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Dorsiflexion and Plantarflexion Test and Analysis for a new Carbon Fiber Ankle-Foot Prosthesis

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Abstract

Dorsiflexion and plantarflexion are an important dynamic function by which the ankle-foot prosthesis must simulate the human foot. Dorsiflexion and plantarflexion are essential functions to the walking pattern. However, most ankle-feet prostheses have a notice lack in mimicking the normal gait dorsiflexion and plantarflexion functions. A new carbon fiber ankle-foot prosthesis has been designed and manufactured. Dorsiflexion and plantarflexion tests achieved using a 25 KN tensile test device. The tests have been simulated and analyzed using ANSYS l6 and the results compared with the experimental results. Both test approaches pointed that the new prosthesis satisfy the ISO 10328 requirements that can be classified as multiaxial as it flexed 10º and 8º in dorsiflexion and plantarflexion respectively, under testing loading less than 1230 N.

Keywords: prosthetic foot, dorsiflexion, plantarflexion, ankle joint motion, walking gait.
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1. Introduction

The ankle joint permits the foot to move with two main movements, up as dorsiflexion movement and down as plantarflexion. The upward movement achieved using the anterior muscle compartment (muscles located in the front of the leg), while the downward movement achieved using the posterior muscle compartment (muscles located in the back of the leg). Ankle joint has a dorsiflexion range of 0 to 10 degrees from initial contact to terminal stance phase of the gait cycle. While the ankle joint plantarflexion varied from 0º at initial contact to 15º at pre swing phase [1].

One of the common activities that one daily habituated is walking on inclined ground. This is a difficult activity to achieve by people with lower limb amputation because of the used ankle-foot prosthesis design [2]. Most of ankle-foot prostheses are flexible, however mostly they lack the articular joint of the ankle. While the human sound ankle has a dorsiflexion to plantarflexion range of motion up to70 degree, that permits easy slopes confirmation. The insufficient range of the ankle motion, force the amputees to adapt their walking in such a way that they participating their sound limb and around the knee or hip muscles in their movement. This way of adaption can be causing cartilage impairment and osteoarthritis due to the increased muscle usage, increased loading of joints, and accelerated fatigue. Many prostheses were developed to enhance the amputee's adaption with inclined ground, but in fact there is quite lack of lack of experimental data on how the amputee to adapt during walking gait [3].

In addition, the natural human ankle joint provides the most work capable biological foot to propelling the body forward by storing energy during the stance phase and return it at the push off. The natural human ankle together with leg muscles functions as shock absorber, control the motion, and generate power. But, in typical lower limb amputation, all ankle joint and leg muscles must be compensated by the ankle-foot prosthesis that will be a prosthesis design challenge [4].

The ankle joint range of motion during the gait cycle is approximately 27 degrees, as Winter declares [5]. At the beginning of the gait cycle, the ankle takes a neutral position when the heel strikes the ground then the ankle starts to take a negative angle (plantarflexion) to permit the forefoot lowered till it contacts the ground. The ankle joint will take a positive angle (dorsiflexion) through the mid stance phase and continue progress in positive angle during the heel off to the toe off. During the pre-swing phase, the ankle will develop a large negative angle, then returns back to the neutral position through the period of swing phase preparing for the next gait cycle [6]**.** These sequences of dorsi-plantarflexion of the ankle joint can be summarized in the following as seen in the figure (1):

Stage 1: Heel Strike to Foot Flat — Plantarflexion.

Stage 2: Mid-stance — Dorsiflexion.
Stage 3: Heel-Off and Toe-Off — Dorsiflexion.

Stage 4: Toe-Off to pre-swing — Plantarflexion.

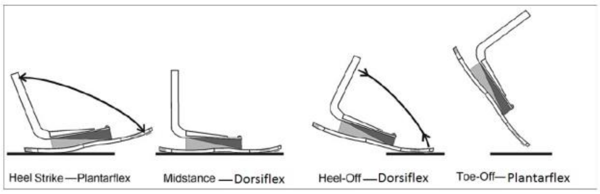

Figure (1) sequence of dorsi-plantarflexion of the ankle joint during gait cycle [6].

2- AOPA's Tests and Codes

The American Orthotic and Prosthetic Association project, was begun in 2007 at the behest of the Centers for Medical and Medicaid Services Statistical Analysis Durable Medical Equipment Regional Carrier (SADMERC). One of its objectives was to improve the accuracy and consistency of the prosthetic foot coding by developing standard tests that would verify the presence of some foot features. Thresholds of testing were created based on the mechanical and functional characteristics of the commercially available prostheses [7].

This project developed the following tasks:

- Test descriptions and methodology.
- Outline thresholds of test.
- Test criteria and corresponding codes of the Healthcare Common Procedure Code System (HCPCS).
- Prosthetic feet and corresponding HCPCS codes.

3- Experimental work

The AOPA test conditions and requirements have been adopted in the achievement of the new ankle-foot prosthesis dorsiflexion and plantarflexion tests and evaluations. The tests conditions and requirements can be summarized in the following procedures.

Dorsiflexion test

Equipment & Conditions:

- The tensile test instrument QUASAR 25, with max tensile load of 25KN, and computer control software, has been used.
- A universal tilting vise.
- Steel loading appliance was manufactured and it used to conform the loading component of the testing devise.
- Roller plate manufactured and used as frictionless bearing support. The roller plate as seen in figure (2) is made of a steel U-channel and four 6200 RS Ball Bearings. The ball bearings fitted to the axel shaft which welded to the U-channel.

Procedure

1- The prosthesis foot mounted to the test devise with the steel loading appliance. Loaded up to 50N, screws tightened, and the foot rose up.
2- The vise equipped with a steel block giving the compensative 15 mm height to the heel contact surface.
3- The vise tilted at angle of 10 degrees.
4- The manufactured roller plate was mounted onto the test devise.
5- The vise assembly mounted onto the roller plate.
6- Prosthetic foot lowered in this step until keel contact the inclined surface of the vise.
7- Loading continue until the foot heel firmly contact the 15mm raised block, or it reach 1230N.
8- The firm contact was verified by placing a piece of paper between the heel and the heel block, and sliding it continuously until it was fixed. The loading process was stopped and the test was terminated.

Figure (2) the new ankle-foot prosthesis under dorsiflexion test.

Data Evaluation

The tested foot can be pointed as pass the dorsiflexion test when the piece of paper stope sliding under the heel while the testing load less than 1230N. Otherwise the prosthesis is pointed as fail in the dorsiflexion test and it is can't be considered as multiaxial prosthesis, and required no more testing.

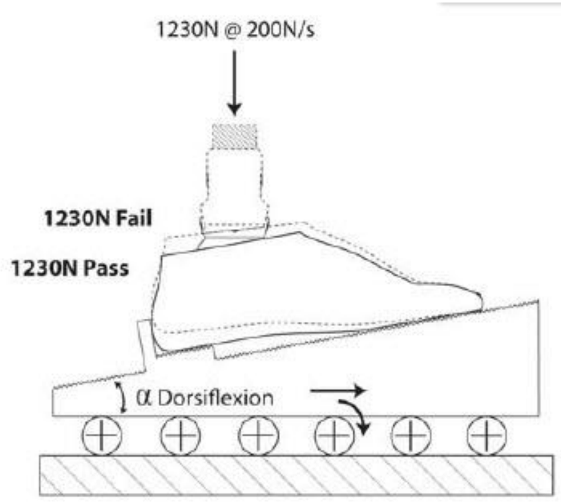

Figure (3) the AOPA schematic illustrate dorsiflexion test evaluation [7].

Plantarflexion test

Equipment & Conditions:

Same tools and equipment of dorsiflexion test, have been used in the plantarflexion test.

Procedure

1- The prosthesis foot mounted to the test devise with the steel loading appliance. Loaded up to 50N, screws tightened, and the foot raised up.
2- The vise equipped with a steel block giving the compensative 15 mm height to the heel contact surface.
3- The vise tilted at angle of -8 degree.
4- The manufactured roller plate was mounted onto the test devise.
5- The vise assembly mounted onto the roller plate.
6- Prosthetic foot lowered in this step until heel contact the heel block surface of the vise.
7- Loading continue until the foot keel firmly contact the inclined vise surface, or it reach 1230N.
8- The firm contact was verified by placing a piece of paper between the keel and the vise surface and sliding it continuously until it was fixed. The loading process was stopped and the test was terminated.

Figure (4) the new prosthesis under plantarflexion test.

Data Evaluation

The tested foot can be pointed as pass the plantarflexion test when the piece of paper stopped sliding under the keel while the testing load less than 1230N. Otherwise the prosthesis is pointed as fail in the dorsiflexion test and it is can't be considered as multiaxial prosthesis, and required no more testing.

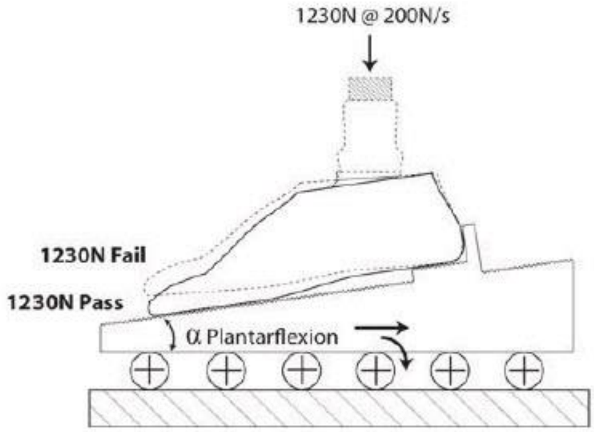

Figure (5) the AOPA schematic illustrate plantarflexion test evaluation [7].

Table (1) dorsiflexion and plantarflexion values

Plane(s) of Motion	Sagital Dorsiflexion	Sagital Plantarflexion
Multiaxial:	10° α Dorsiflexion 1230N @ 200 N/s	8° α Plantarflexion 1230N @ 200 N/s
Second Loading Pass	Heel Contact	Toe Contact
Second Loading Fail	No Heel Contact	No Toe Contact

4- Results and Discussion

Dorsiflexion test result and discussion

Dorsiflexion test is the first required test of prosthesis classification whether it is multiaxial one or not. The new ankle-foot prosthesis was pass the dorsiflexion test according to the AOPA classification requirements, since the heel component firmly contact the heel block when the applied load reaches about 1150-1200N, then loading was paused. The testing devise head recorded a displacement about 14.6 mm when the test was ended. The load-deflection curve was recorded figure (6), which shows a non-linear behavior of the prosthesis under the dorsiflexion test conditions.

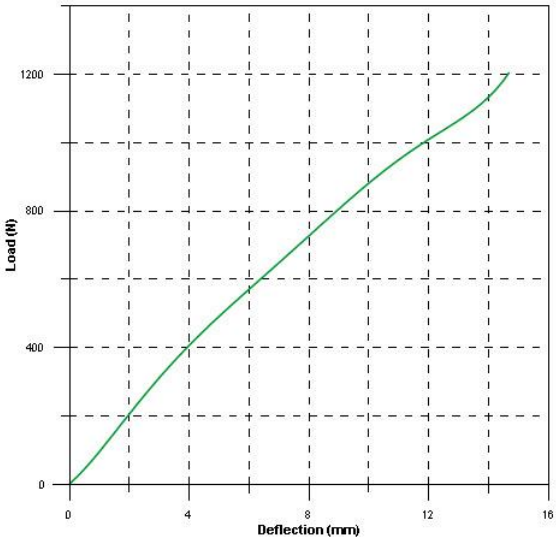

Figure (6) dorsiflexion experimental load- deflection curve.

Plantarflexion test result and discussion

The plantarflexion test is the second requirement of the ankle-feet prostheses multiaxial test procedure. It accomplished after the prosthesis pass the dorsiflexion test. The experimental test of the plantarflexion, pointed that the prosthesis passes the test according to the AOPA requirements, since the foot keel component firmly contact the 8º inclined surface of the testing apparatus. The contact was achieved when the applied load reached about 300N, and the devise headstock displaced about 19.5mm. The prosthesis behaves non-linearly during the most test period. The loading stopped when the load proceeds up to about 325N. Because the prosthesis was highly deflected under the applied load, as seen in figure (7), the firmly contact seems achieved at load under the 300N, since the curve varies sharply near the test end period.

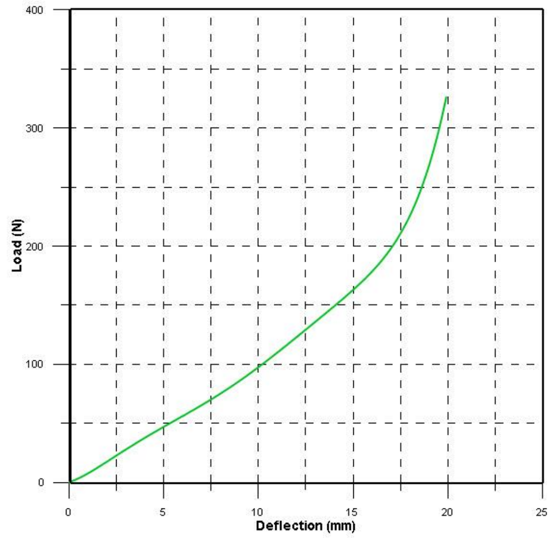

Figure (7) plantarflexion experimental load- deflection curve.

Dorsiflexion and Plantarflexion FE Analysis results

Dorsiflexion and plantarflexion tests are an indication of the ankle-foot prosthesis components flexibility. In the dorsiflexion test keel with ankle function together, while heel and ankle function together at plantarflexion test.

By applying the boundary conditions specified by AOPA for the dorsiflexion test, on ANSYS workbench, the heel compactly contact the 10degree inclined base after deflected about 16.2mm under loading force of 1125N. This result indicated that the ankle-foot prosthesis was successfully pass the dorsiflexion test requirement, as seen in figure (8).

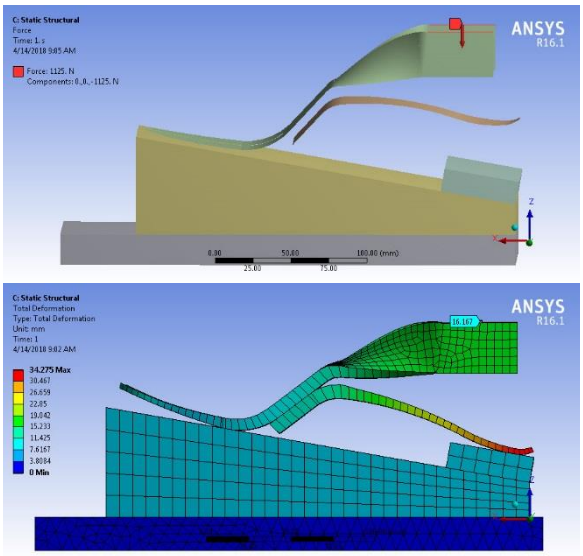

Figure (8) dorsi-flexion test ANSYS loading and result.

After applying the required conditions for the plantarflexion test, which stated by the AOPA, the keel firmly contact the 8 degree tilted base after deflected about 21mm by applying load of 300N.The ANSYS workbench test result, figure (9), declared that the new prosthesis design passing the required planter-flexion test.

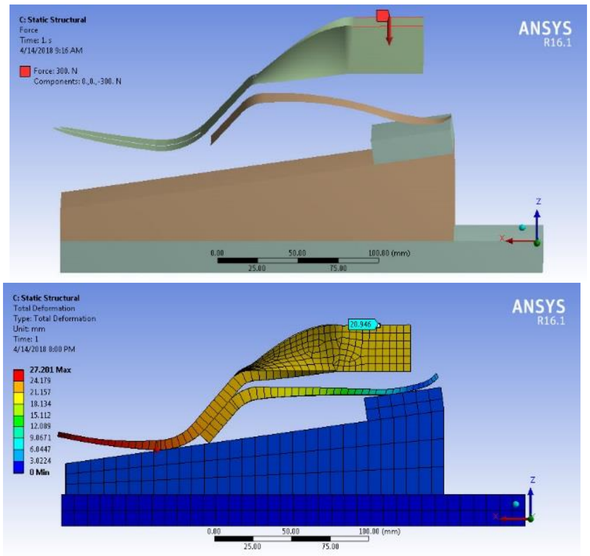

Figure (9) planter flexion test ANSYS loading and result.

The obvious difference between the loads values required to satisfy the two tests was due to the differences in keel and heel components stiffness. The more loading value required, the stiffer component. So the analysis predicts that the keel component is stiffer than the heel, due to geometry reasons.

5- Conclusions and Future work

The most important conclusions can summarize as following:

1- The plantarflexion test requirement was satisfied under loading clearly less the dorsiflexion loading due to the high flexibility of the prosthesis heel comparing to the prosthesis keel.
2- The differences between the amount of test loading that occur in plantarflexion and dorsiflexion tests was due to the geometries differences between the new prosthesis heel and keel.
3- The heel relatively high flexibility allowing the new prosthesis to function effectively as shock absorber.
4- The keel relatively high stiffness is demanded in order to function together with the prosthetic ankle as energy store then release it during the toe off.

The recommended future work can be concentrated on the following jobs to enhance the new ankle-foot prosthesis performance:

1- Study the effect of the prosthesis heel and keel geometry parameters on the dorsiflexion and plantarflexion loading requirements.
2- Study the effect of the prosthesis ankle geometry on the ankle range of motion.
3- Test and analyze the energy store and return that the new ankle-foot prosthesis provided during the gait cycle.
4- Study the relationship between the ankle range of motion and the percentage of the energy store and release.

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