Kinematic analysis for passive multi-axes ankle joint

AKADÉMIAI KIADÓ

Pollack Periodica • An International Journal for Engineering and Information Sciences

17 (2022) 2, 36–41

DOI: 10.1556/606.2022.00593

Muhammad Safa Al-Din Tahir[1,2*], Shakir Sakran Hassan[2] and Jumaa Salman Chiad[3]

[1] Department of Computer Engineering Technology, Faculty of Information Technology, Imam Ja'afar Al-sadiq University, Bagdad, Iraq

[2] Department of Mechanical Engineering, University of Technology, Baghdad, Iraq

[3] Department of Mechanical Engineering, Faculty of Engineering, University of Al-Nahrain, Bagdad, Iraq

Received: January 11, 2022 • Revised manuscript received: February 8, 2022 • Accepted: February 13, 2022
Published online: April 25, 2022

ORIGINAL RESEARCH PAPER

ABSTRACT

The commercially available and research-developed positive-type ankle joints do not provide eversion and inversion movements and are limited to dorsiflexion and plantar-flexion. The aim of the research is to create an ankle joint that is simple to install, low in cost and closes in performance to the biological joint. The passive ankle joint is designed to perform dorsiflexion, plantar-flexion, eversion, and inversion movements. A biomechanical test was performed to find the similarity between the functions of the engineered ankle joint and the biological ankle joint. The conclusions show, the designed ankle joint on the simplicity of its structure and components, has come close to the biological function of the ankle in terms of angles.

KEYWORDS

prosthetic foot, ankle joint, passive ankle joint, multi-axis ankle joint, biomechanic test

1. INTRODUCTION

The direction of development researches is the prosthetic foot and ankle in general. In particular, the ankle joint is the race to create a compensatory part that is close to biological ankle joint performance. This race usually faces some problems whenever increasing symmetry to the biological joint, like complexity in design and the high manufacturing cost.

In his research Brackx et al. [1] developed a positive-type prosthesis model (energy storage and return), where the researcher worked to change the amount of liberated energy that was stored in the springs during the terminal stance phase in the gait cycle, to be more similar to that of the healthy foot by using a planetary gearbox that works to change the amount of ankle joint angle. In their study Nickel et al. [2] developed a prosthetic foot with an ankle joint that moves in two movements, dorsiflexion and plantar-flexion, able to walk on inclined surfaces ascent and descent in the direction of walking. This is realized by using a cam-shaped link between the footplate and the pylon to control the energy stored and released at the tip when walking on inclined surfaces. Rice et al. [3] designed a model of the foot - the ankle prosthetics positive type with two degrees of freedom of the ankle. The ankle consists of two joints, the prismatic joint its function shock absorption where the greatest displacement it moves is 15 mm and can be increased, but the increase causes deformation of the walking process, the second is rotation joint that works to provide dorsiflexion, and plantar flexion with a maximum angle of 20° for each of the two movements. The spring stiffness was set to perform the biological ankle's average properties. Hamzah et al. [4] designed a simple prosthetic foot to be of the positive type. It consists of two pieces of a fiber spring made of a composite material consisting of epoxy as a base material and carbon fiber

*Corresponding author.
E-mail: mohammed.safaaldin@sadiq.edu.iq

AKJournals

as a reinforcing material. This foot can give a linear stiffness curve in the plantar-flexion phase and a nonlinear stiffness in the dorsiflexion phase. This foot was tested by a device that simulates the forces affecting the gait process and a simulation program. Both tests gave positive results indicating the safety of the design from a mechanical point of view. Shepherd et al. [5] created a model of a prosthetic foot that performs many functions other than walking on a flat track like walking on a slope or stairs. This goal was achieved by controlling the shape of the relationship between the torque in the ankle joint and its angle by controlling the stiffness in the leaf spring located in the foot. This variability can be implemented by changing the type of leaf spring foot support from the cantilever beam to the variable propped cantilever beam by using a Direct Current (DC) motor to change the support location.

2. IDENTIFICATION OF DESIGN PASSIVE FOOT-ANKLE PROSTHETIC

The design of an ankle-foot prosthetic that provides comfort and in behavior it is closer to the amputee's biological foot. Many aspects must be taken into consideration, as it will be listed below:

2.1. Range of motion

The ankle joint should move toward the DorsiFlexion (DF) 30° and the Plantar-Flexion (PF) 60° around the frontal axis and around the sagittal axis in the direction of INversion (IN) by 60° and Ele-Vation EV by 30°.

2.2. Size of ankle joint

The designed ankle prosthetic size should be similar to the biological size.

2.3. Weight

The weight of the prosthesis must be within the appropriate limit for use. This is achieved by choosing the lightest materials.

2.4. Simplicity of components

The simplicity of the components is a factor that directly affects the cost of the prosthesis in terms of manufacturing and maintenance, as the simplicity of installation, which includes the availability and number of components, requires a lower cost of manufacturing. When the prosthesis is not complicated, the cost of replacing or repairing any of its parts is low.

3. COMPONENTS AND MATERIAL OF FOOT – ANKLE PROSTHETIC

The prosthesis was designed that fulfill the above requirements, as it consists of 7 parts made of different materials and manufacturing processes. The prosthesis's final shape was drawn by the Solid Works program shown in Fig. 1. The weight of prostheses was 920 g.

3.1. Fiber carbon leaf springs

As it is shown in Fig. 2, this mechanical part consists of two pieces, made of a composite material whose base material is resin and reinforced with carbon fibers. Its function is to store energy in certain gait cycle phases and release energy in other phases [6–8]. These leaves are fixed to the holder by two screws for the small leaf and one for the large piece.

3.2. Holder

The holder, shown in Fig. 3 is made of aluminum material. Aluminum is a suitable choice to perform the function the

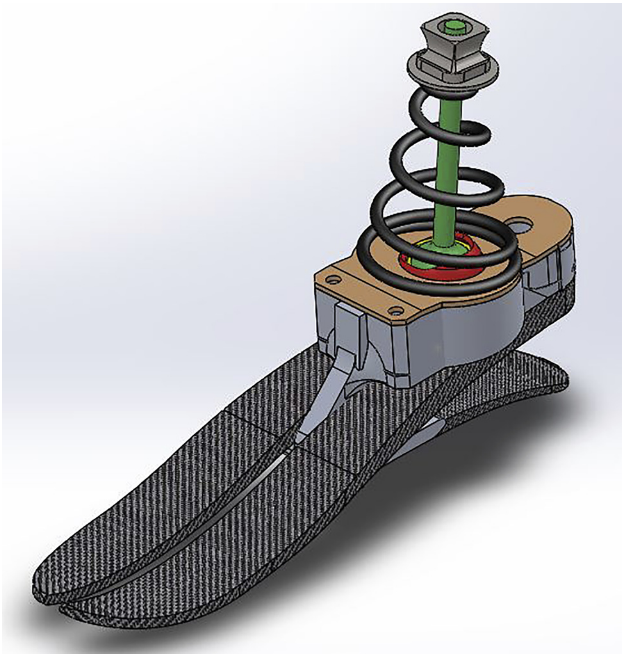

Fig. 1. The software ankle-foot design

Fig. 2. Fiber carbon leaf springs

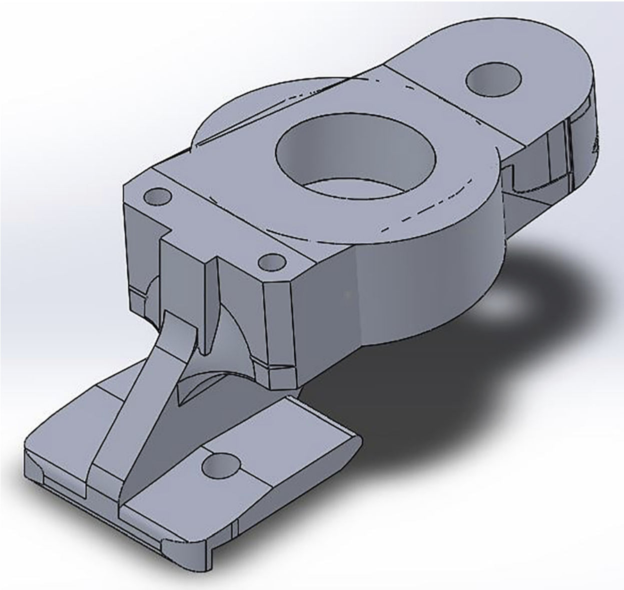

Fig. 3. Holder of ankle-foot prosthesis regained

connect all parts of the ankle-foot prosthesis (fibrous springs, components of the ankle joint, conical spring) [9, 10].

3.3. Ankle joint

The ankle joint consists of three pieces, as it is shown in Fig. 4. The first piece is made of steel, in a ball, with a toothed rod attached to the ball. This toothed used for holding the adapter. This ball rotates, and the rod is tilted with it inside a ball seat made of plastic to reduce friction [11–14], and to determine the amount of tilt of the rod used the cup steel guider with a un circular aperture to give its tilt to the rod and the ball at angles representing DF, PF, IN, and EV like in biological ankle.

3.4. The conical spring

The conical spring connects the holder and the adjuster. Its function is to return the ankle joint to its zero position after all its tilts to perform any of the aforementioned movements and not impede the ankle joint from tilting to perform the biological ankle movements. High carbon steel metal was chosen for manufacturing the spring [15, 16]. The conical spring telescope type shown in Fig. 5 was choosing for the possibility of overlapping its coils to give more freedom [17, 18] and not impede tilt due to the spring rings is the case in other shapes.

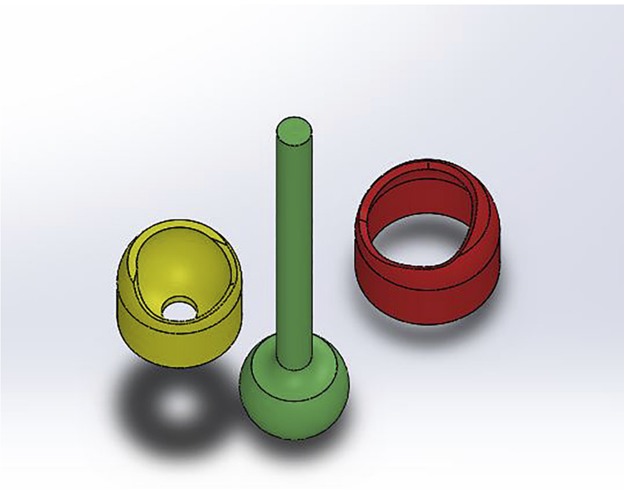

Fig. 4. Component of ankle joint

3.5. The adapter

The adapter is made of aluminum [19–21] with internal teeth attached to the ankle joint rod and has a wide base for support the conical spring (see Fig. 6). This part has two functions: the first is to connect the entire prosthetic foot with the pylon. The other function is to vary the conical

Fig. 5. The conical spring

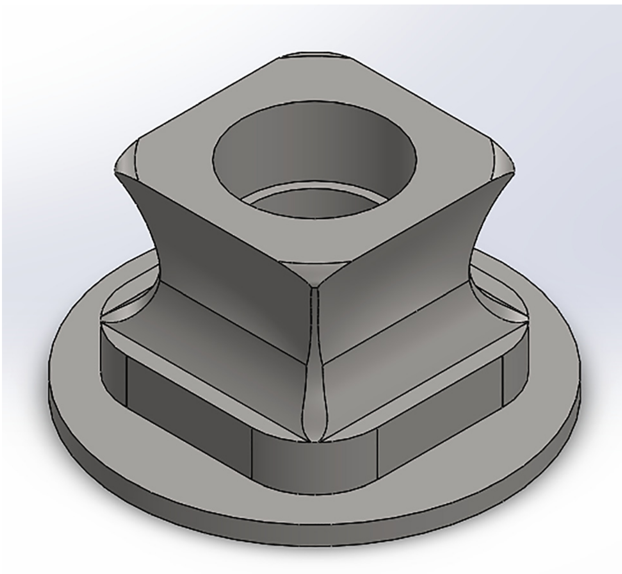

Fig. 6. Aluminum adapter

spring's lateral stiffness value by changing the spring's length when tightening and opening the adapter.

4. BIOMECHANICS TESTES

The biomechanical tests in this section were used to describe the mechanical behavior of a patient's walking while wearing the designed prosthetics. The mechanical behavior of the patient includes the kinematic analysis to describe the movement of the ankle joint [22, 23].

The platform is designed to simulate different walking paths, where it can be tilted to be an inclined up and downward inclined path, and it can also be tilted laterally to the right and left. Figure 7 illustrates the method of tilting the ramp.

The patient who conducted the test had transtibial amputation 29-year-old who weighed 71 kg and was 172 cm tall. The biomechanical tests were carried out on the patient when wearing designed prosthetics. Five walking modes were used (descent ramp, ascent ramp, right-rise, left-rise, and finally flat road). The tilt angle was chosen at 15° from the horizon for each type of slope to determine the performance of the designed prosthetics on difficult roads.

5. THE KINEMATIC ANALYSIS

The design of an ankle joint to perform the biological functions performed by the ankle (dorsiflexion, planter-flexion, elevation, and inversion), it is necessary to know the degree of symmetry of the movement performance between them.

The test was conducted on designed prosthetics cases, with five roads mentioned above. Before starting the test and video recording of movement, a mark is placed on the ankle joint's location on foot to facilitate the determination of the ankle's location when the analysis is shown in Fig. 8.

The movements were video-recorded with a high-resolution camera (Nikon D900). Then the recordings were transferred to the computer for analysis by the KINOVIA program to find the values of the angles of the ankle joint and the biologic foot.

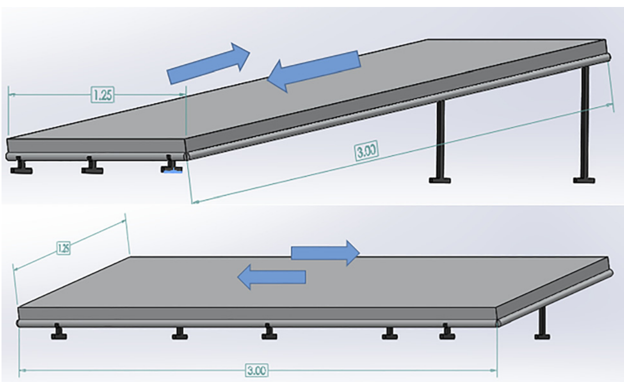

Fig. 7. The variable tilting platform and walk directions, all dimensions in meter

Fig. 8. Marking the ankle joint in the biological foot and the designed prosthetic foot

6. THE KINEMATIC TEST RESULT

The ankle joint kinematic result includes the amount of Maximum Angle of DorsiFlexion (MADF) and Maximum Angle of Plantar-Flexion (MAPF) in three cases (ascent ramp, descent ramp, and flat rood). As for right and lift sloping cases include finding the Maximum Angle of EVersion (MAEV) and Maximum Angle of INversion (MAIN).

The ankle joint's kinematic results are inserted in Table 1. The results show that in the case of walking on an

Table 1. Angles of prosthetic (designed) and biological ankle joint at several roads

Ascent ramp	*MADF (deg°)*	*MAPF (deg°)*
Prosthetic	23	2
Biological	25	1
Descent ramp	*MADF (deg°)*	*MAPF (deg°)*
Prosthetic	2	16
Biological	2	19
Flat road	*MADF (deg°)*	*MAPF (deg°)*
Prosthetic	20	11
Biological	20	11
Left-rise	*MAIN (deg°)*	*MAEV (deg°)*
Prosthetic	20	#
Biological	#	20
Right-rise	*MAIN (deg°)*	*MAEV (deg°)*
Prosthetic	#	19
Biological	20	#

Table 2. The degree of freedom and the maximum movement for the designed ankle at several roads

Prosthetic designed	Frontal axis	Sagittal axis	MADF	MAPF	MAIN	MAEV
Angles	39°	39°	23°	16°	20°	19°

ascent ramp, the MADF is 23° and 25° and MAPF is 1° and 2° for biologic and prosthetic foot respectively. These results attributed to the fact is at the beginning of the walking cycle in the ascent ramp case does not start with a heel strike but rather begins with contact ground by sole and toe. Therefore, the MAPF value is low almost. The descent ramp case is the opposite of the previous case, so the values of MADF are few, and the highest values of MAPF are 16° and 19° for the designed and biological foot respectively. The reason behind the few amounts of MADF is that excess more than that leads to imbalance and falling forward. In the case of left rise road walking, the inclination angles of the ankle joints about the sagittal axis at the stance phase are MAEV 20° for the biological foot and MAIN 20° for the prosthetic foot. In the case of walking on the right rise road, the situation is reversed, so the value MAEV is 19° for the prosthetic foot and MAIN 20° for the biological foot. Finally, in the case of walking on a flat road, the amount of MADF 20° and MAPF 11° is for the biological and prosthetic feet. The degree of freedom for the designed ankle and the maximum movement in several directions are inserted in Table 2.

7. CONCLUSION

The conclusion from the above is the difference between the biological foot and the prosthetic designed when ascent ramp in PF 1° and DF 2°. The difference between DF and PF is (0° and 3°) when descent ramp. The DF and PF differences disappear when walking on the flat road. Walking on the lift rise road and the opposite right rise road, the difference between IN and EV is (0° and 1°), respectively. Also, conclude from the above that the designed ankle joint on the simplicity of its structure and components has come close to the biological function of the ankle in terms of angles.

REFERENCES

[1] B. Brackx, M. Van Damme, A. Matthys, B. Vanderborght, and D. Lefeber, "Passive ankle-foot prosthesis prototype with extended push-off," *Int. J. Adv. Robotic Syst.*, vol. 10, no. 2, pp. 101–109, 2013.

[2] E. Nickel, J. Sensinger, and A. Hansen, "Passive prosthetic ankle-foot mechanism for automatic adaptation to sloped surfaces," *J. Rehabil. Res. Dev.*, vol. 51, no. 5, pp. 803–814, 2014.

[3] J. J. Rice, J. M. Schimmels, and S. Huang, "Design and evaluation of a passive ankle prosthesis with powered push-off," *J. Mech. Robotics,* vol. 8, no. 2, 2016, Paper no. 021012.

[4] M. Hamzah and A. Gatta, "Design of a novel carbon-fiber ankle-foot prosthetic using finite element modeling," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 433, 2018, Paper no. 012056.

[5] M. K. Shepherd and E. J. Rouse, "The VSPA foot: A quasi-passive ankle-foot prosthesis with continuously variable stiffness," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 25, no. 12, pp. 2375–2386, 2017.

[6] K. R. Kaufman and K. Bernhardt, "Functional performance differences between carbon fiber and fiberglass prosthetic feet," *Prosthetics Orthotics Int.*, vol. 45, no. 3, pp. 205–213, 2021.

[7] D. Łączna, F. Dłużniewski, and Tomasz Stręk, "Analysis of eigenfrequencies of the foot prosthesis with auxetic component layer," *Vibrations Phys. Syst.*, vol. 31, 2020, Paper no. 2020214.

[8] H. K. Talla, J. K. Oleiwi, and A. K. F. Hassan, "Performance of athletic prosthetic feet made of various composite materials with PMMA matrix: Numerical and theoretical study," *J. Compos. Adv. Mater.*, vol. 31, no. 4, pp. 257–264, 2021.

[9] E. Efthymiou, "On the sustainable character of structural aluminum," *Pollack Period.*, vol. 3, no. 1, pp. 91–100, 2008.

[10] G. Brando, "Experimental tests on bracing type pure aluminum shear panels," *Pollack Period.*, vol. 2, no. 3, pp. 73–84, 2007.

[11] R. Keresztes, K. Gabor, R. Nagarajan, K. Subramanian, S. Jacob, and S. O. Ismail, "Tribological analysis of engineering plastics/steel friction pairs," *Trans. Indian Inst. Met.*, vol. 74, no. 6, pp. 1537–1548, 2021.

[12] S. Kumar, S. R. Maity, and L. Patnaik, "Friction and tribological behavior of bare nitrided, TiAlN and AlCrN coated MDC-K hot work tool steel," *Ceramics Int.*, vol. 46, no. 11, pp. 17280–17294, 2020.

[13] I. V. Lishevich, A. V. Anisimov, G. I. Nikolaev, A. S. Savelov, and A. S. Sargsyan, "Influence of sliding bearing design on efficiency of the fluoroplast macromodifier for antifriction carbon plastics," *Voprosy Materialovedeniya*, vol. 105, no. 1, pp. 65–75, 2021.

[14] B. Deng, J. Chen, S. Tang, and Y. Guo, "Sub-surface stress analysis of slewing bearing ball based on plastic deformation," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 768, 2020, Paper no. 042027.

[15] S. Pashangeh, M. Somani, and S. S. G. Banadkouki, "Microstructural evolution in a high-silicon medium carbon steel following quenching and isothermal holding above and below the M_s temperature," *J. Mater. Res. Technol.*, vol. 9, no. 3, pp. 3438–3446, 2020.

[16] Y. Kumar and H. Singh, "Application of Taguchi method for optimizing material removal rate in turning of En-47 spring steel," in *5th Internatioanl and 26th All India Manufacturing Technology, Design and Research Conference*, Guwahati, Assam, India, Dec. 12–14, 2013.

[17] M. N. Omar and Y. Zhong, "Flexible mass spring method for modeling soft tissue deformation," *Int. J. Eng. Technol. Sci.*, vol. 7, no. 2, pp. 24–41, 2021.

[18] M. Paredes and E. Rodriguez, "Optimal design of conical springs," *Eng. Comput.*, vol. 25, no. 2, pp. 147–154, 2008.

[19] M. J. Jweeg, K. K. Resan, and A. A. Najm, “Improving fatigue life of bolt adapter of prosthetic SACH foot,” *J. Eng.*, vol. 20, no. 3, pp. 62–71, 2014.
[20] Quickchange adapter. The fast and easy way to change prosthetic feet. [Online]. Available: https://www.ottobock.co.uk/prosthetics/lower-limb-prosthetics/prosthetic-product-systems/quickchange-adapter/. Accessed: Oct. 29, 2021.
[21] Male double adapter AL. [Online]. Available: https://www.ossur.com/en-us/prosthetics/adapters/male-double-adapter-al. Accessed: Oct. 29, 2021.
[22] A. Mattiussi, J. W. Shaw, D. D. Brown, P. Price, D. D. Cohen, C. R. Pedlar, and J. Tallent, “Jumping in ballet: A systematic review of kinetic and kinematic parameters,” *Med. Probl. Perform. Artists*, vol. 36, no. 2, pp. 108–128, 2021.
[23] I. Bon, M. Očić, V. Cigrovski, T. Rupčić, and D. Knjaz, “What are kinematic and kinetic differences between short and parallel turn in Alpine skiing?” *Int. J. Environ. Res. Public Health*, vol. 18, no. 6, 2021, Paper no. 3029.