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Experimental investigations and finite element modelling of a suggested prosthetic foot

M.J. Jweeg [a], A.K. Hassan [b], M.M. Almudhaffar [b,*]
[a] College of Technical Engineering, Al-Farahidi University, Iraq
[b] Prosthetics and Orthotics Engineering Department, College of Engineering, University of Kerbala, Iraq
* Corresponding e-mail address: muslim.m@uokerbala.edu.iq
ORCID identifier: https://orcid.org/0000-0003-4429-5376 (A.K.H.)

ABSTRACT

Purpose: To design and manufacture a dynamic cheap prosthetic foot compatible with amputees' requirements by introducing a natural fibre called kenaf (scientific name Hibiscus cannabinus L).

Design/methodology/approach: In two cases, four suggested designs were analysed using the finite elements method (FEM) with a commercial ANSYS R1 program. The first case was a heel strike. The second was toe-off by subjecting force equal to 70 kg for both cases to select the optimal design.

Findings: The foot found the tensile strength, flexural strength, impact stress, and fatigue test according to ISO 10328 standards successfully.

Research limitations/implications: The selected design was analysed again using the ANSYS R1 program for weights 60, 70, and 80 kg for two sequences, one containing kenaf, to study how such additive could affect the mechanical properties and estimate the proper quality weight of the foot. The winner's design was then produced and tested in a fatigue foot tester according to ISO 10328 standards.

Practical implications: The results showed that the sequence containing the natural fibres kanaf material improved the deformation by 20% for both cases (from 7.47 to 8.92 mm for the heel strike case for a weight of 80 kg for the sequence without and with kanaf, respectively), and the damping ratio increased by 50% (0. 188 and 0.273 for the sequence without and with kenaf, respectively), which means an increase in the stored energy and higher stability. Also, the mechanical properties like maximum tensile strength, flexural strength, impact stress, and natural frequency were modified.

Originality/value: This paper develops an analytical and practical study to design and produce a dynamic cheap prosthetic foot made from natural fibres, which are characterized as renewable, cheap, recyclable, and environmentally friendly materials with good mechanical properties. Authors believe it is the first time to use natural kenaf fibres in the prosthetic foot manufacturing field.

Keywords: Prosthetic foot design, Kenaf fibres, Dynamic foot analysis, Composite materials

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BIOMEDICAL AND DENTAL MATERIALS AND ENGINEERING

1. Introduction

Lower limb amputations are performed in patients of all ages for several reasons. The amputation is performed below the knee and allows patients to use a prosthesis for ambulation. This activity reviews the indications and techniques for lower limb amputations and highlights the role of the interprofessional team in caring for patients who undergo this procedure. Through the last decades, the artificial foot was developed to meet the amputee's requirements [1]. According to this development and to shorten the time and give the designers a good imagination about their works, many powered programs were created to help them use the finite element analysis methods to analyse the foot statically and dynamically [2]. As previously noted, many researchers were focused on analysing the human foot to have information that could help to enhance the knowledge in foot designing criteria [3]. A.D. Kaze et al. 2017 [4] Studied the validation of the finite element method used to estimate the knee joint forces. The study shows that the results obtained from the finite element method are similar to those obtained from the work of Bergmann et al. (file K7L_280710_1_28P of the patient K7L from database OrthoLoad). J.K. Oleiwi et al. 2018 [5] Studied lower limb produced from two composite material sequences, PolyMethyl Methacrylate, Silicon Rubber PMMA/SR, and PolyMehtyl MethaAcrylate. Polyurethane Rubber (PUR) PMMA/PUR strengthened by carbon fibres (CF) numerically using the finite element method and experimentally. The study concluded that the modulus of elasticity was improved for both sequences as the ratio of carbon fibres to the other materials increased while the dorsiflexion was decreased. M.J. Jweeg et al. 2012 [6] Investigated the reciprocations between fatigue and creep for composite materials used to produce the artificial composites. The study was focused on determining the fatigue defeat at room temperature till 50ºC, which are proper with summer medium in Iraq and the Middle East zone. In the same year, M.J. Jweeg et al. [7] have investigated an empirical and academic study on the specifications of the strengthening fibre kinds of composite materials like long, short, woven, fine grain, and particle strengthening through diverse volumes and particles strengthening with portions of fibres. The outcomes show that the modulus of elasticity in cross directions woven type is better than the unidirectional woven even though the unidirectional outcomes are still accepted. M. Carpenter et al. 2008 [8] studied two types of feet: are the International Committee of the Red Cross SACH foot and Northwestern Shape and Roll (SR) prosthetic foot. Using the finite element technique and empirically. The study concluded that the (SR) foot result proposed the (SR) foot does not proceed like the SACH foot beneath high loading situations and could conduct premature wear of the artificial device. By comparing the FEM results with the experimental test, the study shows the results were closed to each other. J.K. Oleiwi et al. 2021 [9] studied the specification of materials and foot patterns. The study concluded that the SACH feet have good durability than the other types. SACH has good mechanical specifications because of its components and the sole rubber. The absorption criterion is better than in SACH than Jaipur and Seattle. The Jaipur behaviour is closer than the SACH and Seattle feet to the human foot. For the last decades, Polymers, like carbon fibres, fibre glass, and Kevlar fibres, have been most widely used to manufacture artificial elastic feet like the strength to density ratio and shock absorption. KK. Resan et al. 2018 [10] investigated three types of polymer sequences used in artificial feet to estimate the fatigue and mechanical specifications experimentally and numerically. The sequences were: eight layers of perlon, next four layers of perlon, two layers of carbon, four layers of perlon, and four layers of perlon, two layers of Nglass, four layers of perlon. The outcomes show that the difference between what is obtained from the experimental test and the FEM method was 8.93%. Accordingly, those programs that are used FE technique, such as the ANSYS program, are useful for predicting the stress, deformation, and fatigue values with good accuracy. Also, the use of carbon fibres leads to modifying the elasticity modulus and gives a good fatigue factor of safety results. K.M. Olesnavage 2014 [11] studied the characteristics of a low-cost cantilever beam artificial foot and how the stiffness could affect the rollover shape and energy stored in the constrained and unconstrained prosthetic foot using beam bending theory and the FA technique. It concluded that it is difficult to achieve a balance between the rollover shape and the stored energy. For the constrained cantilever beam, the returned stored energy is enhanced, while the rollover shape has deviated from the physiological shape. H. Tryggvason et al. 2020 [13] studied the effect of the damping ratio on prosthetic foot stiffness. The study outcomes that the rise of the damping coefficient increases the overall rotational stiffness. This work appears to design and analyse a new prosthetic foot and compare the number of cycles, dorsiflexion, and impact with the SACH foot. There are many references that can be consulted for the design parameters used in this work [14-21]. The researchers used numerical method to treat with bending and strength problems is finite element method that has been computed one of the preferable techniques for tackling a wide difference of practical problems efficiently [22-24]. It has put forward suggestions. And it is certain that no one used kenaf in the design that improved the mechanical properties, and foot shape is new. Many researches were accomplished and are related to the work conducted here either in research line or materials used and the numerical modelling for the prostheses [25-35]. In this research, an attempt will be achieved for both of these aspects.

2. Plan of work

The flow chart shown in Figure 1 summarizes the search steps

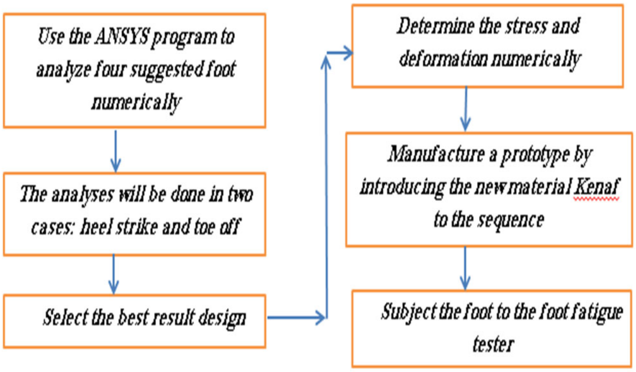


Fig. 1. The search steps

3. The suggested prosthetic foot designs

Four suggested prosthetic foot designs Figures 2-5 have been drawn in Solid Works 2020 and transferred to the ANSYS program R1 2020. The subjected load on these feet, used for analyses, was 70 kg (824 N).

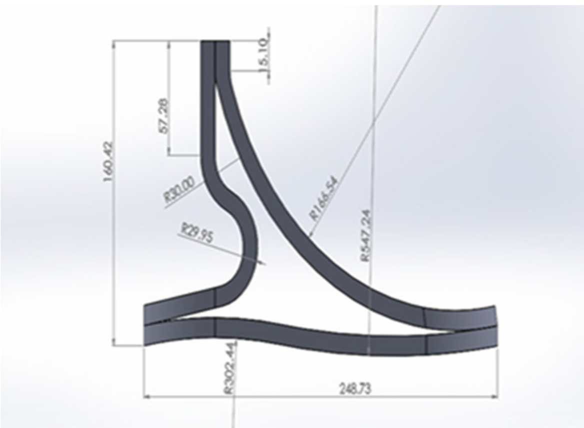


Fig. 2. The first shape

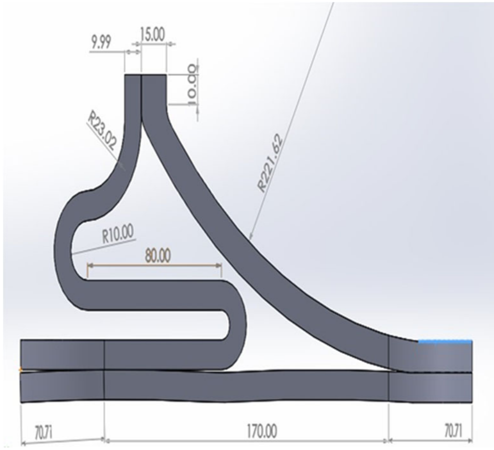


Fig. 3. The second shape

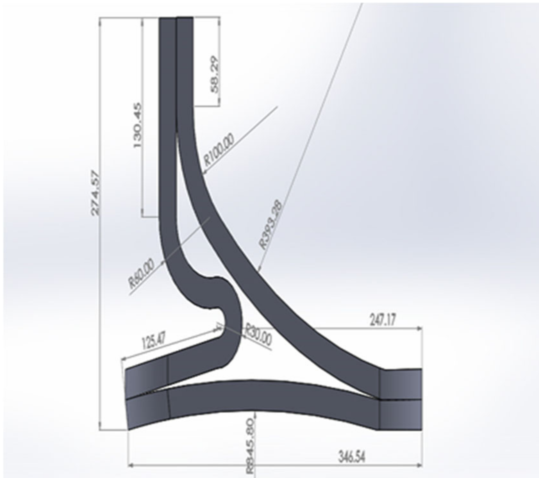


Fig. 4. The third shape

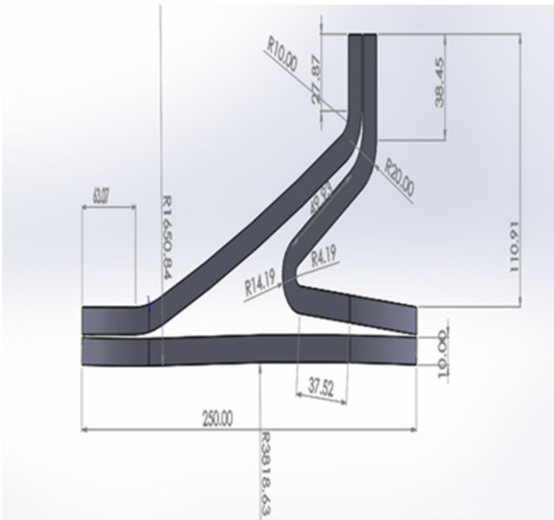


Fig. 5. The fourth shape

4. Meshing the models

Volume mesh was used in this work. Solid 185 code, which is suitable for 3-D solid structure analyses, was used in this process, as shown in Figure 6. Iterations were done to choose the optimum mesh size element. The indicator of optimum mesh was the stability of stress and directional deformation for two elements size serial. A 9 mm was the best element size with total nodes (12103) and elements.

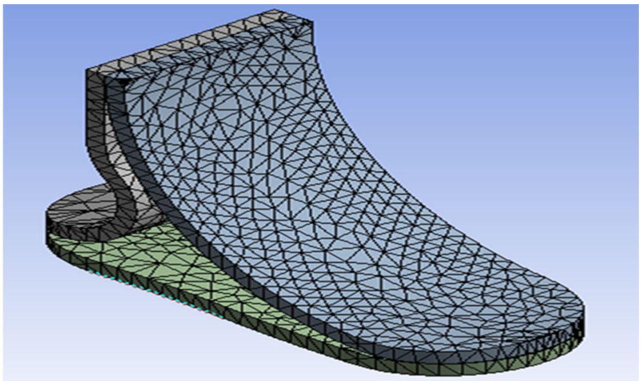


Fig. 6. Meshing the model

5. Defining the load

The load is defined from the workbench, as illustrated in Figure 7. The contact between parts was defined in ANSYS as bonded and the material characterization as isotropic.

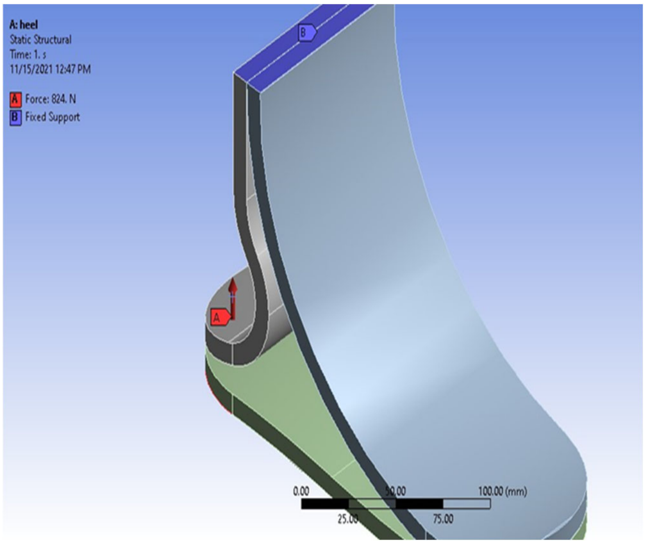
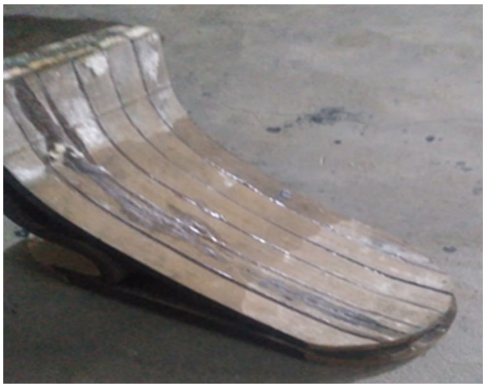


Fig. 7. Defining the Load

6. Design and manufacture new prosthetic foot

After the foot choice had been done, the next step was to construct the foot. A wood mould was created as a casting mould, as seen in Figures 8a,b, then the aluminium die was produced by casting to manufacture the foot parts. As seen in Figures 9a,b, the aluminium was three parts represent the heel, keel, and the base (sole). The sequences with and without kenaf was pressed by the aluminium dies to create the foot parts, as seen in Figures 10a,b,c. Table 1 shows the kenaf properties. Kenaf material (Hibiscus cannabinus L) is considered a natural material and is characterized as cheap, renewable, recyclable, and has excellent flexural strength, tensile strength damping characteristics. The introducing of the kenaf fibres in the manufacturing of a composite prosthetic foot is to play a role in the damping the vibrations during the gait cycle of the patient [12]. Table 2 represents the sequence arrangement, while Table 3 summarizes the tensile, impact, flexural and natural frequency test results.

a)



b)

Fig. 8. The wooden mould: a) assembled, b) individual parts

a) b)

Fig. 9. Aluminium die: a) after casting, b) after finishing

a) b) c)

Fig. 10. The manufacturing process of a foot prosthesis: a) the pressing process, b) foot part after casting, c) assembled foot

Table 1.
Kenaf properties [11]

Fibre	Density, gm/cm^3	Tensile test, MPa	Elastic modulus, GPA	Elongation at brake, %
Kenaf	1.45	930	53	1.6

Table 2.
Sequence arrangement [12]

Sequence with kenaf	Sequence without kenaf
4 perlon, 2 carbon, 1 kenaf, 1 perlon, 1 kenaf, 2 fibre glass, 4 perlon	4 perlon , 2 carbon , 1 perlon , 2 fibre glass, 4 perlon

Table 3.
Sequence with and without kenaf properties [14]

Sequence	Tensile test		Impact, "Average", J,	3 point bending		Damping ratio
	E_{AV}, GPa	σ_{AV}, GPa	Initial energy/energy after impact	E_{AV}, GPa	σ_{AV}, GPa	ξ
without kenaf	2.1	132.40	300/6	3.92	96.88	0.18
with kenaf	1.76	165.84	300/7.5	11.43	235.23	0.27

After the foot had been constructed, the foot was subjected to ISO 10328 standard and it succeeded to reach 1000,000 steps according to the above standard. Figure 11 shows the foot according to the ISO 10328 standard.

Fig. 11. ISO 10328 test [36]

7. Results and discussion

The four suggested designs were drawn in Solid Works 2020 and transferred to ANSYS Workbench R1 2020. Both sequences were analysed statically with a human body weighing 70 kg in heel strike and toes off cases to obtain the best design. Table 4 shows the results.

Table 4.
Numerical analyses results

Weight, kg	Case	Analysis	Directional deformation [Y], mm	Max. stress, MPa
80	Without kenaf	Heel	7.47	34.13
		Toe	36.94	45.71
	With kenaf	Heel	8.92	34.13
		Toe	44.15	45.71
70	Without kenaf	Heel	6.49	29.8
		Toe	32.202	40.3
	With kenaf	Heel	7.81	29.8
		Toe	38.66	40.3
60	Without kenaf	Heel	5.56	25.6
		Toe	27.6	34.3
	With kenaf	Heel	6.7	25.6
		Toe	33.12	34.3

The Figures 12-15 show that the second shape has a very large heel strike deflection. The third one also has a very toe-off deflection. The fourth shape is nearest to SACH's foot [8,15] than ESR's foot. The first shape has a reasonable deflection in both cases for both sequences. The first shape will be chosen to construct the dies and complete the analyses. After the foot had been selected, the wooden moulds were prepared to create the aluminium dies to manufacture the foot. The foot was made from sequences with and without the kenaf natural fibres. Also, the numerical analyses were completed on the selected foot using several loads (80, 70, 60) to see how the kenaf natural fibres affect the sequence. The analyses were done in heel strike and toe-off cases for both feet (made from the sequence with and without kenaf). Figures 16 and 17 show the equivalent Von-Mises stress and the deformation (in the Y direction) for the foot in heel strike and toe-off cases under a load of 80 kg.

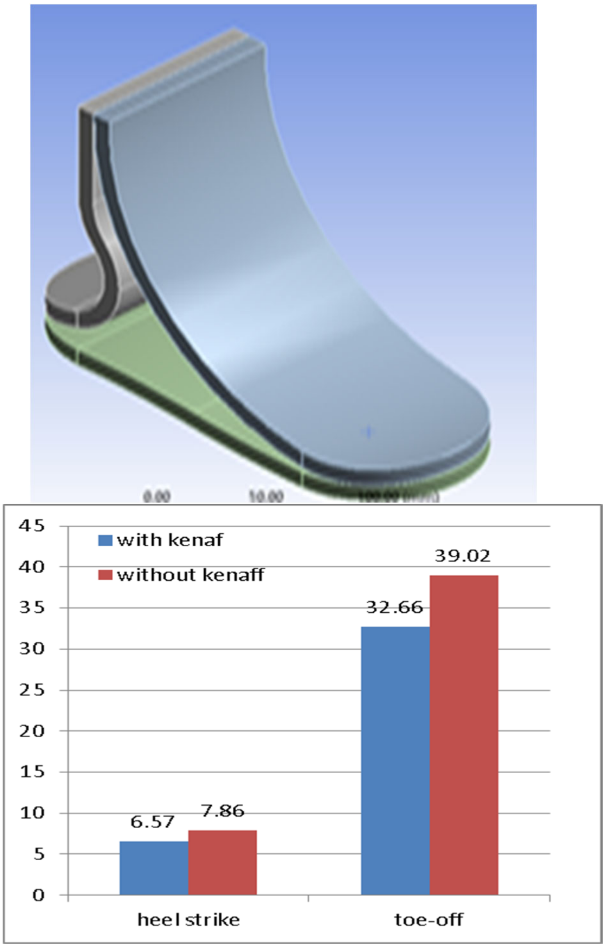


Fig. 12. Heel strike and toe-off for sequence with and without kenaf for the first shape

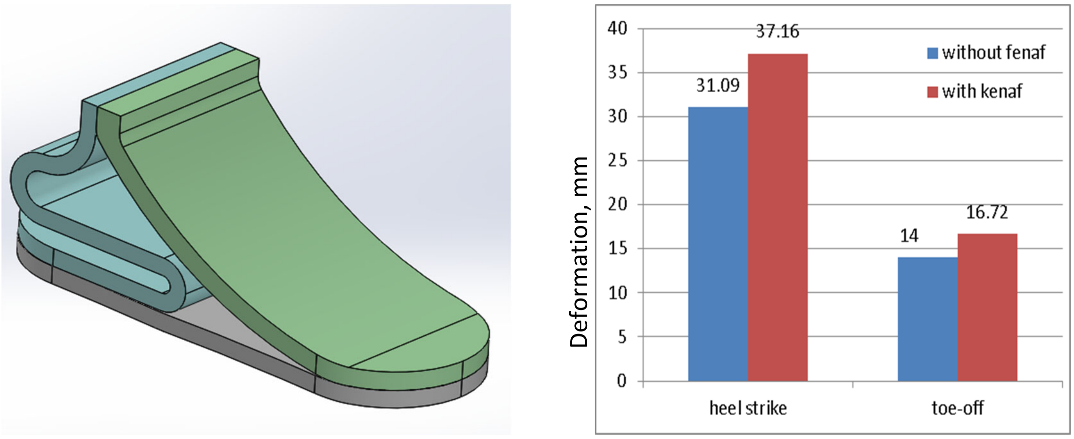


Fig. 13. Heel strike and toe-off for sequence with and without kenaf for the second shape

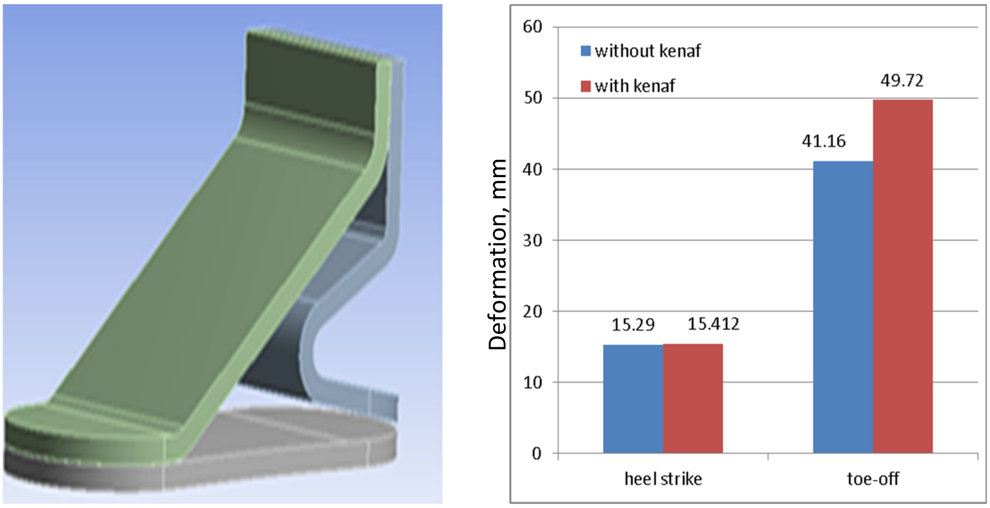


Fig. 14. Heel strike and toe-off for sequence with and without kenaf for the third shape

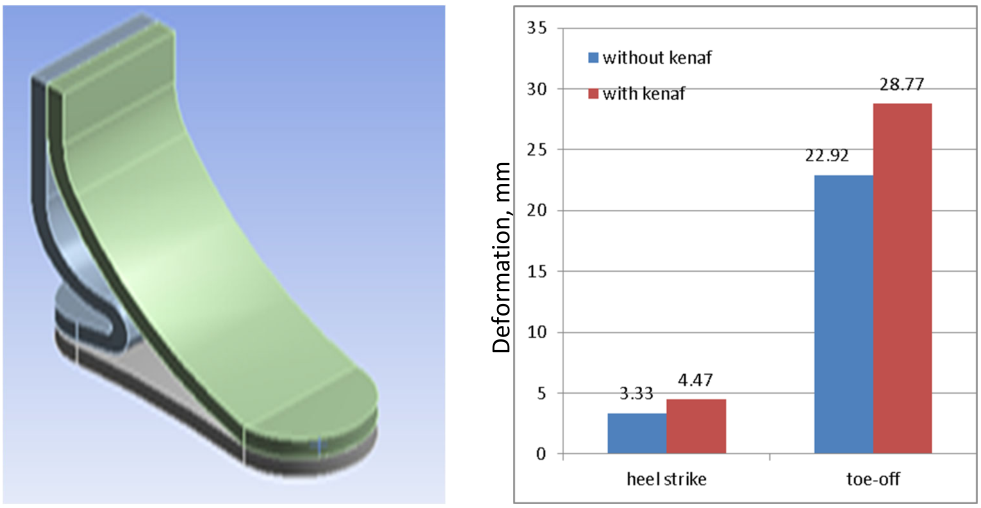


Fig. 15. Heel strike and toe-off for sequence with and without kenaf for the fourth shape

a) b)

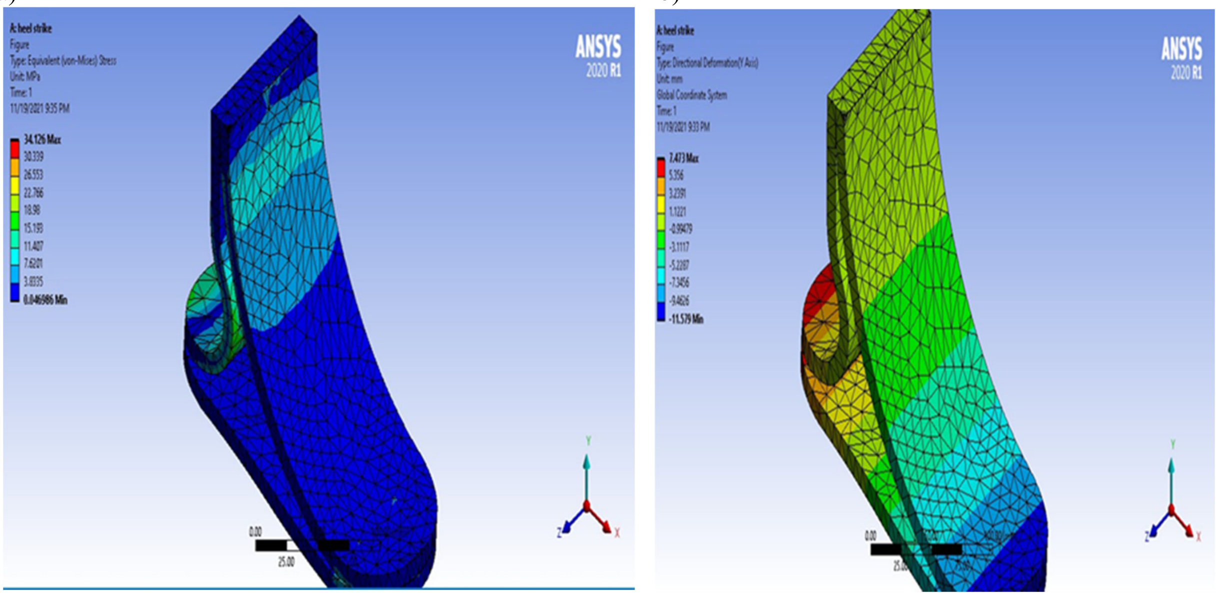


Fig. 16. For load of 80 kg heel strike case for sequence without kenaf (SWOK): a) equivalent Von-Mises Stress, b) deformation in (Y) direction

a) b)

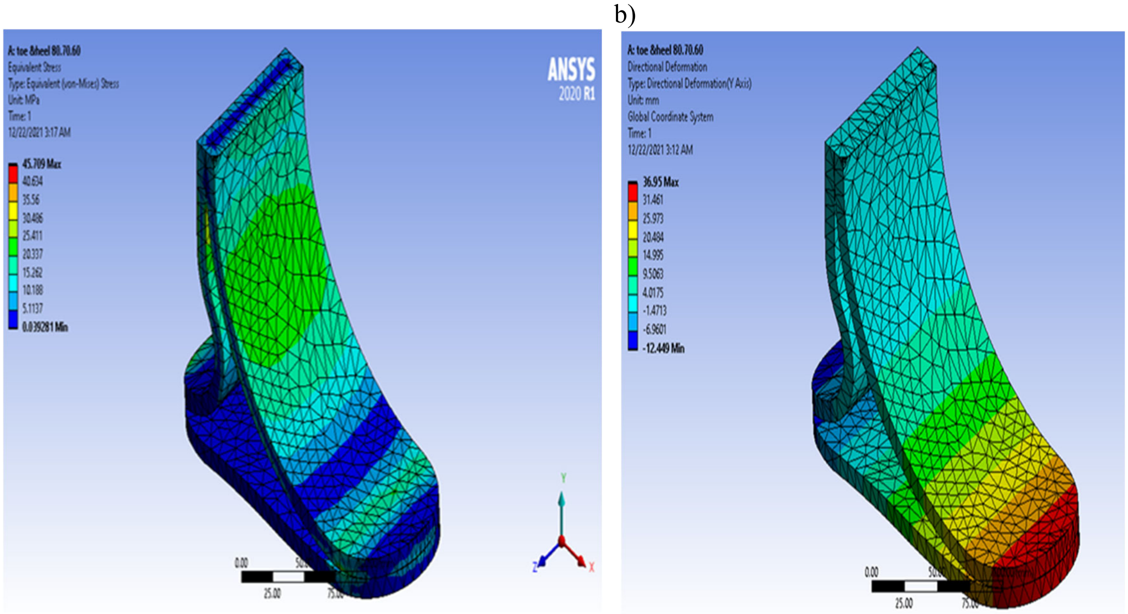
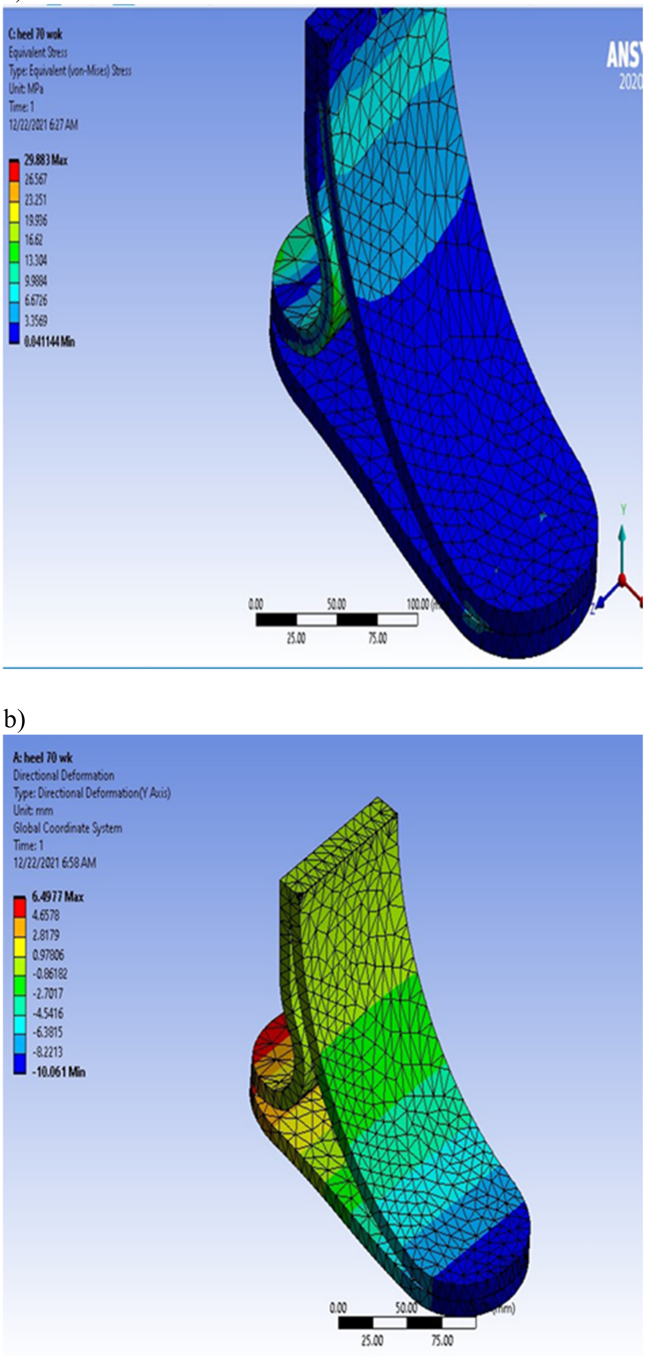


Fig. 17. For load of 80 kg toe-off case (SWOK) a) equivalent Von-Mises Stress, b) deformation in (Y) direction

The reason for using several weights because the produced foot was not made for a specific case and to specify the optimum weight that the foot can serve it. Comparing the results, they showed that the obtained foot is proper for a person weighing about 80 to 70 kg. However, it is recommended to use a 70 kg human body weight.

Figures 18-21 show stress and deformation results of 70 kg, respectively. Table 4 represents full details results for applied loads 80, 70, and 60 kg, and Figure 22 shows heel and toe-off analyses for the foot made of sequence without and with kenaf.

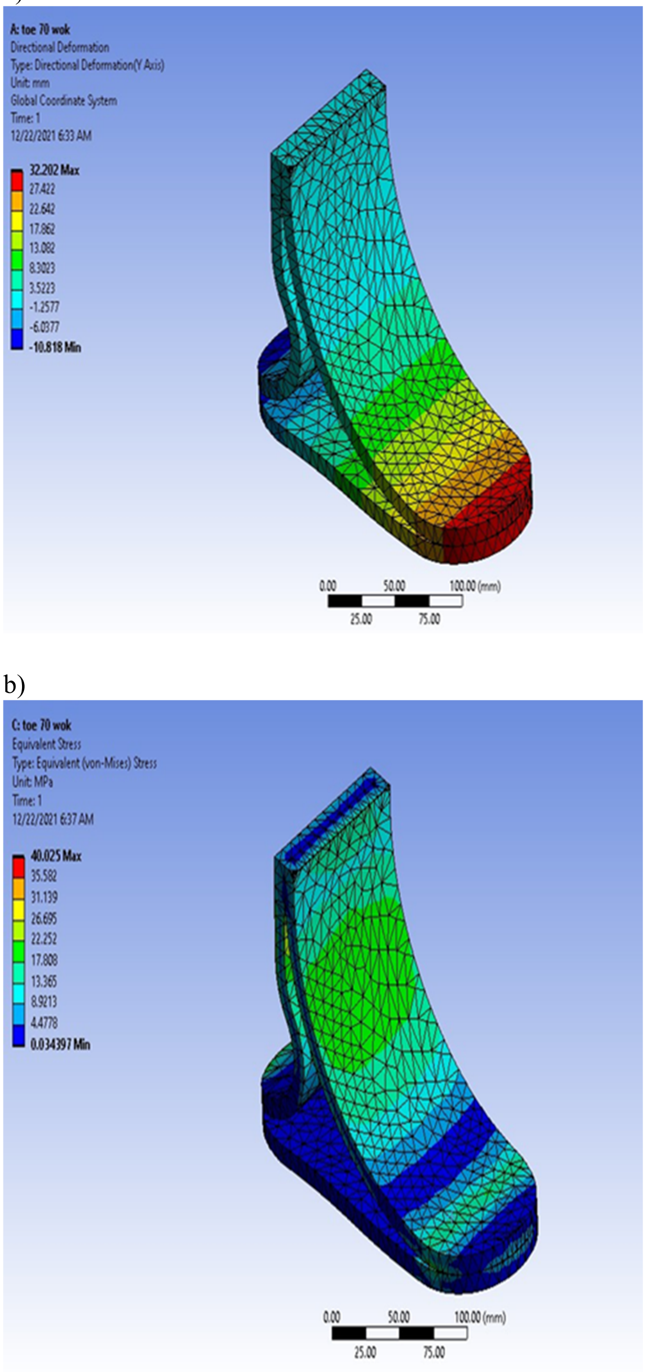
a)



b)

Fig. 18. For load of 70 kg heel strike case for (SWOK): a) equivalent Von-Mises stress, b) deformation in (Y) direction

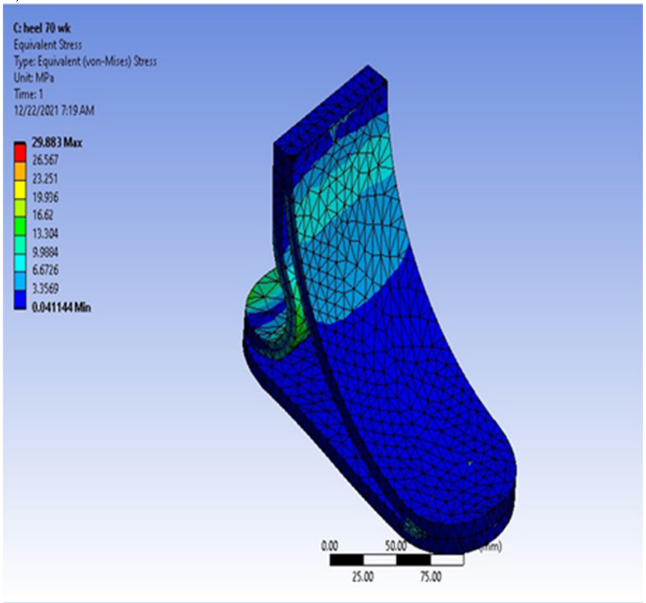
a)



b)

Fig. 19. For load of 70 kg toe-off Case (SWOK): a) equivalent Von-Mises stress, b) deformation in (Y) direction

a)



b)

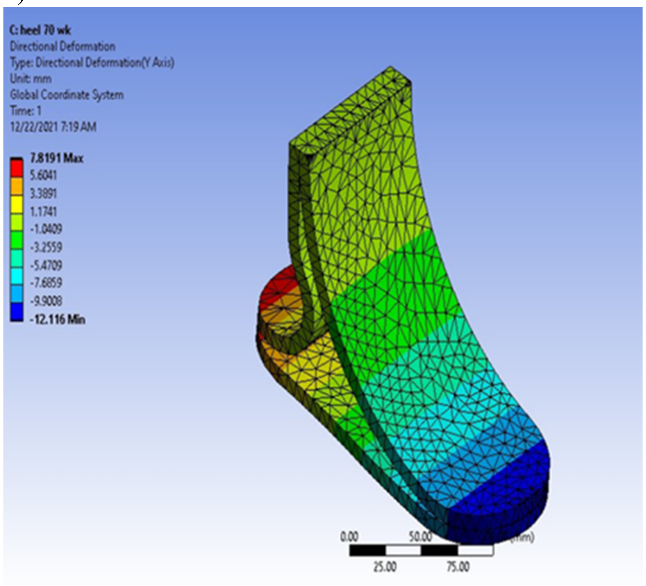
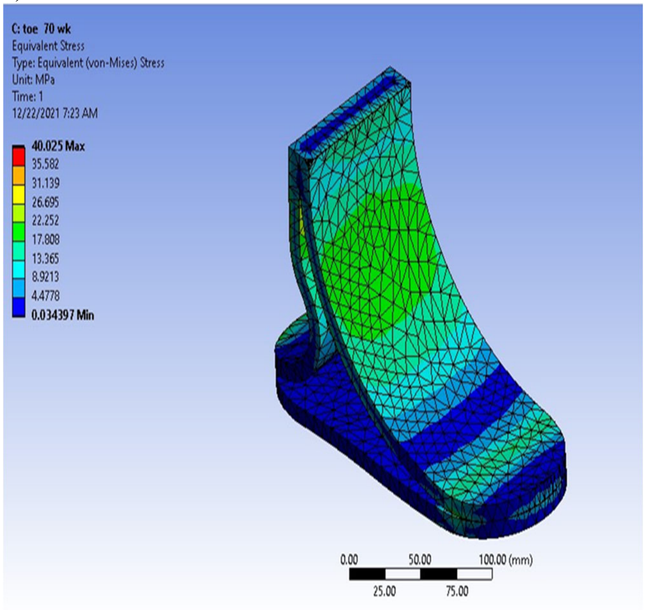


Fig. 20. For load of 70 kg heel strike case for sequence with kenaf (SWOK): a) equivalent Von-Mises stress, b) deformation in (Y) direction

a)



b)

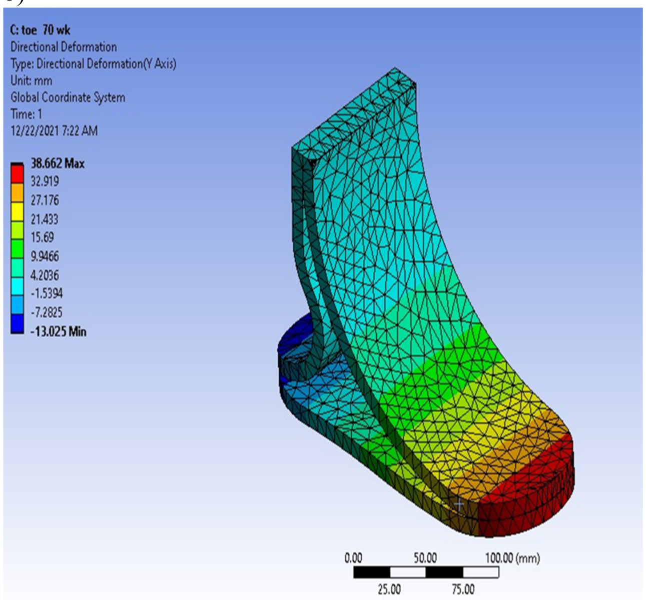


Fig. 21. For load of 70 kg toe-off case (SWOK): a) equivalent Von-Mises stress, b) deformation in (Y) direction

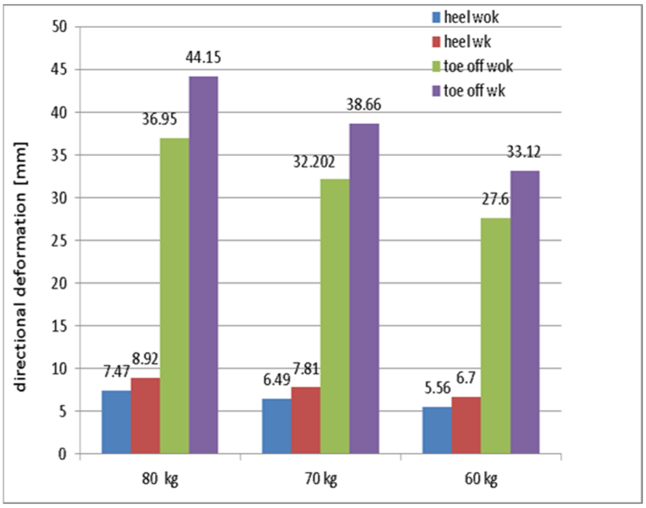


Fig. 22. Heel strike and toe off chart for weights 60, 70, and 80 kg

Comparing the obtained results with the commercial feet, the results obtained from the Ansys work are near the Niagara Foot™ [16]. The results of the directional deformation for Niagara Foot™ are shown in Table 5.

Table 5.
Niagara foot displacement results [15]

Zone	Max. directional displacement, mm
Heel	8
Toe	40

8. Conclusions

The following conclusions are supported by the design, analysis, results, and discussion of this research:

1. The new material improved the mechanical properties.
2. The ultimate stress was modified when kenaf was used by an amount equal to 33.44 MPa (about 25%).
3. The damping was modified, which resulted in more stability and more smooth steps.
4. The toes-off was modified by 20%, as well as heel strike when kenaf was used.
5. The foot was passed successfully 1000,000 steps for both sequences according to ISO 10328 standards.

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