering and Technology) vol 9 no 11 pp 121–129

[21] Muhannad Al-Waily, Emad Q Hussein, Nibras A Aziz Al-Roubaiee 2019 *Numerical Modeling for Mechanical Characteristics Study of Different Materials Artificial Hip Joint with Inclination and Gait Cycle Angle Effect* (Journal of Mechanical Engineering Research & Developments) vol 42 no 04 pp 79–93

[22] Yousuf Jamal Mahbob, Mohsin Abdullah Al-Shammari 2019 *Enhancing Wear Rate of High-Density Polyethylene (HDPE) By Adding Ceramic Particles To Propose An Option For Artificial Hip Joint Liner* (IOP Conference Series: Materials Science and Engineering, ICMSMT) vol 561

[23] Jawad K Oleiwi, Shihama I Salih, Hwazen S Fadhil 2018 *Water Absorption and thermal Properties of PMMA Reinforced by Natural Fibers for Denture Applications* (International Journal of Mechanical and Production Engineering Research and Development) vol 08 no 03

[24] Esraa A Abbod, Muhannad Al-Waily, Ziadoon M Al-Hadrayi, Kadhim K Resan, Saif M Abbas 2020 *Numerical and Experimental Analysis to Predict Life of Removable Partial Denture* (IOP Conference Series: Materials Science and Engineering) vol 870, 1st International Conference on Engineering and Advanced Technology, Egypt

[25] Muhannad Al-Waily, Iman Q Al Safar, Suhair G Hussein, Mohsin Abdullah Al-Shammari 2020 *Life Enhancement of Partial Removable Denture made by Biomaterials Reinforced by Graphene Nanoplates and Hydroxyapatite with the Aid of Artificial Neural Network* (Journal of Mechanical Engineering Research and Developments) vol 43 no 6 pp 269–285

[26] Nada N Kadhim, Qahtan A Hamad, Jawad K Oleiwi 2020 *Tensile and Morphological Properties of PMMA Composite Reinforced by Pistachio Shell Powder used in Denture Applications* (2nd International Conference on Materials Engineering & Science), AIP Conference Proceedings

[27] S H Bakhy, S S Hassan, S M Nacy, K Dermitzakis, A H Arieta 2013 *Contact Mechanics For Soft Robotic Fingers: Modeling and Experimentation* (Robotica)

[28] S H Bakhy 2014 *Modeling of Contact Pressure Distribution and Friction Limit Surfaces For Soft Fingers In Robotic Grasping* (Robotica)

[29] Sadeq Bakhy, Enass Flaeih, Mortada Jabbar 2018 *An Experimental Study For Grasping and Pinching Controls For An Underactuated Robotic Finger Using A PID Controller* (2nd International Conference on Engineering Sciences) vol 433, IOP Conference Series: Materials Science and Engineering

[30] Yusra Alyas Shafeeq, Jumaa S Chiad, Yassr Y Kahtan 2018 *Study, Analysis, the Vibration and Stability For the Artificial Hand During Its Daily Working* (International Journal of Mechanical Engineering and Technology) vol 9 no 13 pp 1706–1716

[31] Mortada A Jabbar, Sadeq H Bakhy, Enass H Flaeih 2020 *A New Multi-Objective Algorithm For Underactuated Robotic Finger During Grasping and Pinching Assignments* (3rd International Conference on Engineering Sciences) vol 671, IOP Conference Series: Materials Science and Engineering

[32] Jumaa S Chiad 2014 *Study the Impact Behavior of the Prosthetic Lower Limb Lamination Materials due to Low Velocity Impactor* (ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis, ESDA)
[33] Mahmud Rasheed Ismail, Muhammad Al-Waily, Ameer A Kadhim 2018 *Biomechanical Analysis and Gait Assessment for Normal and Braced Legs* (International Journal of Mechanical & Mechatronics Engineering) vol 18 no 03

[34] S I Salih, J K Oleiwi, H M Ali 2018 *Study the Mechanical Properties of Polymeric Blends (SR/PMMMA) Using for Maxillofacial Prosthesis Application* (International Conference on Materials Engineering and Science) vol 454, IOP Conference Series: Materials Science and Engineering

[35] Fahad M Kadhim, Ayad M Takhakh, Jumaa S Chia 2020 *Modeling and Evaluation of Smart Economic Transfemoral Prosthetic* (Defect and Diffusion Forum Journal) vol 398

[36] Muhsin J. Jweeg, Ali S Hammad, Muhammed Al-Waily 2012 *A Suggested Analytical Solution of Isotropic Composite Plate with Crack Effect* (International Journal of Mechanical & Mechatronics Engineering) vol 12 no 05

[37] Ahmed M Hashim, E K Tanner, Jawad K Oleiwi 2016 *Biomechanics of Natural Fiber Green Composites as Internal Bone Plate Rafted* (MATEC Web of Conferences)

[38] Muhammed Al-Waily, Alaa Abdulzahra Deli, Aziz Darweesh Al-Mawash, Zaman Abud Almalik Abud Ali 2017 *Effect of Natural Sisal Fiber Reinforcement on the Composite Plate Buckling Behavior* (International Journal of Mechanical & Mechatronics Engineering) vol 17 no 01

[39] Mohsin Abdullah Al-Shammari, Muhammed Al-Waily 2018 *Analytical Investigation of Buckling Behavior of Honeycombs Sandwich Combined Plate Structure* (International Journal of Mechanical and Production Engineering Research and Development) vol 08 no 04

[40] Mahmud Rasheed Ismail, Zaman Abud Almalik Abud Ali, Muhammed Al-Waily 2018 *Delamination Damage Effect on Buckling Behavior of Woven Reinforcement Composite Materials Plate* (International Journal of Mechanical & Mechatronics Engineering) vol 18 no 05

[41] A A Taher, A M tahkakh, S M Thahab 2018 *Experimental study of improvement shear strength and moisture effect PVP adhesive joints by addition PVA* (IOP Conference Series: Materials Science and Engineering) vol 454, International Conference on Materials Engineering and Science

[42] Mohsin Abdullah Al-Shammari 2018 *Experimental and FEA of the Crack Effects in a Vibrated Sandwich Plate* (Journal of Engineering and Applied Sciences) vol 13 no 17

[43] Mohsin Abdullah Al-Shammari, Sahar Emad Abdullah 2018 *Stiffness to Weight Ratio of Various Mechanical and thermal Loaded Hyper Composite Plate Structures* (IOP Conference Series: Materials Science and Engineering) vol 433, 2nd International Conference on Engineering Sciences

[44] Alaa A Mohammed, Emad S Al-Hassani, Jawad K Oleiwi, Seyed R Ghaffarian 2019 *the Effect of Annealing on the Behavior of Polyetheretherketone Composites Compared To Pure Titanium* (Materials Research Express) vol 6 no 12

[45] Marwah Ali Husain, Mohsin Abdullah Al-Shammari 2020 *Analytical Solution of Free Vibration Characteristics of Partially Circumferential Cracked Cylindrical Shell* (Journal of Mechanical Engineering Research and Developments) vol 43 no 3 pp 442–454

[46] Ekhlas Edan Kader, Akram Mahdi Abed, Mohsin Abdullah Al-Shammari 2020 *Al2O3 Reinforcement Effect on Structural Properties of Epoxy Polysulfide Copolymer* (Journal of Mechanical Engineering Research and Developments) vol 43 no 4 pp 320–328

[47] S E Sadiq, S H Bakhy, M J Jweeg 2020 *Crashworthiness Behavior of Aircraft Sandwich Structure with Honeycomb Core Under Bending Load* (IOP Conference Series: Materials Science and Engineering)

[48] Muhammad Al-Waily, Zaman Abd Almalik Abud Ali 2015 *A Suggested Analytical Solution of Powder Reinforcement Effect on Buckling Load for Isotropic Mat and Short Hyper Composite Materials Plate* (International Journal of Mechanical & Mechatronics Engineering) vol 15, no 4

[49] Ameer A Kadhim, Muhammad Al-Waily, Zaman Abd Almalik Abud Ali, Muhsin J Jweeg, Kadhim K Resan 2018 *Improvement Fatigue Life and Strength of Isotropic Hyper Composite
Materials by Reinforcement with Different Powder Materials (International Journal of Mechanical & Mechatronics Engineering) vol 18 no 02

[50] Jumaa S Chiad, Muhamad Al-Waily, Mohsin Abdullah Al-Shammari 2018 Buckling Investigation of Isotropic Composite Plate Reinforced by Different Types of Powders (International Journal of Mechanical Engineering and Technology) vol 09 no 09 pp 305–317

[51] Jawad K Oleiwi, Qahtan Adnan Hamad, Hadil Jabbar Abdul Rahman 2018 Tensile Properties and Morphological Test of Heat Cured Acrylic Resin Reinforced by Natural Powders (International Journal of Mechanical and Production Engineering Research and Development) vol 8 no 6 pp 325–334

[52] Siham Issa Salih, Jawad Kadhim Oleiwi, Arkan Saad Mohamed 2018 Investigation of Mechanical Properties of Pmma Composite Reinforced with Different Types of Natural Powders (ARPN Journal of Engineering and Applied Sciences) vol 13 no 22

[53] Jawad K Oleiwi, Qahtan Adnan Hamad, Hadil Jabbar Abdul Rahman 2018 Experimental Investigation of Flexural and Impact Properties of PMMA Reinforced by Bamboo and Rice Husk Powders (International Journal of Mechanical Engineering and Technology) vol 9, no 10

[54] Ehab N Abbas, Muhsin J Jweeg, Muhammad Al-Waily 2018 Analytical and Numerical Investigations for Dynamic Response of Composite Plates Under Various Dynamic Loading with the Influence of Carbon Multi-Wall Tube Nano Materials (International Journal of Mechanical & Mechatronics Engineering) vol 18 no 06 pp 1–10

[55] Jawad K Oleiwi, Basim A Abass 2018 thermal Properties of Polymeric Composites Reinforced by Nanoceramic Materials (International Journal of Mechanical and Production Engineering Research and Development) vol 8 no 6 pp 517–524

[56] Marwah Mohammed Abdulriddha, Nasreen Dakel Fahad, Muhammad Al-Waily, Kadhim K Resan 2018 Rubber Creep Behavior Investigation with Multi Wall Tube Carbon Nano Particle Material Effect (International Journal of Mechanical Engineering and Technology) vol 9, no 12

[57] Ahmed A Taher, Ayad M Takhakh, Sabah M Thaha 2018 Experimental Study and Prediction the Mechanical Properties of Nano-Joining Composite Polymers (Journal of Engineering and Applied Sciences) vol 13 no 18 pp 7665–7669

[58] Siham I Salih, Jawad K Oleiwi, Hajir Mohammed Ali 2019 Investigation the Properties of Silicone Rubber Blend Reinforced by Natural Nanoparticles and UHMWPE fiber (International Journal of Mechanical Engineering and Technology) vol 10 no 1

[59] Siham Issa Salih, Jawad Kadhim Oleiwi, Hajir Mohammed Ali 2019 Modification of Silicone Rubber by Added PMMA and Natural Nanoparticle Used For Maxillofacial Prosthesis Applications (ARPN Journal of Engineering and Applied Sciences) vol 14, no 4

[60] Alaa a Mohammed, Emad S Al-Hassani, Jawad K Oleiwi 2019 the Nanomechanical Characterization and Tensile Test of Polymer Nanocomposites for Bioimplants (AIP Conference Proceedings)

[61] Mohsin Abdullah Al-Shammari, Qasim H Bader, Muhamad Al-Waily, A M Hasson 2020 Fatigue Behavior of Steel Beam Coated with Nanoparticles under High Temperature (Journal of Mechanical Engineering Research and Developments) vol 43 no 4 pp 287–298

[62] Muhammad Al-Waily, Mohsin Abdullah Al-Shammari, Muhsin J Jweeg 2020 An Analytical Investigation of thermal Buckling Behavior of Composite Plates Reinforced by Carbon Nano Particles (Engineering Journal) vol 24 no 3

[63] Ahmed A Taher, Ayad M Takhakh, Sabah M Thahab 2020 Study and Optimization of the Mechanical Properties of PVP/PVA Polymer Nanocomposite as A Low Temperature Adhesive In Nano-Joining (3rd International Conference on Engineering Sciences) vol 671, IOP Conference Series: Materials Science and Engineering

[64] Kahtan Al-Khazraji, Jawad Kadhim, Payman Sahbah Ahmed 2012 Tensile and Fatigue Characteristics of Lower-Limb Prosthetic Socket Made from Composite Materials (Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey)
Kahtan Al-Khazraji, Jawad Kadhim 2015 *Improving Mechanical and Fatigue Characteristic of Trans-Tibial Prosthetic Socket* (Proceedings of the 2015 International Conference on Industrial Engineering and Operations Management, Dubai, United Arab Emirates (UAE), March 3 – 5)

Jawad Kadhim Oleiwi, Shaymaa Jumaah Ahmed 2016 *Studying the Tensile and Buckling for PMMA Reinforced by Jute Fibers for Prosthetic Pylon* (Eng &Tech.Journal) vol 34 no1

Jawad Kadhim Oleiwi, Shaymaa Jumaah Ahmed 2016 *Tensile and Buckling of Prosthetic Pylon Made from Hybrid Composite Materials* (Eng. &Tech.Journal) vol 34 Part (A) no14

Sihama I Salih, Jawad Kadhim Oleiwi, Sajid Abd Alkhidhir 2018 *Comparative Study of Some Mechanical Properties of Hybrid Polymeric Composites Prepared By Using Friction Stir Processing* (Journal of Advanced Research in Dynamic and Control Systems) vol 10 no 02 Special Issue

Suhair Ghazi Hussein, Mohsin Abdullah Al-Shammari, Ayad M Takakh, Muhammad Al-Waily 2020 *Effect of Heat Treatment on Mechanical and Vibration Properties for 6061 and 2024 Aluminum Alloys* (Journal of Mechanical Engineering Research & Developments) vol 43 no 1

Hugh H, Graham Paul W and Dudley Ch 2011 *Biomimetic Orthotic and Prosthetic Technology* (Northwestern University Handbook, USA)

Hansen A H, Childress D S, Miff S C 2004 *the human ankle during walking: implications for design of biomimetic ankle prostheses* (J Biomech) vol 37 pp 1467–1474

Takahashi K Z, Stanhope S J 2013 *Mechanical Energy Profiles of the Combined Ankle-Foot System In Normal Gait: Insights For Prosthetic Designs* (Gait Posture) vol 38 no 4 pp 818–823

Daher R L 1975 *Physical Response of SACH Feet under Laboratory Testing* (Bulletin of Prosthetics Research) vol 10 no 23 pp 4–50

R Deval 1986 *the Seattle Foot* (Journal of Orthotics and Prosthetics) vol 40, no 8

H W Wevers, Durance J P 1987 *Dynamic Testing of Below–Knee Prosthesis: Assembly and Components* (J of Prosthetics and Orthotics International) vol 11

Van jaarsveld H 1990 *Stiffness and Hysteresis Properties of Some Prosthetic Feet* (Journal of Prosthetics and Orthotics International)

Kabra S, Narayanan R 1991 *Equipment and Methods for Laboratory Testing of Ankle – Foot Prostheses as Exemplified by the Jaipur Foot* (J of Rehabilitation Research and Development) vol 28 no 3 pp 23–34

Toh S L 1993 *Fatigue testing of energy storing prosthetic feet* (Journal of Prosthetics and Orthotics International)

Muhsin J Jweeg, Kadhim K Resan, Ali Abdulameer Najim 2013 *Mproving Fatigue Life of Bolt Adapter of Prosthetic SACH Foot* (Journal of Engineering)

R Figueroa, C M Müller-Karger 2009 *Using FE for Dynamic Energy Return Analysis of Prosthetic Feet during Design Process* (25th Southern Biomedical Engineering Conference)

Arya A P 1995 *A Biomechanical Comparison of the SACH, Seattle and Jaipur Feet Using Ground Reaction Forces* (Journal of Prosthetics and Orthotics International)

Glenn K Kulte, Jocelyn S Berge, Ava D Segal 2004 *Heel –Region Properties of Prosthetic Feet and Shoes* (J of Rehabilitation Research and Development) vol 41 no 4 p 535–545

Sam M, Hansen A, Childress D 2004 *Characterization of Prosthetic Feet Used In Low-Income Countries* (International Society for Prosthetics and Orthotics)

Anne Schmite (nee Bans) 2007 *Stiffness Analyses For the Design Development of A Prosthetic Foot* (MSc thesis, University of Wisconsin-Madison)

Jensen J S 2007 *Mechanical Testing of Prosthetic Feet Utilized In Low-Income Countries To ISO-10328* (Journal of prosthetic and Orthotics International)

Mohammadniay M H 2009 *Comparison of Lower Limbs Amputees’ Gait Sloped Surfaces with Different Prosthetic Feet* (journal of biomechanics)
[87] Haberman A 2010 Mechanical Properties of Dynamic Energy Return Prosthetic Feet (A thesis submitted to the Department of Mechanical and Materials Engineering, Queen’s University Canada)

[88] Adalarasu K 2001 Comparison on Jaipur, SACH and Madras Foot (Journal of advanced engineering and technologies)

[89] Bryce D, Philip S, Noroosi S 2013 How Should We Assess the Mechanical Properties of Lower-Limb Prosthesis Technology Used In Elite Sport?—An Initial Investigation (Journal of Biomechanical Science and Engineering)

[90] Nooranida Arifin, Noor Azuan Abu Osman, Sadeeq Ali, Hossein Gholizadeh, Wan Abu Bakar Wan Abas 2014 Postural Stability Characteristics of Transtibial Amputees Wearing Different Prosthetic Foot Types When Standing on Various Support Surfaces (the Scientific World Journal) vol 2014

[91] Jensen J S, Nilsen R, Zeffer J, Fisk J, Hartz C 2006 Clinical Field Testing of Vulcanized Rubber Feet For Trans-Tibial Amputees In Tropical Low-Income Countries (Journal of prosthetic and Orthotics International)

[92] Jensen J S, Nilsen R, Zeffer J, Fisk J, Hartz C 2006 Clinical Field Testing of Polyurethane Feet-Tibial Amputees In Tropical Low-Income Countries (Journal of prosthetic and Orthotics International)

[93] Klodd E 2010 Effects of Prosthetic Foot Forefoot Flexibility on Gait of Unilateral Transtibial Prostheses Users (journal of JRRD)

[94] Hafner, B J 2005 Clinical Prescription and use of Prosthetic Foot and Ankle Mechanisms: A Review of the Literature (Journal of Prosthetics and Orthotics) vol 17 no 4 pp 5–11

[95] Francis J T 1989 Energy Storing Feet (Journal of the association of children’s prosthetics orthotics clinics) vol 24

[96] Nicholas P F, Brian J S, Carolyn C S, Richard R N 2009 Topology Optimization and Freeform Fabrication Framework for Developing Prosthetic Feet (Department of Mechanical Engineering), the University of Texas at Austin

[97] Zahra Safaeepour, Ali Esteki, Farhad Tabatabai Ghomshe, Mohammad E Mousavai 2014 Design and Development of A Novel Viscoelastic Ankle-Foot Prosthesis Based on the Human Ankle Biomechanics (Prosthetics and Orthotics International) vol 38 no 5 pp 400–404

[98] R E Quesada, J M Caputo, S H Collins 2016 Increasing Ankle Push-off Work with A Powered Prosthesis Does Not Necessarily Reduce Metabolic Rate For Transtibial Amputees (Journal of Biomechanics) vol 49 pp 3452–3459

[99] H Houdijk, E Pollmann, M Groenewold, H Wiggerts, W Polomski 2009 the Energy Cost For the Step-To-Step Transition In Amputee Walking (Gait & Posture) vol 30

[100] David C Morgenroth, Ava D Segal, Karl E Zelik, Joseph M Czerniecki, Glenn K Klute, Peter G Adamczyk, Michael S Orendurff, Michael E Hahn, Steven H Collins, Art D Kuo 2011 the Effect of Prosthetic Foot Push-off on Mechanical Loading Associated with Knee Osteoarthritis In Lower Extremity Amputees (Gait & posture) vol 34 pp 502–507

[101] H M Herr, A M Grabowski 2012 Bionic Ankle-Foot Prosthesis Normalizes Walking Gait For Persons with Leg Amputation (Proceedings of the Royal Society B-Biological Sciences) vol 279

[102] Burgess E M, Hittenberger D A, Forsgren S M, Lindh D 1983 the Seattle Prosthetic Foot-A Design For Active Sports: Preliminary Studies (Orthot Prosthet) vol 37 no 1 pp 25–31

[103] Burgess E M, Poggie D L, Hittenberger D A 1985 Development and Preliminary Evaluation of the VA Seattle Foot (J Rehabil Res Dev) vol 22 no 3 pp 75–84

[104] John Michael 1987 Energy Storing Feet: A Clinical Comparison (Clinical Prosthetics Orthotics) vol 11 no 3 pp 154–168

[105] Wagner J, Sienko S, Supan T, Barth D 1987 Motion Analysis of SACH Vs Flex-Foot In Moderately Active Below-Knee Amputees (Clinical Prosthetics Orthotics) vol 11 no 1 pp 55–62

[106] Morgan C 2008 Testing and Analysis of Low Cost Prosthetic Feet (Worcester Polytechnic Institute)
[107] R Figueroa, C M Müller-Karger 2009 Using FE for Dynamic Energy Return Analysis of Prosthetic Feet during Design Process (25th Southern Biomedical Engineering Conference 2009, IFMBE Proceedings 24) pp 289–292

[108] Catalina Quintero, Vera Zasúlich P 2019 Materials For Lower Limb Prosthetic and Orthotic Interfaces and Sockets: Evolution and Associated Skin Problems (Rev. Fac. Med.) vol 67 no 1

[109] Karunakaran V 2006 Quality Assurance and Optimization Studies of Light Weight PU Prosthetic Foot (Tends Biomaterial Artif)

[110] Kadhim K R 2011 Design and Analysis of A New Prosthetic Foot for People of Special Needs (A thesis submitted to the Department of Mechanical and Materials Engineering, Technology University)

[111] EMAD K H 2011 A Modified Version of the Prosthetic Foot (A thesis submitted to the Department of Mechanical and Materials Engineering, Technology University)

[112] Muslim M 2011 Design and Analysis of A New Prosthetic Foot for People of Special Needs (A thesis submitted to the Department of Mechanical and Materials Engineering, Technology University)

[113] Yadan Z 2009 Design and Testing of A Passive Prosthetic Ankle with Mechanical Performance Similar To That of A Natural Ankle (Master theses and Professional Projects, Marquette University)

[114] Matt A 2013 An Improved Foot and Ankle Prosthetic Device By Designed Prosthetic Foot (Project Proposal Document Department of Mechanical Engineering Northern Arizona University)

[115] Muhsin J Jweeg, Muhammad Al-Waily, Ahmed K Muhammad, Kadhim K Resan 2018 Effects of Temperature on the Characterisation of a New Design for a Non-Articulated Prosthetic Foot (IOP Conference Series: Materials Science and Engineering) vol 433, 2nd International Conference on Engineering Sciences, Kerbala, Iraq, 26–27 March

[116] Hafner B, Sanders J, Czerniecki J, Fergason J 2002 Transtibial Energy-Storage-and-Return Prosthetic Devices: A Review of Energy Concepts and A Proposed Nomenclature (J Rehabil Res Dev) vol 39 no 1 pp 1–11

[117] Asgeirsson S, Olafsson G 2006 Ingimarsson: Prostetic Foot (United States Patent), US7503937B2 US Grant

[118] Nolan L 2008 Carbon Fibre Prostheses and Running In Amputees: A Review (Foot and Ankle Surgery) vol 14 no 3 pp 125–129

[119] Królikowski W 1984 Tworzywa wzmacnione i włókna wzmacniające (Politechnika Szczecińska, Szczecin)

[120] Czerniecki J, Gitter A, Munro C 1991 Joint Moment and Muscle Power Output Characteristics of Below Knee Amputees During Running: the Influence of Energy Storing Prosthetic Feet (Biomech) vol 24 no 1 pp 63–75

[121] Hassan S M, Majid Habeeb Faith-Allah 2014 Develops New Composite Materials For Prosthetic Foot Industry (International Journal of Materials, Methods and Technologies)

[122] Postema K, Hermens H, De Vries J, H Koopman, Eiswa W 1997 Energy Storage and Release of Prosthetic Feet Part 2: Subjective Ratings of 2 Energy Storing and 2 Conventional Feet, User Choice of Foot and Deciding Factor (Prosthetics and Orthotics International) vol 21 no 1

[123] Alaranta H, Kinnunen A, Karkkainen M, Pohjolainen T, Heliovaara M 1991 Practical Benefits of Flex-Foot In Below-Knee Amputees (Journal of Prosthetics and Orthotics) vol 3 no 4

[124] Shekhar B, Riazi S, Rahamanian S 2009 Mechanical Properties of Carbon Hybrid Braided Structure for Lower Limb Prostheses (Department of General Engineering, San José State University)

[125] M Hamzah, A Gatta 2018 Design of a Novel Carbon-Fiber Ankle-Foot Prosthetic using Finite Element Modeling (IOP Conference Series: Materials Science and Engineering)

[126] Rasaq olawale Medupin, Oladiran Kamardeen Abubakre, Ambali Saka Abdulkareem, Rasheed Aremu Muriana, Asipita Salawa Abdulrahman 2019 Carbon Nanotube Reinforced Natural Rubber Nanocomposite For Anthropomorphic Prosthetic Foot Purpose (Scientific Reportst) vol 9
[127] Jawad Kadhim Oleiwi, Ahmed Namah Hadi 2015 Improving Tensile Strength of Polymer Blends as Prosthetic Foot Material Reinforcement by Carbon Fiber (J Material Sci Eng)
[128] Jawad Kadhim Oleiwi, Ahmed Namah Hadi 2015 Improve Flexural Strength of PMMA/SR Polymer Blend by Reinforcement with Carbon Fibers as Prosthetic Foot Polymer Material (IJAITEM) vol 4 no 2
[129] Jawad K Oleiwi, Ahmed Namah Hadi 2018 Experimental and Numerical Investigation of Lower Limb Prosthetic Foot Made From Composite Polymer Blends (International Journal of Mechanical and Production Engineering Research and Development) vol 08 no 02
[130] Jawad Kadhim Oleiwi, Ahmed Namah Hadi 2016 Design of Prosthetic Foot from Polymer Materials Reinforced by Carbon Fibers (Eng. &Tech.Journal) vol 34 Part (A) no9
[131] Mohammed H S, Jasim M Salman 2020 Design and Modeling the Prosthetic Foot from Suitable Composite Materials (American Journal of Engineering and Applied Science) vol 13 no 3 pp 516–522
[132] Bragaru M, Dekker R, Geertzen J H, Dijkstra P U 2011 Amputees and Sports: A Systematic Review (Sports Med) vol 41 no 9 pp 721–740
[133] Shephard R J 1991 Benefits of Sport and Physical Activity For the Disabled: Implications For the Individual and For Society (Scand J Rehabil Med) vol 23 no 2 pp 51–59
[134] Moffat M 2010 Braving New Worlds: To Conquer, To Endure (Phys ther) vol 84 no 11
[135] South B J, Nicholas P Fey, Gordon Bosker, Richard R Neptune 2010 Manufacture of Energy Storage and Return Prosthetic Feet Using Selective Laser Sintering (Journal of Biomechanical Engineering) vol 132 no 1
[136] Rino Verslyus, Pieter Beyl, Michael Van Damme, Anja Desomer, Ronald Van Ham, Dirk Lefebre 2009 Prosthetic Feet: State-of-the-Art Review and the Importance Mimicking Human Ankle–Foot Biomechanics (Disability and Rehabilitation: Assistive Technology) vol 4 no 2 pp 65–75
[137] Bryce T J Dyer, Siamak Noroozi, Sabi Redwood, Philip Sewell 2014 the Design of Lower-Limb Sports Prostheses: Fair Inclusion In Disability Sport (Disability & Society) vol 25 no 5
[138] Phillips VLSC (UT) 1985 Composite Prosthetic Foot and Leg (United States Patent), Flex Foot, Inc. (Irvine, CA): United States
[139] Sarah McCarvill 2005 Essay: Prosthetics For Athletes (Lancet) vol 366
[140] Romo H D 1999 Specialized prostheses for activities: an update (Clin Orthop Relat Res) vol 361 pp 63–70
[141] Louis-Philippe Riel, Jérôme Adam-Côté, Stéphane Daviault, Christophe Salois, Julien Laplante-Laberge, Jean-Sébastien Plante 2009 Design and Development of A New Right Arm Prosthetic Kit For A Racing Cyclist (Prosthet Orthot Int) vol 33, no 3, pp 284–291
[142] Francis J Torst 2000 Energy Storing Feet (J. of the Association of Children's Prosthetic – Orthotic Clinics) vol 24 no 4 pp82–101
[143] Saleel H Abood, Majid Habeeb Faidh-Allah 2019 Analysis of Prosthetic Running Blade of Limb Using Different Composite Materials (Journal of Engineering) vol 25 no 12
[144] Muhsin J Jweeg, Shaker S Hassan, Ammar S Hamid 2015 Impact Testing of New Athletic Prosthetic Foot (International Journal of Current Engineering and Technology)
[145] Mohsin N Hamzah, Ammar S Merza, Lamees Hussein Ali 2017 Experimental and Numerical Investigations of Athlete Prosthetic Feet Made of Fiber Glass Reinforced Epoxy (First International Conference on Recent Trends of Engineering Sciences and Sustainability)
[146] Ekhlas M Fayyadh, Sadeq H Bakhy, Yasir M Shkara 2014 A New Multi-Objective Evolutionary Algorithm For Optimizing the Aerodynamic Design of HAWT Rotor (ASME 2014 12th Biennial Conference on Engineering Systems Design and Analysis, ESDA)
[147] Muhammad Al-Waily, Maher A R Sadiq Al-Baghhdadi, Rasha Hayder Al-Khayat 2017 Flow Velocity and Crack Angle Effect on Vibration and Flow Characterization for Pipe Induce Vibration (International Journal of Mechanical & Mechatronics Engineering) vol 17 no 5
[148] Kadhim K Resan, Abbas A Alasadi, Muhammad Al-Waily, Muhsin J Jweeg 2018 Influence of Temperature on Fatigue Life for Friction Stir Welding of Aluminum Alloy Materials (International Journal of Mechanical & Mechatronics Engineering) vol 18 no 02
[149] Rasha Hayder Al-Khayat, Maher A R Sadiq Al-Baghdadi, Ragad Aziz Neama, Muhammad Al-Waily 2018 Optimization CFD Study of Erosion in 3D Elbow During Transportation of Crude Oil Contaminated with Sand Particles (International Journal of Engineering & Technology) vol 07 no 03 pp 1420–1428

[150] Ragad Aziz Neama, Maher A R Sadiq Al-Baghdadi, Muhammad Al-Waily 2018 Effect of Blank Holder Force and Punch Number on the Forming Behavior of Conventional Dies (International Journal of Mechanical & Mechatronics Engineering) vol 18, no 04

[151] Muhsin J Jweeg, Kadhim K Resan, Esraa A Abbod, Muhammad Al-Waily 2018 Dissimilar Aluminium Alloys Welding by Friction Stir Processing and Reverse Rotation Friction Stir Processing (IOP Conference Series: Materials Science and Engineering) vol 454International Conference on Materials Engineering and Science, Istanbul, Turkey, 8 August

[152] H J Abbas, M J Jweeg, Muhammad Al-Waily, Abbas Ali Diwan 2019 Experimental Testing and theoretical Prediction of Fiber Optical Cable for Fault Detection and Identification (Journal of Engineering and Applied Sciences) vol 14 no 02 pp 430–438

[153] Sadiq E Sadiq, Sadeq H Bakhy and Muhsin J Jweeg 2020 Effects of Spot Welding Parameters on the Shear Characteristics of Aluminum Honeycomb Core Sandwich Panels In Aircraft Structure (Test Engineering and Management) vol 32 no 7 pp 7244–7255

[154] Akeel Z Mahdi, Samir A Amin, Sadeq H Bakhy 2020 Influence of Refill Friction Stir Spot Welding Technique on the Mechanical Properties and Microstructure of Aluminum AA5052 and AA6061-T3 (IOP Conference Series: Materials Science and Engineering) 671

[155] Russul A Kadhim, Ekhlas M Fayyadh, Sadeq H Bakhy 2020 Stirrer Speed Control of A Fluidized Bed Dryer For Biomass Particles Using Pwm Technique (Plant Archives) vol 20

[156] Ehab N Abbas, Muhammad Al-Waily, Tariq M Hammza and Muhsin J Jweeg 2020 An Investigation to the Effects of Impact Strength on Laminated Notched Composites used in Prosthetic Sockets Manufacturing (IOP Conference Series: Materials Science and Engineering, 2nd International Scientific Conference of Al-Ayen University) vol 928

[157] Sadiq Emad Sadiq, Muhsin J Jweeg and Sadeq H Bakhy 2020 The Effects of Honeycomb Parameters on Transient Response of an Aircraft Sandwich Panel Structure (IOP Conference Series: Materials Science and Engineering) vol 928

[158] Muhammad Al-Waily, Moneer H Tolephih and Muhsin J Jweeg 2020 Fatigue Characterization for Composite Materials used in Artificial Socket Prostheses with the Adding of Nanoparticles (IOP Conference Series: Materials Science and Engineering, 2nd International Scientific Conference of Al-Ayen University) vol 928