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Structural static characterization of a novel 3D printed prosthetic foot

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Abstract: The new possibilities in Additive Manufacturing allow the development and manufacture of functional, high strength, and customizable 3D printing prosthetic components. This study characterizes the structural resistance, under static loads, of a 3D printed prosthetic foot fabricated with additive manufacturing of continuous filament deposition. Two conditions (keel and heel tests) were evaluated according to the standard ISO 22675. Peak forces of 4106 N were applied to the prosthetic foot with a maximum deformation of 40.8 mm, as a result, no visible fractures were found, and total shape recovery was achieved.

I. Introduction

Additive manufacturing (AM) technology makes it possible to develop and to fabricate customized [1] and parameterized prosthetic components [2] from composite materials. An example of this is Continuous Filament Fabrication (CFF) AM, developed by Markforged®.

CFF produces 3D printed parts reinforced by continuous fiber (carbon fiber, fiberglass, or Kevlar) embedded into a polymeric matrix (Nylon 6 or a mixed Nylon 6 with carbon fiber, commercially known as Onyx) resulting in functional, high strength and customizable 3D printing prosthetic components. CFF technology has been mechanically characterized and has shown higher properties than conventional technologies such as Fused Filament Fabrication (FFF) [3], [4], [5].

This study is conducted to characterize, by performing static load tests, the structural resistance of a prosthetic foot manufactured by AM CFF technology.

II. Material and methods

Static load tests were conducted according to the standard ISO 22675 and the AOPA'S Prosthetic Foot Project (APFP) [6]. Both documents are based on the standard ISO 10328 for structural testing of lower-limb prostheses.

II.I. Foot fabrication

The prosthetic foot (Fig.1) was fabricated with the Mark Two 3D printer (Markforged, Watertown, MA, USA) and is formed by a matrix of Nylon 6 with a continuous reinforcement of fiberglass filament.

The proportional relationship between both materials was 87.8% of Nylon 6 and 12.2% of fiberglass. The size of the component is 257.7 mm length, 100.0 mm height, and 55.0 mm width.

Figure 1: CFF 3D printed prosthetic foot.

II.II. Static test parameters

Based on the standard ISO 22675, two conditions of the prosthetic foot were tested. The first condition evaluates the structural resistance of the heel, in a support angle of -15º, and the second condition evaluates the structural resistance of the keel, in a support angle of 20º. As it shows in Table 1, both conditions must be evaluated by the Static Load Test Force (Fsp) and Static Load Force at Break (Fsu).

Table 1. Static test loads parameters based on ISO 22675.

Test type	First condition	Second condition
Static load test force (Fsp)	2053 N	2026 N
Static test force at break Lower level (Fsu-LL)	3079 N	3039 N
Static test force at break Superior level (Fsu-SL)	4106 N	4052 N

These loads are defined by the Standard ISO 22675 concerning the patient weight. The proposed 3D printed prosthetic foot is developed to resist from 60 to 80 kilograms.

II.III. Test Application

The static tests were performed in an MTS Bionix® Servohydraulic Test System through the implementation of fixtures that allowed proper placement and alignment of the 3D printed prosthetic foot.

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III. Results and discussion

As evidenced in Fig. 3 and Fig. 4, a nonlinear stiffness behavior was recorded from Fsp and Fsu-SL tests in both conditions, increasing stiffness as the applied force grows. At the end of both conditions' trials, the foot recovered its original shape without visible fractures.

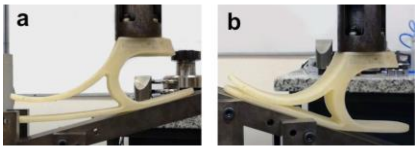

Figure 2: Maximum deformation of the prosthetic foot in both conditions. (a) 2053 N heel test. (b) 2026 N keel test.

III.I. First condition test (heel test)

In heel test, a force of 2053 N was applied in the Fsp, resulting in a deformation of 15.7 mm (Fig. 2a). The Fsu-SL with an applied force of 4106 N caused a maximum deformation of 17.5 mm (Fig. 3).

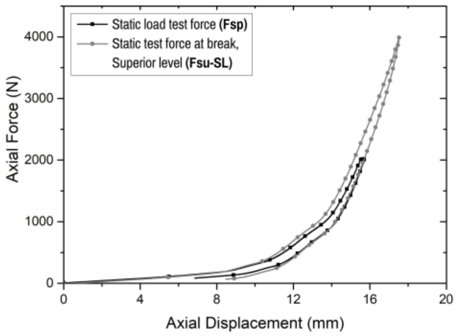

*Figure 3: Total deformation comparison when Fsp and Fsu-L specific forces were applied in **heel test**.*

III.II. Second condition test (keel test)

In keel test, the Fsp with a load force of 2026 N was applied to the keel, generating a deformation of 40.5 mm (Fig 2b). The Fsu-SL with a load force of 4052 N generated a maximum deformation of 40.8 mm (Fig. 3).

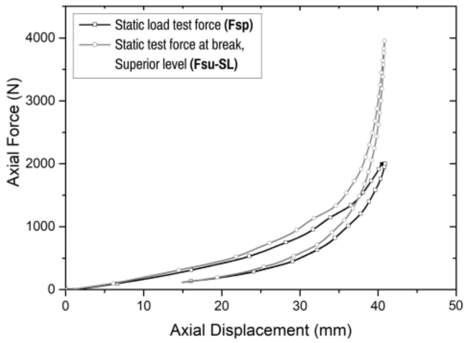

*Figure 4: Total deformation comparison when Fsp and Fsu-L specific forces were applied in **keel test**.*

As shown in Fig. 4, the deformation has similar values at the end of both tests (40.5 and 40.8 millimeters) as a consequence of very different loads being applied (2026 N and 4052 N), This behavior is a result of the keel design considerations, developed to be less rigid than the heel to allow more compression. The keel should have the capability of energy storage and return during walking and the heel should have a stiffer behavior which gives balance to the patients [7].

IV. Conclusions

It was possible to validate the structural resistance, based on the standard ISO 22675, of the proposed 3D printed prosthetic foot. The component could recover its original shape without visible fractures under loads greater than 4000 N.

The desired behaviors were obtained from each evaluated condition. In the first condition, the test proved that the heel has a major stiffness which results in constant deformation according to the applied force. This behavior is important for the standing balance during the gait.

In the second condition, the characterization showed that the keel has less rigidity being able to easily change its shape under different loads. Which can be related to a higher energy absorption capacity that allows a better propulsion during the gait.

It is necessary to characterize, through dynamic tests, the proposed prosthetic foot to determine its fatigue resistance and its energy storage and return capacity.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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