Al-Khwarizmi Engineering Journal
ISSN (printed): 1818 – 1171, ISSN (online): 2312 – 0789
Vol. 20, No. 4, December (2024), pp. 13-24

Al-Khwarizmi Engineering Journal

An Improved Prosthesis for Through Ankle Joint Amputation

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(Received 9 April 2023; Revised 29 September 2023; Accepted 4 October 2023; Published 1 December 2024)
https://doi.org/10.22153/kej.2024.10.006

Abstract

Prosthetics through the ankle joint are prescribed to patients with a Symes amputation after rehabilitation. Energy can be stored and discharged from the flexible parts, such as the foot, leg and joints of the prostheses. This work improves the prosthetics for amputation through the ankle joint by providing the prosthetics with a movable ankle joint. The most important achievement of the ankle joint is that it performs important walking movements, the most important being planter flexion, dorsiflexion, inversion and eversion. A movable ankle joint was suggested and modelled in the SOLIDWORK program, and it was analysed using the finite element method to evaluate stresses and deformations. This model was used to improve a patient's gait and reduce exertion. The suggested ankle joint was evaluated through several experimental tests, such as the ground reaction force (GRF) test, 6 min walking test and range of motion test. All the results indicate an improvement in gait parameters and patient adaptation to the suggested ankle-joint prosthetic. The GRF test showed the behaviour of the normal state approaches when using the suggested ankle-joint prosthetic. The results of the GRF test illustrate the percentage difference in the forces for the healthy limb from the suggested movable prosthetic and thetraditional one, with approximate values of 10.96% and 38.88%, respectively. Calculation revealed that the weight of the movable prosthetic with the suggested ankle joint was reduced by 32.69% compared with traditional prosthetic. In addition, a questionnaire was conducted to determine the extent of patient satisfaction when the moving prosthetic was used for a certain period. The questionnaire presented a considerable improvement in patient comfort and other aspects compared with the traditional prosthetic.

Keywords: *prosthetic, amputation, eversion, inversion, ankle joint, solid work, suggested prosthetic*

1. Introduction

Prostheses restore body parts lost due to trauma, genetic defects or other causes [1]. These parts allow amputees to have a normal work and social life [2]. Amputation changes a person, from being a healthy individual into one with a disabled body and hurt. This condition causes sadness, pain and poor energy when interacting with the society, which causes difficulty in adaption [3]. Walking is one of the basics of daily life necessary for everyone. However, this movement is a complex functional process that involves the combination of muscles and tendons. A person can move from one place to another while keeping his body image balanced and stable. Walking is difficult for those with amputated lower limbs. The development of the lower extremities is aimed at improving the image of walking through modern and advanced innovative mechanisms [4]. Comprehending the functioning of prostheses is necessary to identify foot movements: eversion (EV)–inversion (IN), dorsiflexion (DF) and plantar flexion (PF) [5] (Figure 1).

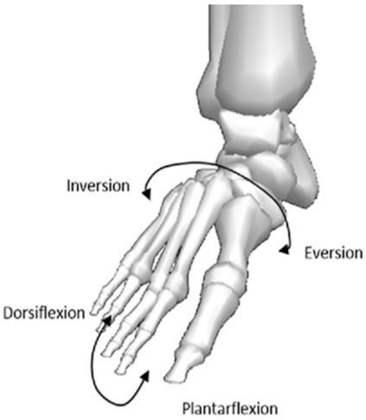


Fig. 1. Different foot movements [6]

Ruben C. Martinez, et al. (2014) [7] designed an ankle joint for BK amputation with a one-way spring. This spring is meant to store and release energy to aid in toe movement. The weight of the joint can be reduced by changing its component materials. Positive results were obtained in walking while using the joint, but difficulty in standing, sitting and ascending and descending stairs remained. These issues will all be fixed in the future. Eric Nickel et al. (2014) [8] developed a foot-and-ankle model by making a flat foot plate with a thickness of 10 mm from nylon 6/6 with a black crepe layer for cushioning and a rubber layer for guaranteed high stability while walking on sloping ground. In addition, the foot was provided with an annular bottom arch to form a natural rocking shape for the ankle to walk at ground level. The low rigidity of the PF and neutralisation were achieved using a polyurethane rubber bumper (compensating absorber) placed inside the keel ring. According to the initial mechanical test, this stiffness was sufficient to reduce the PF velocity (reducing foot slap), with which positive results were obtained in downhill walking. Pierre Cherelle et al. (2017) [9] proposed an ankle joint design with an mechanism of locking and unlocking four columns by pushing them out of position against the mechanical stop. At this point, the necessary torque is produced during the early stopping phase when the leg’s action compresses the PF springs. To recover the maximum amount of energy from walking, scholars have added additional locking mechanisms to AMP-Foot 3, such as the natural capability to adapt to different walking speeds and incline and improved energy storage during early standing. Experiments involving climbing hills and walking on flat ground were conducted. Dianbiao Dong, et al. (2017) [10] designed a new energy mechanical ankle joint using a five-bar spring mechanism due to its flexibility during various special foot movements in walking. The most important of these movements include PF and DF without restriction. In the future, the act of walking on various terrains must be developed. The ankle joint was suggested due to its importance in performing the crucial movements used for walking. This work aimed to design an ankle joint that is suitable for ankle joint amputation, comfortable while walking, low cost and easy to use and maintain and provides important walking movements (PF, DF, IN and EV).

2. Numerical Analysis Modelling of Ankle Joint using SOLIDWORKS Program

An ankle joint design consisting of two pieces, with one attached to the foot and the other to the socket, was proposed. The first model was designed for the ankle joint, and the lateral opening was oval to perform movements (IN and EV). The joint was designed and manufactured using the Solid Work 2018 program. The design failed because it did not activate these movements, which when applied realistically failed to meet the requirements. The function appeared in walking. Figure 2 shows the upper part and Figure 3, the lower part. All the dimensions are in millimeters (mm).

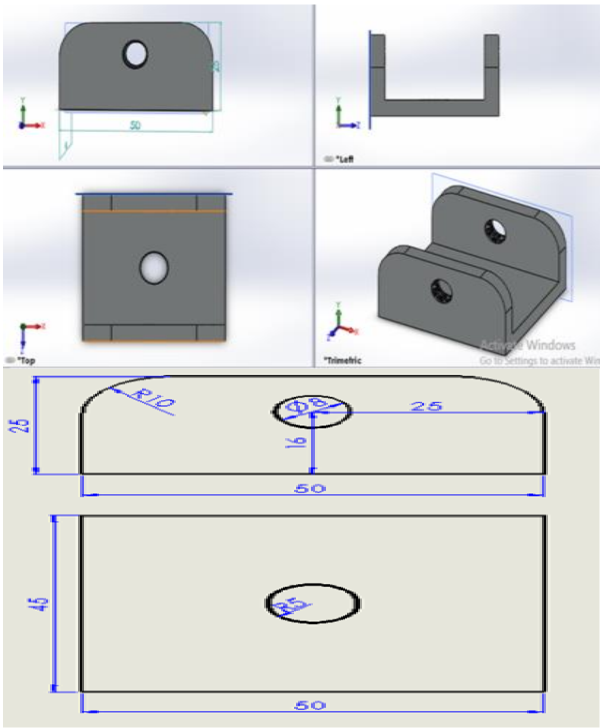


Fig. 2. Upper part of the suggested ankle joint

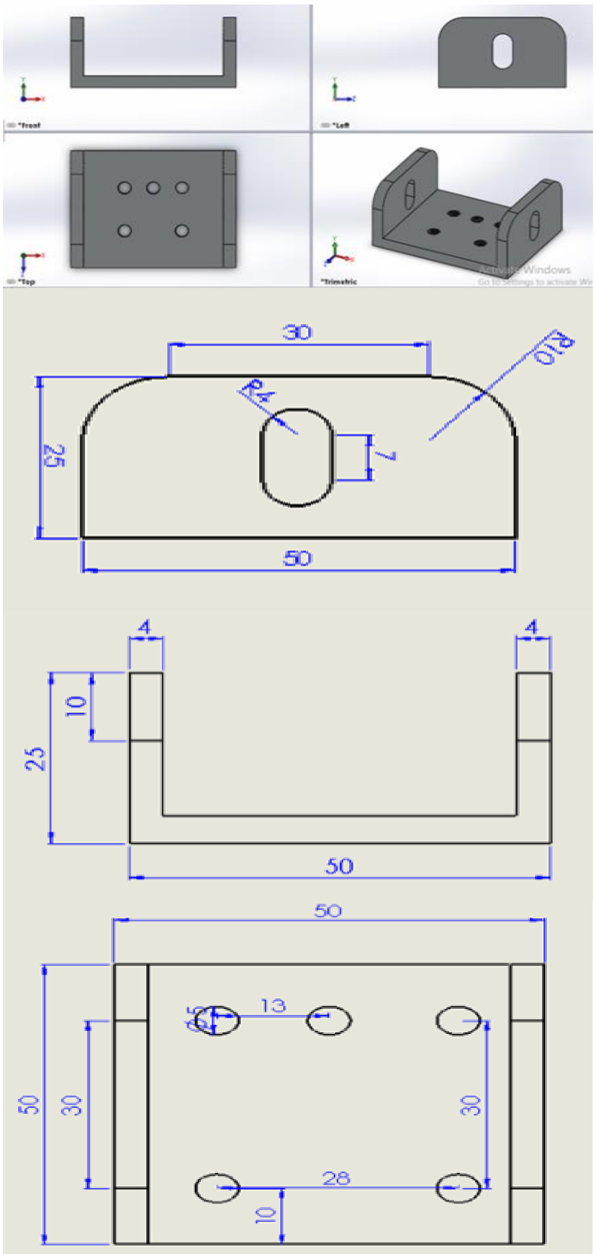


Fig. 3. Lower part of the ankle joint

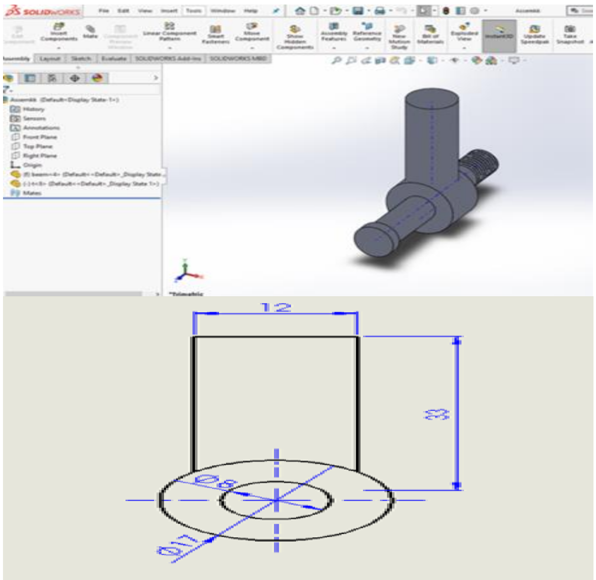


Fig. 4. Beam for the ankle joint design

Another two-piece ankle joint design with a ball end bolt was proposed (Figure 4). The lateral holes assume a circular shape to allow movements of DF and the plantar muscles (Figure 5). The upper hole connected to the socket of the prosthesis has an oval shape with a bolt fixation, and the middle oval hole promotes lateral movements (Figure 6).

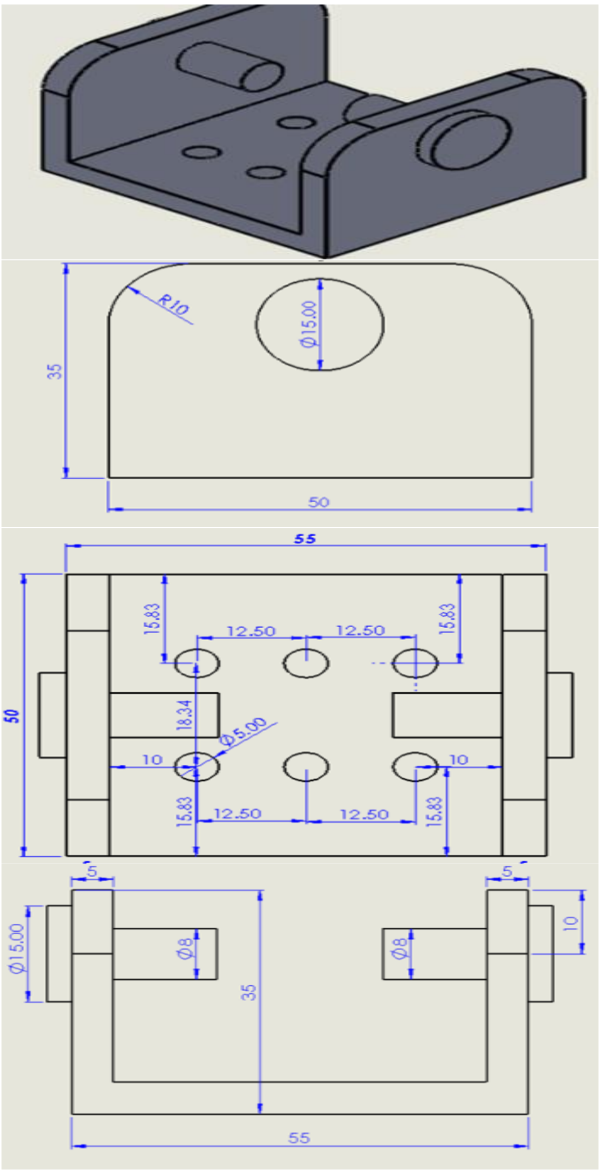


Fig. 5. Lower part of the ankle joint

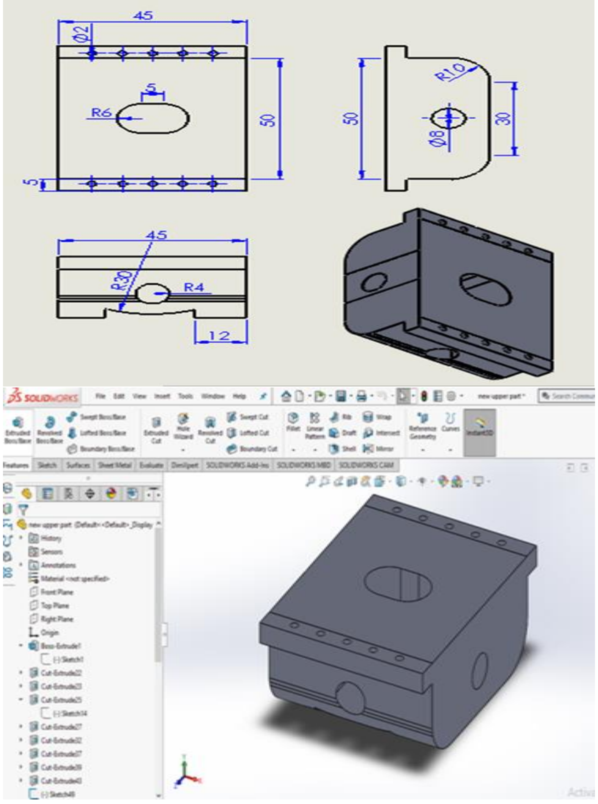


Fig. 6. Upper part of the ankle joint

The final form of the suggested ankle joint was manufactured from aluminum in CNC Vector 610 at the University of Technology (Figure 7). Figure 8 shows the final assembly for the suggested ankle joint and foot.

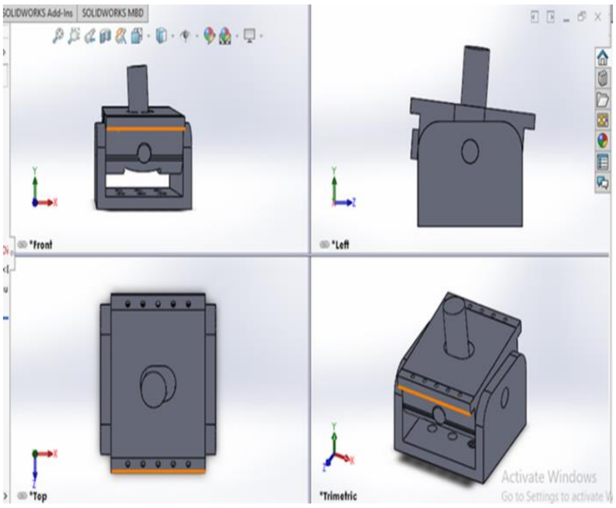


Fig. 7. Assembly of the designed suggested ankle joint

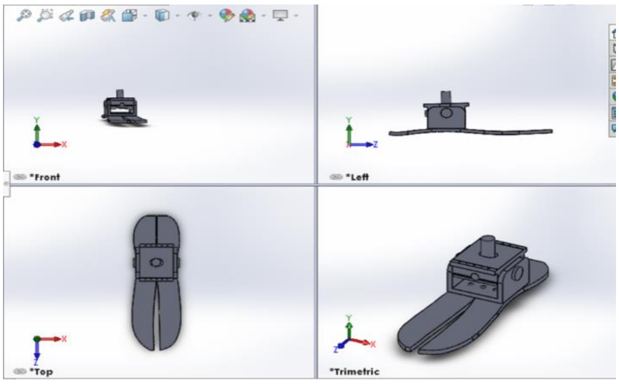


Fig. 8. Final assembly for the suggested ankle joint with foot

3. Finite Element Analysis (FEA)

Often substantive in the phrasing of formulated equations is the use of mechanics samples to solve the command equation of a known phenomena and the capability to predict deterministic and various phenomena in the fields of science and engineering. Numerical styles have been adopted to remove difficult-to-eliminate sacrificial solutions from equations. Among these numerical styles, FEA approximates continuity with an infinite degree of freedom by a discrete body. The finite element method has become a powerful instrument for finding numerical solutions of a vast range of engineering problems [11]. ANSYS–19 was adopted to generate the finite element model (Figure 9).

Table 1.
Mechanical properties of the parts of movable prosthetic (the suggested ankle joint).

Mechanical properties	**Bolt**	**Ankle joint**	**Foot**
Material	**Stainless steel**	**Aluminum alloy**	**Carbon fibre**
Tensile Ultimate Strength (MPa)	586	310	345
Tensile Yield Strength (MPa)	207	280	230
Young modulus (GPa)	193	71	395
Passion ratio	0.31	0.33	0.2

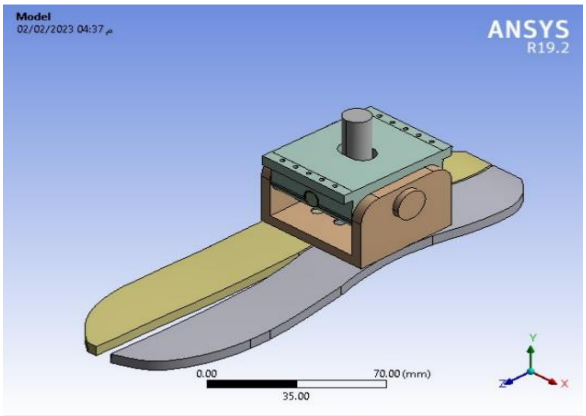


Fig. 9. Ankle joint in ANSYS-19 software

4. Design and Manufacture of the Ankle Joint

After designing the joint in the Solid Work program, it was implemented in real life. A piece of aluminum 7075 metal was purchased (20 * 25 cm^2), and an X-ray fluorescence test was carried out to determine its material contents and the percentage of each. The joint was manufactured at the University of Technology, in the Laboratories and Workshops section, Turning Department (in a machine; Vector 610) (Figures 10 and11).

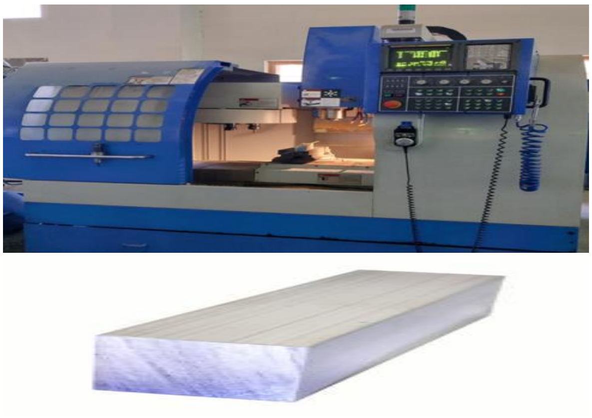
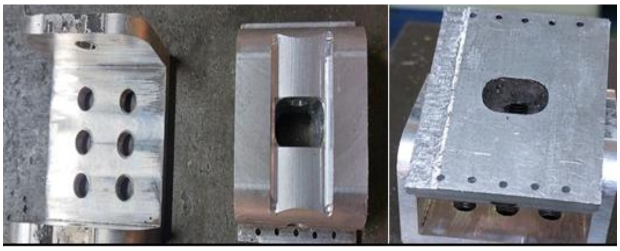


Fig. 10. CNC machine vector 610 and aluminum block



lower part Upper part final shape

Fig. 11. Final design shape of the ankle joint

The ankle joint was assembled using screws, with the addition of springs and a piece of rubber, to enable the necessary movements and absorbance of energy (storage and waste of energy) during the stance phase and push off (Figures 12 and 13).

Fig. 12. Ankle joint components

Fig. 13. Bolts; the first is half tooth and the other is smooth

Figure 14 shows the connection of the joint with the foot and socket.

Fig. 14. Final shape of the prosthetic

The bolt nut connects every two parts with each other. However, the nut was dispensed in a manner that made the bolt half smooth and half serrated (Figure 15), with the teeth of the pieces to which it was attached to making it like a nut to prevent the addition extra weight when adding nuts. The mathematical equations below were applied:

Fig. 15. Bolts

The tension stress (Figure 16), and stress bearing can be calculated using the following:

$$\sigma = \frac{F}{A}$$

where σ: stress bearing (Pa), F: tensile Load in the axial direction (N) and A: sectional area= 2td (mm)

The bolt shear (Figure 17) can be calculated as follows:

$$\tau = \frac{F}{A}$$

where τ: shear stress (Pa), F: shear load (N) and A: sectional area = $\pi d^2/4$ (mm)

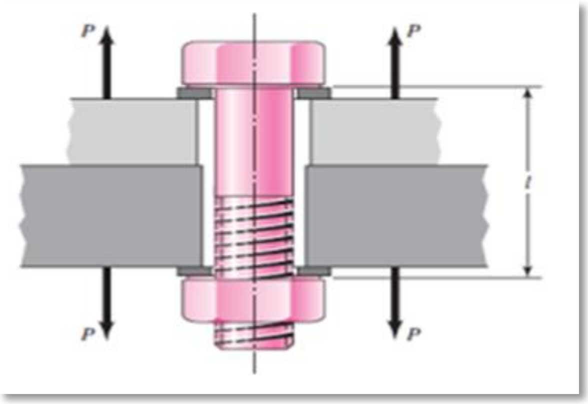


Fig. 16. Tension load of bolt

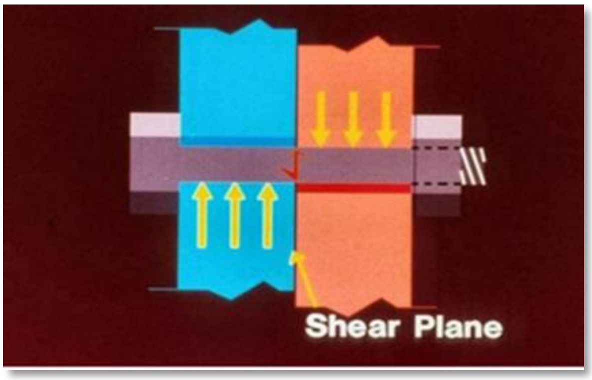


Fig. 17. Bearing joint

5. Results and Discussions

5.1 Numerical Simulation conducted using FEA Results

Numerical analysis was carried out using the workbench ANSYS-19 software to determine stress analysis results, deformation and safety factors. Force (900 N) was applied on the bolt and surface of the upper part of the suggested ankle joint (Figure 18).

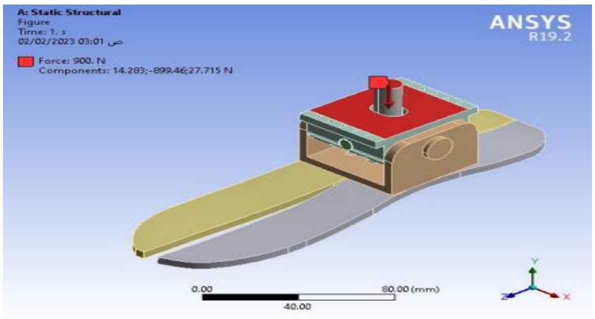


Fig. 18. Applied force in ANSYS software

The following steps were suitable for the FEA when using the ANSYS program. The ankle joint was analysed in the static structure by applying load on the top of the ankle joint for two cases (heel strike and toe off), by making the fixation the base for the entire foot in one and by making the fixation only with the heel and toes in another.

Heel-Strike Phase ANSYS Analysis

Numerical analysis was conducted to determine the stresses and deformations expected to occur during heel strike. When fixation was at the base of the entire foot, and the angle of force was 20°, the von Mises stress reached 17.292 MPa, and the total deformation was 0.015158 mm (Figures 19 and 20, respectively). On the other hand, when the fixation was only at the foot heel, the von Mises stress reached 26.49 MPa, and the total deformation was 0.057475 mm (Figures 21 and 22, respectively).

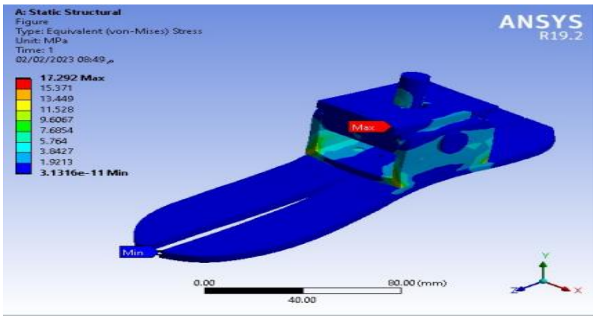


Fig. 19. Von Mises stress in heel strike of the whole-foot fixed support

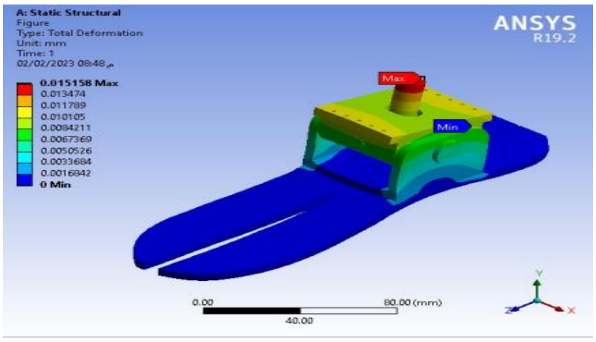


Fig. 20. Total deformation in heel strike of the whole-foot fixed support

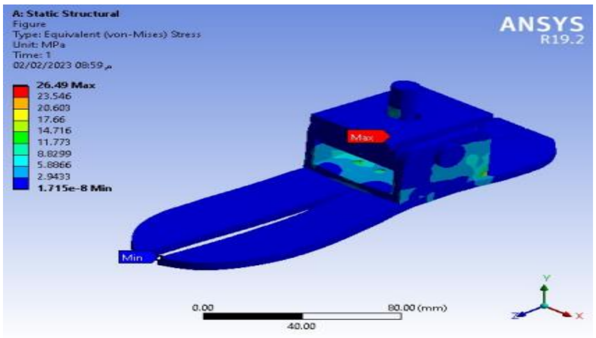


Fig. 21. Von Mises stress in heel strike and heel fixed support

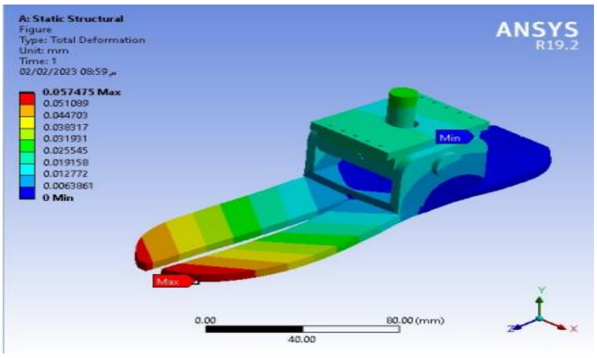


Fig. 22. Total deformation in heel strike and heel fixed support

Toe-Off Phase ANSYS Analysis

Numerical analysis was conducted to determine the stresses and deformations expected to occur during toe off. When fixation was at the base of the whole foot, and the angle of force was 40.5°, the von Mises stress reached 21.326 MPa, and the total deformation was 0.015172 mm (Figures 23 and 24, respectively). On the other hand, when fixation was only at the front of the foot, the von Mises stress reached 38.62 MPa, and the total deformation was 0.063299 mm (Figures 25 and 26, respectively).

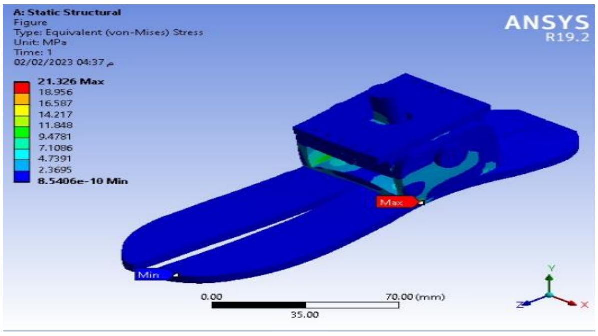


Fig. 23. Von Mises stress in toe off for the whole-foot fixed support

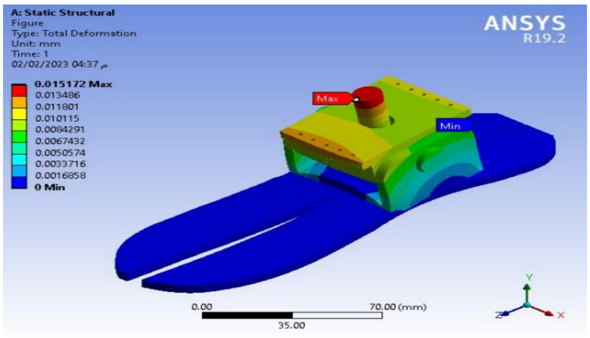


Fig. 24. Total deformation in toe off for the whole-foot fixed support

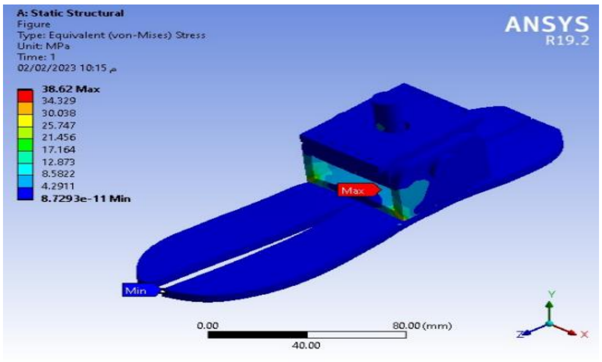


Fig. 25. Von Mises stress in toe off for front-foot fixed support

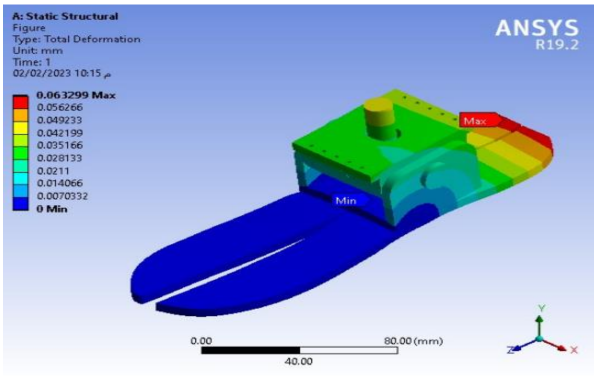


Fig. 26. Total deformation in toe off for front-foot fixed support

The safety factor for all phases was 15 (Figure 27).

Table 2.
ANSYS program results

	Fixed support	Von Mises stress (MPa)	Total deformation (mm)
Heel Strike	Total Foot	17.292	0.015158
Heel Strike	Heel	26.49	0.057475
Toe Off	Total Foot	21.326	0.015172
Toe Off	Front Foot	38.62	0.063299

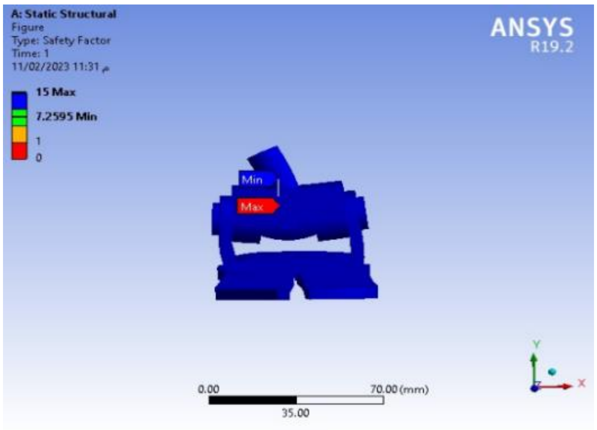


Fig. 27. Safety factor

Table 2 contains the von Mises stresses and total deformations for all phases. The minimum von mises stress applied was approximately 5 MPa, which was obtained in the standing phase.

The highest von Mises stress was approximately 38 MPa, which was obtained in the toe-off phase. This finding indicates that the stronger the movement, the higher the increase in the von Mises stress values.

5.2 Prosthetics Weight

The weight of the foot is approximately 23% of the foot length [12]. The weight of a traditional prosthetic for an amputation through the ankle is approximately 1.3 kg. The weight of the movable prosthetic with the suggested ankle joint is 875 g, with the weight of the socket at 500 g. The suggested ankle joint has a weight of 375 g (Figure 28).

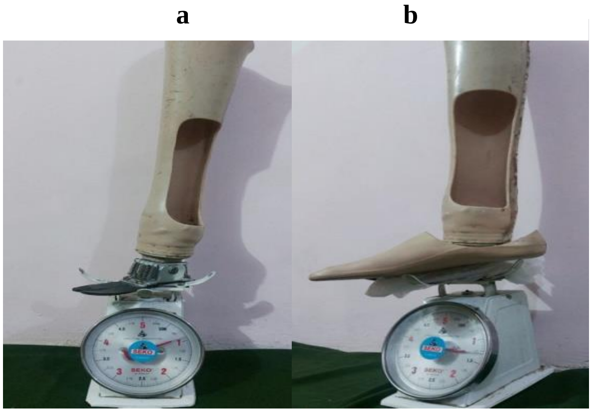


Fig. 28. a) Weight of the movable prosthetic; b) weight of a traditional prosthetic

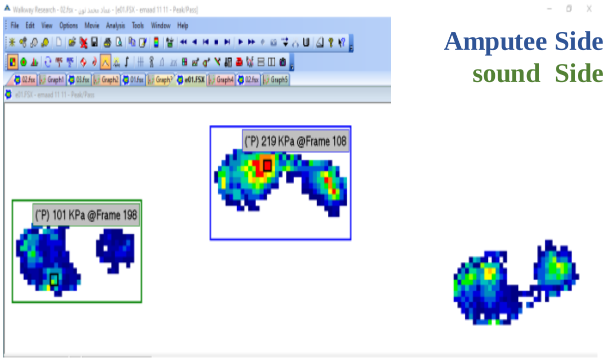
The difference between the weight of the movable prosthetic with the suggested ankle joint and that of a traditional prosthetic was calculated as follows:

$$\left(\frac{1.3 - 0.875}{1.3}\right) \times 100 = 32.69$$

The weight of the movable prosthetic with the suggested ankle joint was reduced by 32.69% compared with that of the traditional prosthetic, which indicates an increase in patient comfort.

5.3 Ground Reaction Force (GRF) Test Results

The GRF test was conducted by a patient walking on the strength board in the rehabilitation laboratory at the Department of Orthotic and Prosthetic Engineering, Al-Nahrain University, once while wearing the traditional prosthesis with a fixed joint (Figure 29) and then while wearing the prosthesis with a movable joint (Figure 30). The test was performed thrice, and the patient rested for 2 min between each attempt.



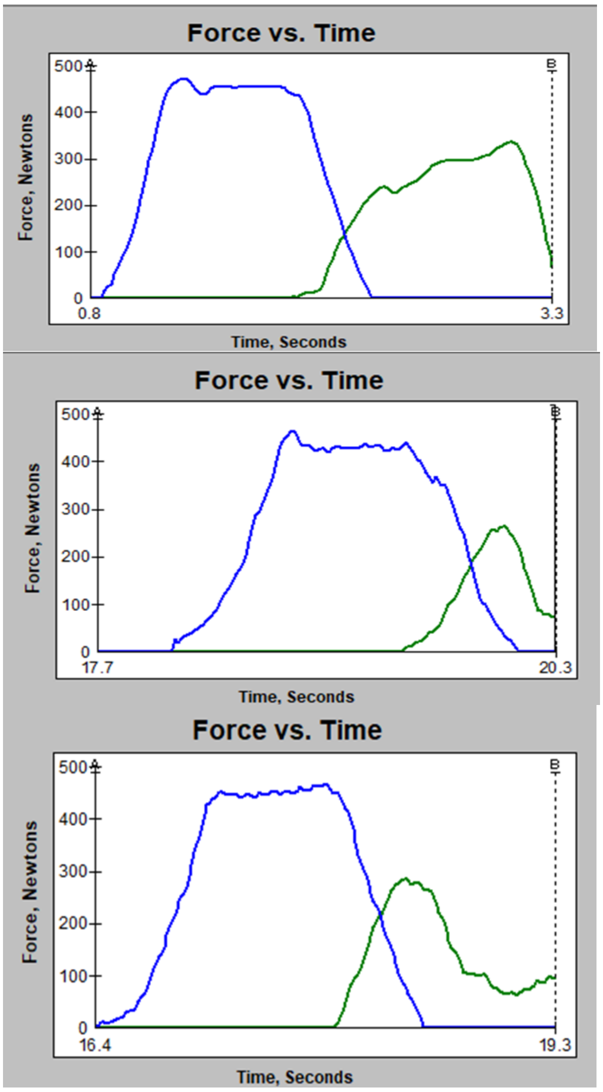
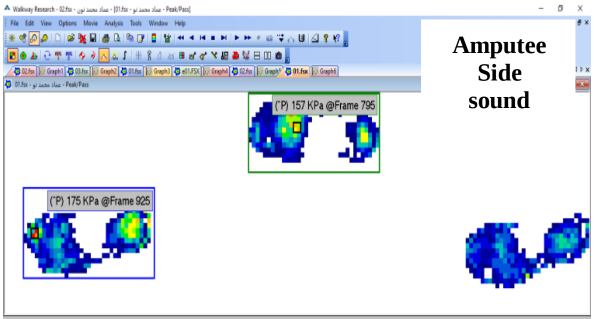
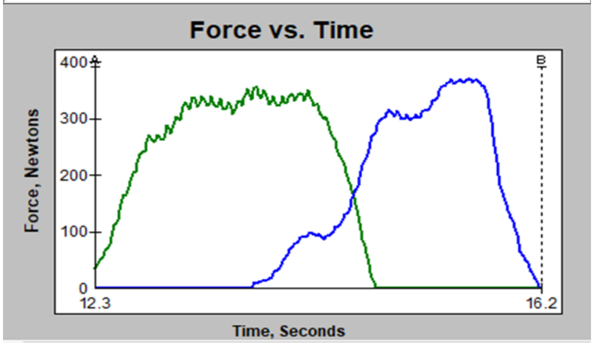


Fig. 29. GRF curve results obtained when using the traditional prosthetic





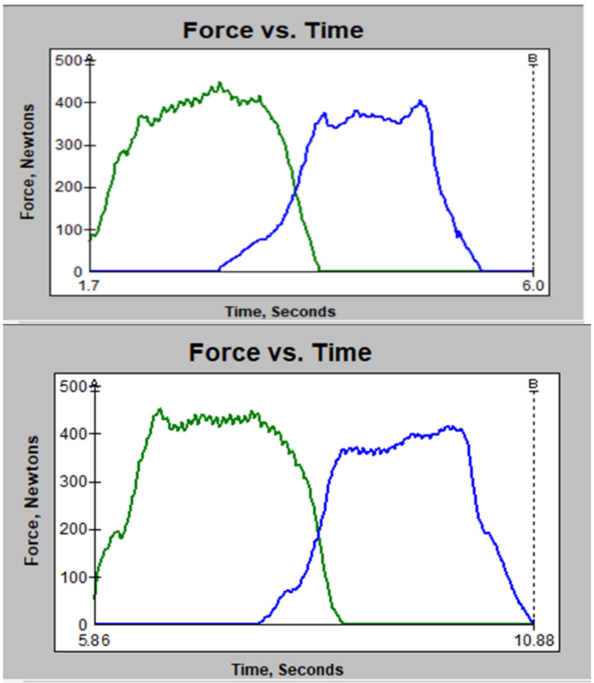


Fig. 30. GRF curves results obtained when using the movable prosthetic

The results of the GRF test for the first case (which is the traditional limb) were obtained. The force was higher in the amputated part than in the healthy ones, which shows the extent of the patient’s confusion in using the limb. The patient was attempting to reach the ground at a high speed due to fear of falling.

The findings of the GRF test for the second (which is the limb with a movable joint)were acquired. A convergence was observed in the peak force reached by the amputated and healthy parts, which indicates the extent of the patient’s comfort, balance and confidence when walking while wearing the limb with a movable ankle joint (Table 3).

Table 3,
Maximum forces observed for both prosthetics.

	Traditional prosthetic test		**Moveable prosthetic test**	
	Max. forces amputee side, N	**Max. forces sound side, N**	**Max. forces amputee side, N**	**Max. forces sound side, N**
1	472.76	336.56	417.55	453.29
2	468.90	286.57	317.14	356.19
3	464.68	264.75	405.62	449.92

Table 3 shows the ratio of the change in the curve in relation to the sound and amputated sides. The results were compared with those observed when using the traditional prosthetic and the prosthetic limb with the suggested ankle joint (Table 4).

Table 4,
Force ratio of traditional and moveable prosthetics

Type of prosthetic	The force ratio %
Traditional prosthetic	38.88
Movable prosthetic	10.96

The results of the GRF test reveal that the percentage differences in the forces of the healthy limb from the (suggested) movable prosthetic and traditional prosthetics were approximately 10.96% and 38.88%, respectively.

5.4 Results of Ankle Joint Angle Measurement

The range of motion of the patient's ankle joint was measured while wearing the prosthesis with the movable joint while walking and measured again in the standing phase (Figure 31).

Fig. 31. Ankle range of motion

Table 5 shows the degrees of special movements necessary for walking.

Table 5.
Ranges of motion of the manufactured ankle joint

Motion	DF	PF	IN/EV
Normal range limits	20 deg.	20 deg.	5 deg.
Range limits for patient	20 deg.	50 deg.	12 deg.

This indicates a closeness in the values of normal ankle joint motions compared with those of the manufactured ankle joint and fixed joint.

6. Conclusions

A two-piece ankle joint was suggested to provide important movements for walking (PF, DF, IN and EV). One of the pieces is attached to the foot and the other to the socket. Bolts connect the pieces to each other. The upper hole of the piece connected to the socket is characterised by an oval shape for performing IN and EV movements. The movable ankle joint was modelled using the SOLIDWORK program and analysed with the FEA program. Experimental tests were carried out to evaluate the acceptability of the prosthesis for the patient, and the following were observed:

1 . The designed prosthetic with a movable ankle joint is the best for performing movements necessary for walking functions because it was made to be lightweight (the weight of the movable prosthetic was 32.69% lower than that of a traditional prosthetic), inexpensive and small in size compared with a traditional prosthetic limb. The ankle joint was designed using the SolidWork program, analysed with the FEA program and then manufactured using a CNC machine.

2. The results obtained from the FEA program indicate that the highest stress was 38 MPa in the toe-off phase, but it was obtained only when the front of the foot was connected to the ground. The least amount of stress (5 MPa) was reached in the standing phase. The whole-foot fixed support and safety factors in all cases were equal to 15.

3. From the GRF test, when using the traditional prosthetic, instability was observed in the gait compared with the moving limb, which is close to a sound foot. According to the results of the GRF test, the percentage difference in the forces for the sound limb from the (suggested) movable and traditional prosthetics were approximately 10.96% and 38.88%, respectively. The extent of the amputee's comfort and satisfaction with the movable prosthesis was observed in the 6 min walking test with the prosthetic limb with a movable ankle joint and by measuring the stride length, step length and step width.

4. In general, the patient felt more satisfied while using the prosthesis with a movable ankle joint.

Abbreviations: PF Planter flexion, DF Dorsiflexion, IN Inversion, EV Eversion, ROM Range of Motion, 6MWT Six Minute Walking Test, GRF Ground Reaction Force, FEM Finite Element Method

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تحسين الطرف الصناعي لبتر خلال مفصل الكاحل

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المستخلص

يتم وصف الأطراف الاصطناعية من خلال مفصل الكاحل للمرضى الذين يعانون من بتر (Symes) بعد عملية إعادة التأهيل. يمكن تخزين الطاقة وتفريغها من الأجزاء المرنة مثل القدم والساق ومفاصل الأطراف الاصطناعية. وتتمثل فائدة هذا العمل في أنه يحسن الأطراف الاصطناعية للبتر من خلال مفصل الكاحل من خلال تزويد الأطراف الاصطناعية بمفصل كاحل متحرك. أهم إنجاز لمفصل الكاحل هو أنه يؤدي حركات مهمة في المشي أهمها (انثناء اخمصي ، عطف ظهري ، انقلاب للداخل ، انقلاب للخارج). تم اقتراح وتصميم مفصل الكاحل المتحرك في برنامج SOLIDWORK وتحليله باستخدام طريقة العناصر المحدودة لتقييم الضغوط والتشوهات. يستخدم هذا النموذج لتحسين مشية المريض وتقليل الجهد المبذول. يتم تقييم مفصل الكاحل المقترح من خلال عدة اختبارات تجريبية مثل اختبار قوة رد الفعل الارضي واختبار ست دقائق مشي مستمر واختبار مدى الحركة. تشير جميع النتائج إلى تحسن في معايير المشية وتكيف المريض مع مفصل الكاحل الاصطناعي المقترح ، ويظهر اختبار قوة رد الفعل الارضي أن سلوك مفصل الكاحل يقترب من الحالة الطبيعية عند استخدام مفصل الكاحل الاصطناعي المقترح . أوضحت نتائج اختبار قوة رد الفعل الارضي أن النسبة المئوية للاختلاف في القوى للطرف السليم من الطرف الاصطناعي المتحرك (المقترح) والطرف الاصطناعي التقليدي حوالي ١٠,٩٦٪ ، ٣٨,٨٨٪ على التوالي. عند حساب الوزن ، تشير النتائج إلى أن وزن الطرف الاصطناعي المتحرك مع مفصل الكاحل المقترح انخفض بنسبة ٣٢,٦٩٪ مقارنةً بالأطراف الصناعية التقليدية. بالإضافة إلى ذلك ، تم إجراء استبيان لمعرفة مدى رضا المريض عند استخدام الطرف الاصطناعي المتحرك لفترة من الزمن. قدم الاستبيان تحسنا كبيرا في راحة المريض والجوانب الأخرى للاستبيان بالمقارنة مع الأطراف الصناعية التقليدية.