



Optimal selection of stiffness for prosthetic foot and ankle: Manufacturing and testing

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ABSTRACT

A major object of prosthetics fitting procedure his to provide the amputee with the greatest potential long-term rehabilitation result by providing the finest feasible design. The foot keel and ankle joint are two key components for transtibial prosthetic users. This essay’s objective is to determine the effect of systematically altering the stiffness of prosthetic foot keel and ankle joint on standing in individuals who have undergone unilateral transtibial amputations. A balance analysis was carried out to select the optimal combination of prosthetic foot and joint. According to the findings, the medium foot and soft ankle joint is the best one for standing analysis.

KEYWORDS

prosthetic, amputee, ankle, transtibial, balance

1. INTRODUCTION

Prosthetic feet come in various stiffness categories, but there is no data to help choose the right one during prosthetic foot prescription [1–3]. The effect of “prosthetic foot’s” mechanical properties on several components of gait is yet unclear. Two major mechanical requirements must be met in combination with the “prosthetic knee” joints and socket:

- During the stance phase, the prosthesis must support the body with maximum stability, which means for example that the resulting ground reaction force must pass in front of the knee joint’s immediate center of rotation;
- Walking with prosthesis must be as energy-efficient as feasible.

Stability and use of energy of the foot are influenced by four mechanical features of the foot, as well as the foot’s roll-over behavior:

- The point of application of ground response force on foot is determined by the form and alignment of foot and pylon angle. The form also influences the vertical and horizontal movement of the prosthesis and body during walking;
- According to an experimental investigation, the appropriate choice of mass may greatly enhance various symmetry coefficients of walking;
- Foot stiffness controls the deformation of the foot during weight-bearing; as a result, it has an impact on the foot’s form. Due to the fact that a soft foot may be able to store more energy than a rigid foot under the same force. It may be important to store and release energy during the weight-bearing process;
- Hysteresis is a pure energy issue that happens during the loading and unloading of a deformable object. It signifies a loss of energy as a result of internal friction. Reduce energy cost of walking by minimizing the hysteresis of the foot, as long as the stored energy is retrieved profitably.

The stiffness degree chosen is based on the amputee’s body weight and activity level and is usually limited to the heel grade of the one-foot type. It is unclear how various foot types vary

in stiffness, despite the fact that the growing variety of foot kinds necessitates learning more about the specific benefits of different feet [4].

2. RELATED WORKS

Through the investigative research on the topic, the most important related research can be summarized.

Human gait is determined by a variety of factors, including muscles activation, joint kinematics and kinetics, and the characteristics of the foot-ground contact. Lower limb stiffness is critical in defining how the body interacts with the ground surface. Numerous research has been conducted to better understand high-impact sports' stiffness and damping qualities like hopping and landing [5]. In 2009, Lebedowska et al. [6] present research to evaluate (1) if foot landing location affects the inherent dynamics of the human body and (2) the degree to which the Ground Reaction Forces (GRF) curve accurately represents the response of inherent body dynamics to rapid loading. Eight non-disabled control volunteers did a series of tiny leaps and landed in three different foot landing positions: heel, mid-foot, and toe. They then walked independently across force plates at a self-paced velocity. The stiffness K , damping B , and "dimensionless damping coefficient ξ " were computed. The time interval between the vertical GRF's two peaks T_{GRF} to T was compared. The stiffness K and B dropped and remained constant ($P < 0.01$) between heel and toe landing positions. T_{GRF} was not significantly different from T for toe-landing, indicating that the dynamic body reaction significantly affects the form of GRF. The prosthetic engineering community has traditionally focused on decreasing heel-strike impact using the Solid Ankle Cshioned Heel (SACH) foot to improve prosthetic stiffness. In 2013, using a simple linear compression test, Adamczyk et al. [7] derived and analyzed a technique for estimating the angular stiffness of prosthetic feet. Linear vertical compression experiments were carried out on nine experimental multi-component feet (with known component stiffness properties and geometry), allowing for a parametric change of the hindfoot and forefoot stiffness values and geometries. At different pylon test angles, each arrangement was loaded under displacement control. The rate of change of the Center Of Pressure (COP) concerning linear displacement was used to compute angular stiffness as a function of the pylon angle, normal force, and COP rate of change. This approach should be accessible to a range of labs for estimating the angular stiffness of experimental and commercially available prosthetic feet with minimum equipment. In 2017, Beck et al. [8] highlighted how running-specific prostheses and running speed impact the biomechanics of athletes with bilateral transtibial amputations prosthesis stiffness and height influence biomechanics were attenuated and unaltered at increased running speeds. For athletes with bilateral transtibial amputations, prosthetic stiffness, not height, likely has a greater influence on distance running performance than sprinting. In 2018, Koehler-McNicholas et al. [9] published a study examining the ability

of currently available prosthetic ankle-foot systems to accommodate weighted walking by examining the mechanical characteristics (forefoot stiffness) and dynamic function (rocker radius, effective foot length ratio, and late-stance energy return) of prosthetic feet designed for high-activity users. In 2019, Hedrick et al. [10] wanted to find out how ankle stiffness affects how much energy it takes to walk when there are different forces on the body (i.e., with and without additional load). Individuals wore an immobilizer boot with a robotic ankle-foot prosthetic emulator to imitate an amputation. The prosthetic emulator was programmed to follow five ankle stiffness conditions based on human ankle quasi-stiffness values found in the literature. Individuals walked with and without bearing an extra burden of roughly 30% of body mass with these five ankle stiffness settings (i.e., ten total trials). The maximum stiffness decreased metabolic cost for both load circumstances with the stiffness range they examined, including a 3% drop in metabolic cost with an increase in stiffness of roughly $0.0480 \text{ Nm deg}^{-1} \text{ kg}^{-1}$ during average (no load) walking. In this study one of the most important reasons for picking this subject is its sensitivity and direct influence on patients, since the focus is on giving the best suitable prosthetic foot in terms of performance and comfort comparable to the sound one. This study examines the influence of the stiffness of prosthetic feet and ankle bumpers on the standing and walking of unilateral amputees. Additionally, it seeks to pick the prosthetic foot that is most comparable to the sound one.

3. METHODOLOGY

The approach used in this study was based on selecting a prosthetic foot (SACH foot) from domestic markets, creating a template based on this foot for manufacturing, and investigating the new foot samples, which were then compared on stiffness and balance.

4. MATERIALS

In this study, three types of materials have been used with a degree of flexibility that differs from the other; different polymers with different flexibility were used to make the feet and ankle bumper models. The materials and supplies have been prepared to perform the practical work of manufacturing the feet from the local market based on the recommendations of reference [11]; the following are basic materials used in this study: silicon rubber considered the least complex type, is characterized by a high degree of flexibility; acrylic and thermal silicon the stiffest one of them as it can be seen in Fig. 1.

5. FOOT DESIGN AND MANUFACTURING

In this investigation, a double-axis dynamic prosthetic foot was employed, as shown in Fig. 2, since it is relatively





Fig. 1. a) Silicon Rubber, b) acrylic solution with the arbitrator, c) thermal silicon
(Source: Authors' photo)



Fig. 2. Double-axis dynamic prosthetic foot
(Source: Authors' photo)

straightforward to change the foot material. The ankle bumpers and the exterior cover have been changed. Three versions of this sort were developed for the foot prosthesis, and the material used in each of the three models was different. Additionally, the posterior region of the ankle joint was altered. The feet models are manufactured according to the following percentage for the silicon rubber foot the percent of the silicon rubber material is 50% and the hardener is 50%. As for the foot made of thermal silicon, the foot is made of thermal silicon with a percent 100%, while the model of the foot is made of acrylic and silicone; the foot is made of acrylic material with a percent is 50% and its hardener is 50%.

A plastic template was created using polylactic acid to make the three samples. In contrast, Fig. 3 depicts the material pouring into the plastic mould and the complete feet samples. The weight of the silicone rubber foot is 641.2 gm, the thermal silicon foot weight is 679.9 gm, the weight of the acrylic foot with silicone rubber is 645.4 gm, and the weight of polyurethane foot is 369.9 gm.

Also, when making the ankle bumper, the mixing ratios of the three main materials differ, as the first sample was made of silicon rubber with a weight of 39 and 52.2 g of acrylic, the second sample was made of thermal silicon with a weight of 43.1 and 36.3 g of acrylic. The last sample was made of silicon rubber with a weight of 32 and 52.5 g of acrylic. Figure 4 illustrates the manufactured samples for the ankle bumpers.

Six cases have been conducted on the patient wearing the different types of prosthetic feet, as it is presented in Table 1. Various combinations of the SACH forefoot and the ankle bumper were used in this analysis. The letter *H* refers to the hard materials based on their stiffness, while the letter *S* refers to the soft materials, and the letter *M* refers to the medium materials.

6. EXPERIMENTAL WORK

Two critical tests were employed in this investigation in order to figure out the effect of the foot and ankle stiffness on standing as follows:



Fig. 3. The complete samples
(Source: Authors' photo)

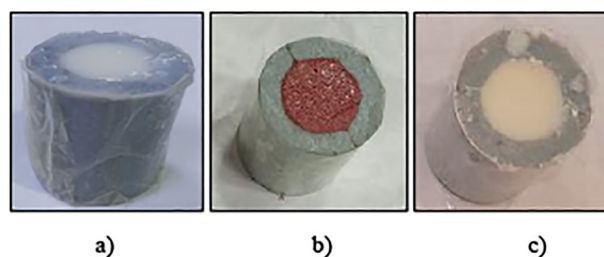


Fig. 4. Ther ankle bumper samples, a) silicon rubber 39 and 52.2 g of acrylic, b) thermal silicon 43.1 and 36.3 g of acrylic, c) silicon rubber 32 and 52.5 g of acrylic
(Source: Authors' photo)

Table 1. Different combinations of used forefeet and ankle bumpers

No.	Case	Description
1	Original polyurethane foot with its ankle	Hard foot based on stiffness Hard ankle bumper
2	Foot: medium stiffness Ankle: hard stiffness	Medium foot (acrylic + silicon rubber) Hard ankle bumper (acrylic + low percentage of silicon rubber)
3	Foot: medium stiffness Ankle: soft stiffness	Medium foot (acrylic + silicon rubber) Soft ankle bumper (silicon rubber + acrylic)
4	Foot: medium stiffness Ankle: medium stiffness	Medium foot (acrylic + silicon rubber) Medium ankle bumper (thermal silicon+ acrylic)
5	Foot: soft stiffness Ankle: hard stiffness	Soft foot (silicon rubber) Hard ankle bumper (acrylic + low percentage of silicon rubber)
6	Foot: hard stiffness Ankle: soft stiffness	Hard foot (thermal silicon) Soft ankle bumper (silicon rubber + acrylic)

Source: Authors'.

6.1. Compression test

The compression test was used to determine the stiffness of the three kinds of feet by applying force or pressure to the shank (foot leg) and measuring the amount of deflection at the front of these forefoot models using the Testometric instrument where fingers fixed the foot on a wooden mould. Figure 5 illustrates the testing process for one of the above samples, where the input device speed was about (3 mm s^{-1}) and a fixed displacement of (5 mm) while the changed parameter is the force.

6.2. Balance test

The amputee stood on the force plate instrument for 30 s wearing one of the manufactured feet with eyes closed and opens for the open and close base as part of the balancing analysis. This procedure was repeated for all the manufactured samples, where the tests were grouped by:

- Eyes open-open base;
- Eyes closed-open base;
- Eyes open-closed base;
- Eyes closed-closed base.

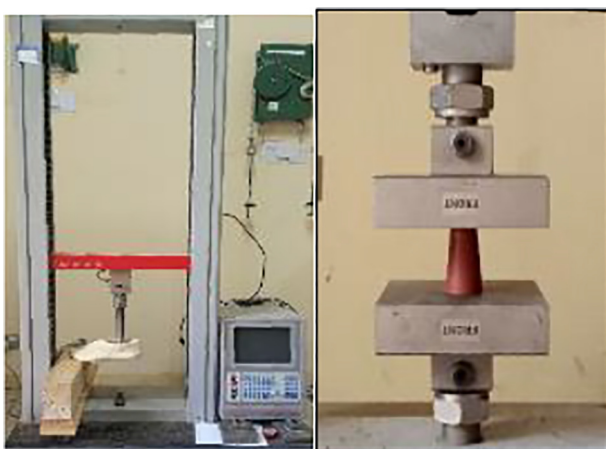


Fig. 5. The installation of foot and ankle bumper in testometric device
(Source: Authors' photo)

The balancing analysis data were collected using the computer, and Fig. 6 shows all the testing cases.

7. RESULTS AND DISCUSSION

7.1. Compression test results

The stiffness of the used forefeet and the ankle bumpers was obtained using the compression test. The results of the foot and ankle samples are introduced in Table 2.

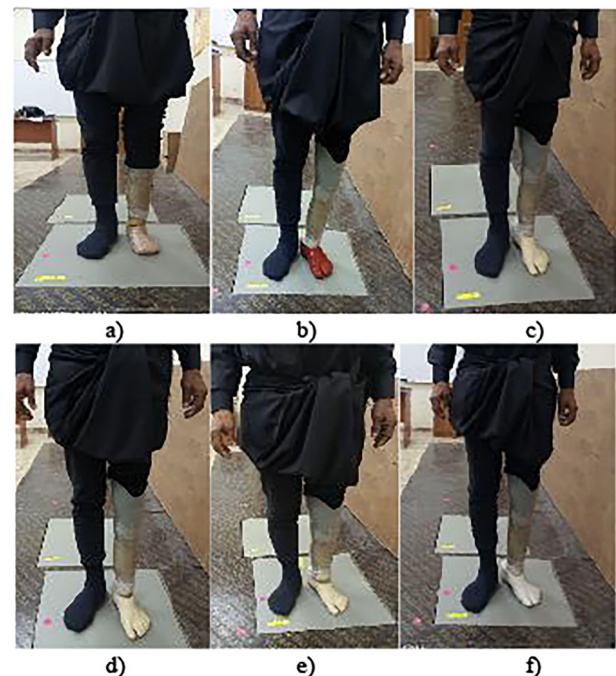


Fig. 6. Balancing analysis cases, a) polyurethane foot, b) silicon rubber foot and soft ankle bumper, c) acrylic foot and hard ankle bumper, d) acrylic foot and medium ankle bumper, e) acrylic foot and soft ankle bumper, f) silicon rubber foot and hard ankle bumper
(Source: Authors' photo)

Table 2. Stiffness results

Type of Material	Stiffness (N mm ⁻¹)
Polyurethane Prosthetic Foot	39.018
Thermal Silicone Prosthetic Foot	45.513
Silicone Rubber Mixed with The Acrylic Prosthetic Foot	19.135
Silicone Rubber Prosthetic Foot	6.859
Polyurethane Ankle Bumper	42.212
Acrylic with Silicone Rubber Ankle Bumper	18.577
Thermal Silicone with Acrylic Ankle Bumper	13.369
Silicone Rubber with Acrylic Ankle Bumper	4.276

Source: Authors'.

It is clear that the thermal silicone double-axis dynamic prosthetic foot has the highest stiffness value as expected. The polyurethane double-axis dynamic prosthetic foot has the second-highest stiffness value. It also shows that the value of the stiffness decreased for the silicone rubber mixed with the acrylic double-axis dynamic prosthetic foot. In

contrast, the smallest stiffness value appeared with the silicone rubber double-axis dynamic prosthetic foot. The polyurethane ankle bumper has the highest stiffness value. The acrylic with silicone rubber ankle bumper has the second-highest stiffness value. It also shows that the stiffness value decreased for the thermal silicone with an acrylic ankle bumper. In contrast, the smallest stiffness value appeared with the Silicone rubber with an acrylic ankle bumper.

7.2. Balance test results

The balance analysis was taken based on the mean root square for the results of the center of pressure in the two directions. Figure 7 shows the balance results for the four conditions.

Figure 7a shows the result of the first condition (eyes open – open base), where the diamond series represents the results of the root mean square for the center of pressure about x-direction. In contrast, the square series represents the results of the root mean square for the center of pressure about the y-direction. The second condition (eyes closed – open base) is depicted in Fig. 7b, where the diamond series depicts the root mean square values for the pressure center

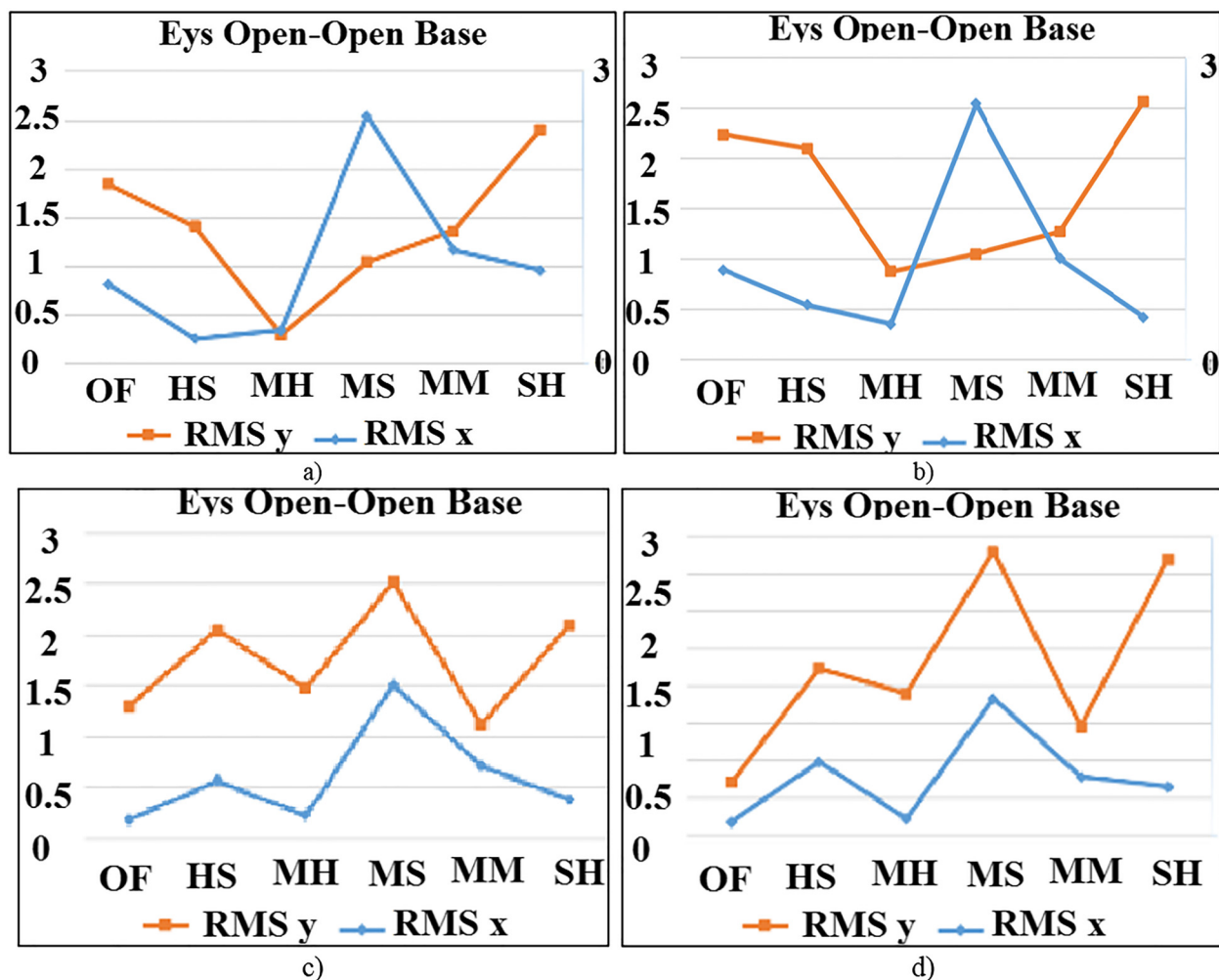


Fig. 7. Root mean square results

about the x -axis. In comparison, the square series represents the results of the root mean square for the pressure center's position relative to the y -axis. Figure 7c depicts the third condition (eyes open – closed base), with the diamond series representing the results of the root mean square for the pressure center about the x -axis. On the other hand, the square series represents the results of the root mean square for the pressure center about the y -axis. The fourth condition (eyes closed – closed base) is depicted in Fig. 7d, with the diamond series reflecting the results of the root mean square for the pressure center around the axis. However, the square series depicts the results of calculating the root mean square for the pressure center around the y -axis, which is represented by the square.

The root mean square for the center of pressure about x -direction is the smallest for the (medium foot + hard ankle bumper) condition and highest for the (medium foot + hard ankle bumper) condition during the standing balancing experiment with eyes closed. The other cases (hard foot + soft ankle bumper, medium foot + medium ankle bumper, and soft foot + soft ankle bumper) are close to each other and better than the original SACH foot. This study shows the relationship between the rigidity of the manufactured material and the weight of the amputee, because each weight has a specific range of stiffness to be acceptable to the person wearing the prosthetic foot in accordance with the body weight and the estimation of the amputee's comfort when wearing the prosthetic foot, as the manufacturers of prosthetic limbs when manufacturing the feet take into account the issue of the rigidity of the prosthetic foot with subject weight ranges within all weight ranges (hardness categories are for a broader range of user body weights than others) as incremental increases in user body weight can lead to inconsistent stiffness increases (e.g., larger changes may be expected in stiffness between classes with wider weight ranges).

8. CONCLUSIONS

The following are the key findings of this research:

1. The findings show that the stiffness of a prosthetic foot and ankle bumper significantly impacts standing performance;
2. The experimental results showed that the thermal silicone double-axis dynamic prosthetic foot has the highest stiffness value, while the smallest stiffness value appeared with the silicone rubber double-axis dynamic prosthetic foot;
3. The root mean square for the center of pressure about x -direction is the smallest for the MH condition and highest for the MS condition during the standing balancing experiment with eyes closed, supporting our theory.

REFERENCES

- [1] F. M. Kadhim, M. S. Al-Din Tahir, and A. T. Naiyf, "The effect of vibrations on the mechanical properties of laminations," *Pollack Period.*, vol. 17, no. 1, pp. 62–65, 2022.
- [2] S. A. D. Tahir, S. S. Hassan, and J. S. Chiad, "Kinematic analysis for passive multi-axes ankle joint," *Pollack Period.*, vol. 17, no. 3, pp. 36–41, 2022.
- [3] E. G. Halsne, J. M. Czerniecki, J. B. Shofer, and D. C. Morgenroth, "The effect of prosthetic foot stiffness on foot-ankle biomechanics and relative foot stiffness perception in people with transtibial amputation," *Clin. Biomech.*, vol. 80, 2020, Paper no. 105141.
- [4] H. W. L. van Jaarsveld, H. J. Grootenboer, J. de Vries, and H. F. J. M. Koopman, "Stiffness and hysteresis properties of some prosthetic feet," *Prosthet. Orthot. Int.*, vol. 14, no. 3, pp. 117–124, 1990.
- [5] T. J. Peterson, "The effect of prosthetic foot component stiffness on initiation and termination of transtibial amputee gait," MSc Thesis, University of Washington, 2012.
- [6] M. K. Lebedowska, T. M. Wente, and M. Dufour, "The influence of foot position on body dynamics," *J. Biomech.*, vol. 42, no. 6, pp. 762–766, 2009.
- [7] P. G. Adamczyk, M. Roland, and M. E. Hahn, "Novel method to evaluate angular stiffness of prosthetic feet from linear compression tests," *J. Biomech. Eng.*, vol. 135, no. 10, 2013, Paper no. 104502-5.
- [8] O. N. Beck, P. Taboga, and A. M. Grabowski, "How do prosthetic stiffness, height and running speed affect the biomechanics of athletes with bilateral transtibial amputations?" *J. R. Soc. Interf.*, vol. 14, no. 131, pp. 1–10, 2017.
- [9] S. R. Koehler-McNicholas, E. A. Nickel, K. Barrons, K. E. Blaharski, C. A. Dellamano, S. F. Ray, B. L. Schnall, B. D. Hendershot, and A. H. Hansen, "Mechanical and dynamic characterization of prosthetic feet for high activity users during weighted and unweighted walking," *PLoS ONE*, vol. 13, no. 9, pp. 1–16, 2018.
- [10] E. A. Hedrick, P. Malcolm, J. M. Wilken, and K. Z. Takahashi, "The effects of ankle stiffness on mechanics and energetics of walking with added loads: A prosthetic emulator study," *J. NeuroEng. Rehabil.*, vol. 16, 2019, Paper no. 148.
- [11] A. I. Al-Mosawi, "Study of some mechanical properties for polymeric composite material reinforced by fibers," *Al-Qadisiyah J. Eng. Sci.*, vol. 2, no. 1, pp. 14–24, 2009.

