DESIGN AND OPTIMISATION OF A 3D PRINTED COMPOSITE PROSTHETIC FOOT: A FINITE ELEMENT FEASIBILITY STUDY

Luca M. Martulli[a], Abdel Rahman Al Tahabi[a], Andrea Sorrentino[b], Marino Lavorgna[b], Emanuele Gruppioni[c] , Andrea Bernasconi[a]

a: Politecnico di Milano, Via La Masa 1, I-20156 Milano, Italy
lucamichele.martulli@polimi.it
b: Polymer, Composites and Biomaterials Institute, National Research Council (CNR), Via Previati 1/E, 23900 Lecco (LC), Italy
c: INAIL, Centro Protesi Inail, Via Rabuina 14, 40054 Vigorso di Budrio (BO), Italy

Abstract: *Currently, the most traditional manufacturing process for composite prosthetic feet is lamination. While allowing the production of light high-performance structures, the process is very expensive and limits both production rate and customisability. Additive manufacturing can be an alternative solution to cope with these limitations. This work explores the possibility to additively manufacture a prosthetic foot with the same stiffness of a laminated one. To this end, a commercially available foot is first analysed via numerical simulations. Using this reference case, a beam elements-based tool is developed and validated. The tool was then used to optimise four different designs of a possible additively manufactured prosthesis. This preliminary work resulted in two possible 3D printed foot designs that could be further analysed to potentially substitute the laminated prosthesis.*

Keywords: 3D printing; additive manufacturing; prosthesis; optimisation; composite structures

1. Introduction

Modern commercially available prosthetic feet for amputees belong to two categories [1]. The first, the Solid Ankle Cushion Heel (SACH), is relatively inexpensive and reliable, but generally displays poor performance: it is thus indicated for people with limited activity on standard terrains. The second, the Energy Storage And Return (ESAR) prosthesis mimics more accurately the human foot by storing and releasing energy during the different phases of the walk; it is therefore more comfortable and allow for a higher level of activity. The ESARs, however, are often made of laminated carbon fibre composites, making them very expensive for the final user.

Additive manufacturing can potentially allow for cheaper, faster, and customised manufacturing of high-performance composite structures [2]. The objective of this work is to assess the feasibility of an ESAR prosthetic foot made by Fused Filament Fabrication (FFF), one of the most popular additive manufacturing techniques for polymeric composites [2].

A reference prosthetic foot was defined, inspired by commercially available models (e.g. [3]) was assumed. Finite Element (FE) simulations were first performed on this geometry. These simulations aimed to define target prosthesis stiffnesses in the different analysed configuration. Moreover, a beam element-based modelling approach is developed and validated on the reference prosthesis. Thanks to the fewer geometrical descriptors it requires, this modelling approach is adopted in the optimisation process of the newly developed 3D printed prosthesis.

2. Modelling methodologies and approaches

2.1 Reference prosthesis models

Figure 1a shows a 3D CAD model of the reference prosthesis. Shell element simulations were performed on Abaqus software by extracting the mid surface of the two springs and the plantar (see Figure 1b). The connection gasket was modelled with tie constraints between the interested surfaces. A rigid coupling was applied to the upper end of the springs to a fixed node-top to simulate the connection to the pylon. Moreover, vertical displacements Δu were applied to the lowest points, as shown in Figure 1b, to simulate the mid-stance phase of the walk [4]. After a mesh sensitivity analysis, a mesh seed of 5 mm was used.

A beam elements model was also obtained by projecting the shell model on the X-Z plane (see Figure 1c). Rigid connections were used as shown. A constant width of 55 mm was assumed for this model, because this approximated best the width of the springs and of the central part of the plantar. The boundary conditions mimic the ones of the shell model: the node-top is fixed, while vertical displacements are applied to nodes A and node B.

The prosthesis was assumed to be made of a Carbon Fibre Reinforced Plastic (CFRP) laminate, with stacking sequences $[(\pm45°)_3(0°)_{24}]_s$ and $[(\pm45°)_2(0°)_{16}]_s$ for the plantar and the springs, respectively. The CFRP material properties are reported in Table 1 as obtained from [5]. For the shell simulations, the composite laminate tool of Abaqus was used. Regarding the beam model, Chou's theory [6] was used to homogenise the laminates and obtain their engineering constants. The reaction force at the node-top was extracted as function of the applied displacement Δu. The slope of this load-displacement curve was considered as the stiffness of the reference prosthesis.

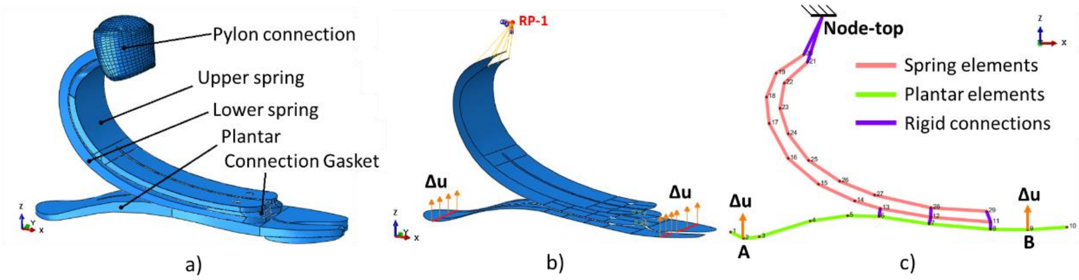

Figure 1: Reference prosthesis: a) real object, b) 3D CAD, c) shell model and d) beam model.

Table 1: CFRP properties [5]. Moduli are in GPa, Poisson's ratio are dimensionless.

E11	E22	E33	G12	G13	G23	ν12	ν13	ν23
121	7.46	7.46	5.2	5.2	2.6	0.13	0.13	0.44

2.2 3D printed prosthesis models

The 3D printed prosthesis will take advantage of the 3D printed sandwich structures concept [7]: the sandwich skins will be made of continuous carbon fibres layers, while the infill will make the sandwich core. The infill is made of Onyx, a micro-carbon fibres reinforced polyamide developed by Markforged [8]. The geometrical complexity of the prosthesis requires it to be printed on the X-Z plane. Therefore, the carbon fibre layers will all be oriented along the local material x-axis (0° orientation). Considering the inherent geometry of sandwich structures and the different stiffness of skins and core, the skins were assumed to bear all the bending stresses, while the core was assumed to bear all the shear stresses. This was possible since Timoshenko beam elements were considered, so to include the shear flexibility of the sandwich beams. For the full theory on Timoshenko's beam elements, the reader is referred to [9].

To fully exploit the additive manufacturing potentials, a unique integrated structure will be considered for the prosthesis. To keep the biomechanical properties of the prosthesis as close as possible to the reference prosthesis, the plantar was left unchanged. Two different spring geometries were considered, namely C-shaped or J-shaped. The exemplificative case of a C-shaped prosthesis is shown in Figure 2a. Moreover, considering similar works on the subject [10], the possible presence of a heel support was evaluated (see Figure 2b and 2c). The spring and heel elements were imposed to have a total thickness of 75% of the thickness of the plantar (as was approximately the case for the springs of the reference prosthesis).

The optimisation procedure was thus performed on four different geometries. Seventy configurations per geometry were considered in the optimisation procedure. This is schematically illustrated in Figure 2a: different configurations per geometry were obtained by varying the parameter ε, which thus becomes an optimisation variable. Configurations 1, 35 and 70 are shown for all geometries in Figure 3, as examples. The other optimisation variables were the thickness of the core *c* and the thickness of the skins *t* of the spring elements. Weight was set as the objective function to minimise, while the design constraint was to have an equal stiffness of the reference prosthesis. The stiffnesses of the 3D printed prostheses were obtained by applying the same boundary conditions as those shown in Figure 1c, with a fixed note-top and applied displacement Δu to both nodes A and B.

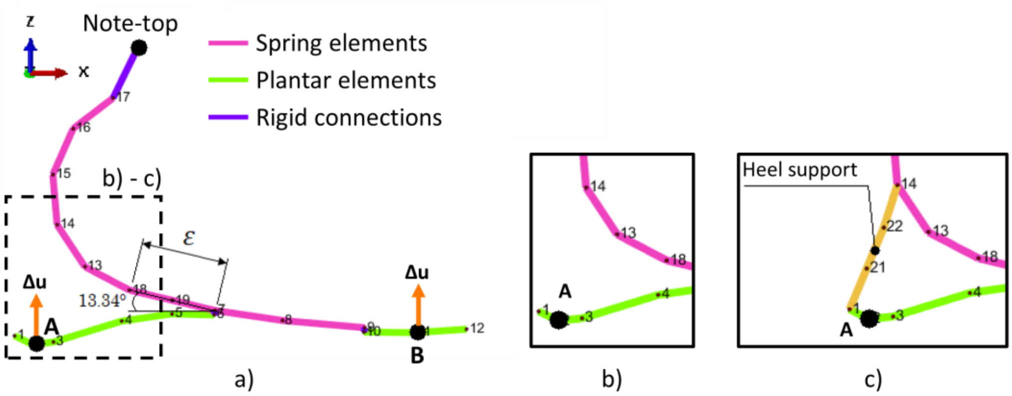

Figure 2: a) Example of the beam model of a 3D printed prosthesis with a C-shaped spring. The optimisation variable ε is shown. Details of the prosthesis b) without and c) with the heel support are also shown.

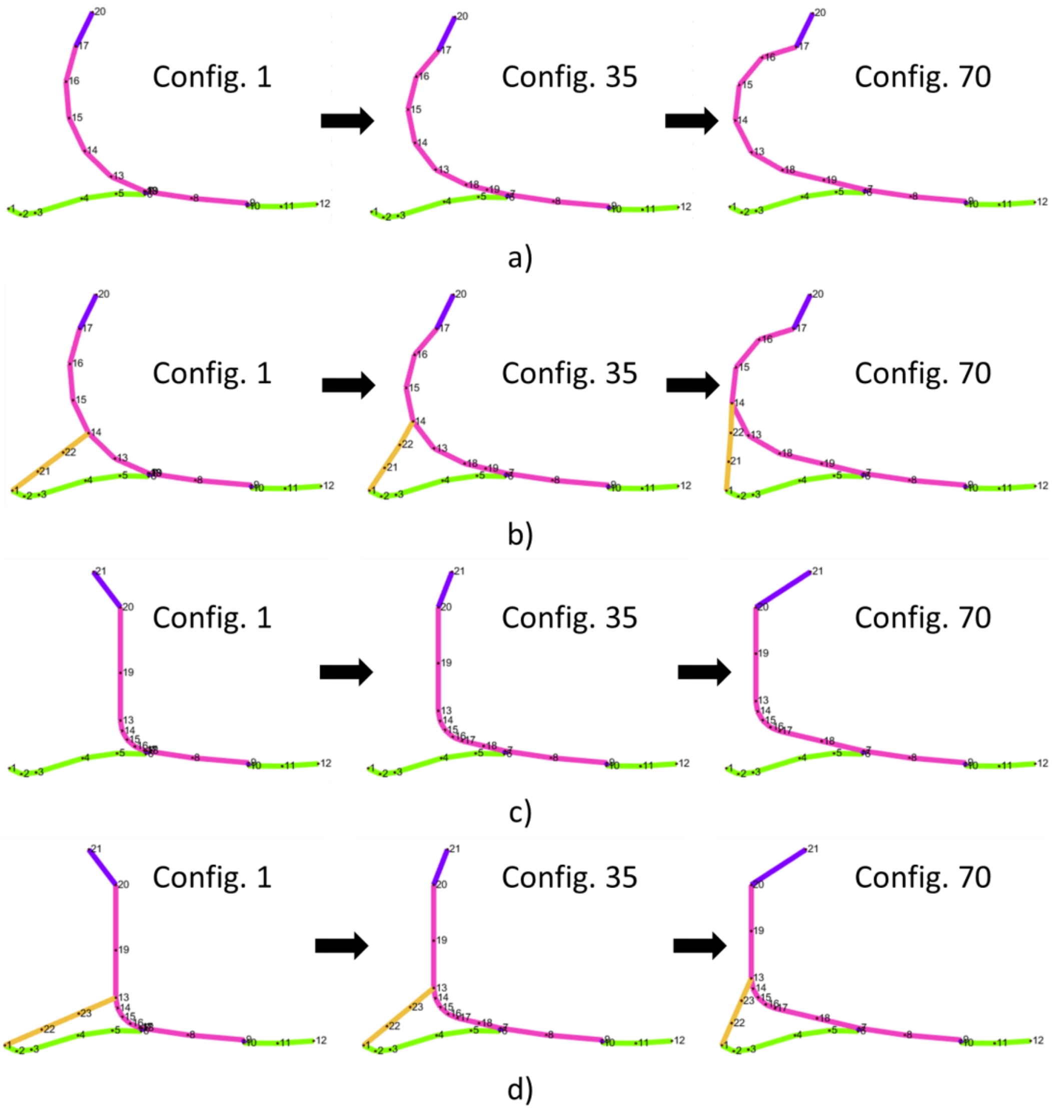

Figure 3: Configurations 1, 35 and 70 for the a) C-shaped spring prosthesis, b) C-shaped spring prosthesis with heel support, c) J-shaped spring prosthesis and d) J-shaped spring prosthesis with heel support.

Finally, Table 3 reports the remaining material and geometrical details adopted in the optimisation procedure, as well as the considered material densities for the weight calculations.

Table 3: Material and geometrical details adopted in the optimization procedure.

Parameter	Value
Young's modulus of the skins E_s [8]	45.0 GPa
Shear modulus of the core G_c [7]	122.0 MPa
Width of all the beam elements b	55 mm
Density of the carbon fibre skins ρ_s [8]	1200 kg/m^3
Density of the core ρ_c (20% rectangular infill) [7]	418 kg/m^3

3. Results and discussion

3.1 Beam model validation

Table 4 reports the comparison of the stiffnesses obtained with the shell FE model on Abaqus and the developed beam FE model. As shown, the developed beam elements-based model overpredicts the stiffness predicted by the shell element model by less than 8%. This is coherent with the different width of the two models. As mentioned, the beam elements-based model considers a constant width equal to the central width of the reference prosthesis. However, the front and rear portions of the prosthesis present a reduction of width, which is considered only by the shell model. Overall, the beam model is thus considered a reliable tool for the optimisation of the 3D printed prosthesis.

Table 4: Comparison of stiffnesses obtained in the shell and beam FE model.

Simulated stiffness	Value
Shell FE model (Abaqus)	294.5 N/mm
Beam FE model	317.1 N/mm

3.2 Optimisation of the new prostheses

Figure 3 reports the results of the optimisation procedure, showing for each design the best configuration and the core and skins thickness *c* and *t*, respectively. As expected, the presence of a heel support significantly increases the stiffness of the prosthesis: the foot with the heel support thus requires much thinner core and skins (see Figure 3c and 3d). However, the thickness of these two designs is likely not to be printable, as printing with continuous fibres usually requires layers of about 1 mm [8]. Moreover, such thin structures may result in too high stresses in the structure. For these reasons, the presence of the heel support must be discarded. The difference between the other two feet (Figure 3a and 3b) highlights the different contributions of the spring shape, with the J-shaped one being stiffer than its C-shaped counterpart. Both designs show skins layers thicker than 1 mm, and can thus be printed. Interestingly, for both these designs the best configuration was the first one, with ε=0.

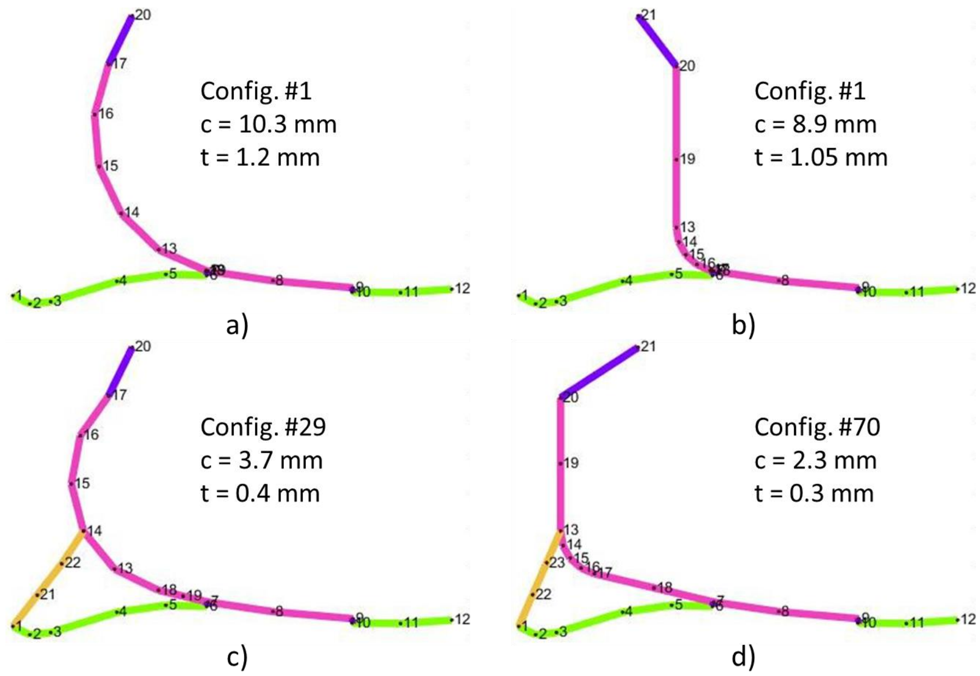

Figure 3: Results of the four optimisations

Considering the above, both prostheses without the heel support could match the vertical stiffness of the laminated structure with reasonable geometrical parameters. Therefore, these geometries can be further analysed to design a 3D printed prosthetic foot with performance similar to that of a commercially available one.

4. Conclusions and future works

The present work aimed to explore possible designs for a 3D printed prosthesis as an alternative to laminated ones. A beam elements-based numerical tool was developed to allow for an efficient optimisation of different prosthesis shapes. The tool was first validated against a reference case, namely a commercially available laminated prosthesis. This prosthesis was also analysed to predict its vertical stiffness. The beam elements-based tool was then used to optimise four different 3D printed prosthesis designs. The reference vertical stiffness was set as optimisation constraint, while weight was the objective function. It was found that the presence of a heel support made the prosthesis too stiff. On the other hand, it was possible to obtain two different designs matching the vertical stiffness of the reference prosthesis.

This work supports the feasibility of a 3D printed prosthetic foot as replacement for a laminated one. This work can thus be the basis for a future design phase, that would require a deeper analysis. First, the vertical stiffness was considered as optimisation constraint: this is equivalent to consider the response of the prosthesis in the mid-stance phase of the gait [4]. However, it is also important to evaluate the overall stiffness of the prosthesis in the other phases of the gait cycle [4]. Once this is done, an assessment on the strength of the obtained 3D printed prosthesis design must also be performed, considering both static, fatigue and creep loading conditions.

Finally, the overall design of the prosthesis should also consider a proper connection device to the upper structures of the prosthesis.

5. References

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