DEVELOPMENT OF A NEW DEFORMABLE FLEXIBLE ACTIVE FOOT FOR HYDROÏD ROBOT USING 3D PRINTING OF COMPOSITE

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Abstract

In the recent century, the composite materials are widely used in aerospace, marine and building construction, but they are poorly introduced in the manufacturing of robotics parts. The classical manufacturing methods of the composite materials bring on the price and time factors to be undesirable ones. Thus, a new technology for 3D printing of composite material is introduced , which is used for the development of a deformable flexible active foot of the under-development HYDROïD humanoid robot [2], the first hydraulic integrated robot. Different composite fibers (carbon, glass and Kevlar) are chosen and the results are compared respecting the specifications. Two methods are used: the least-weight method and the optimization cost function method where the ratio of the bending rigidity per unit mass and price is maximized, in order to identify the optimum parameters. Furthermore, the new foot is designed respecting the constraints of the 3D printer and according to the carried out optimization. These results are verified on a prototype developed by the 3D printer Mark One of the company Markforged [1].

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1. Introduction

In the field of robotics, many researchers aim to build a lightweight robotic system, with a high strength and minimum energy consumption. To achieve that aim, several approaches are suggested [3]. One proposes to redesign the element and select the appropriate material which fits with the new design. Other advises to get more knowledge of load cases and material's conditions, in order to enhance the material fulfillment. The latter recommends the employment of the appropriate composite materials in order to reduce the weight.

Concerning humanoid robots, not only the previously mentioned purposes are required, but also the researchers aim to build a humanoid robot mechanism which is similar in the weight, size, and power proportions to human being [4]. These specified criteria will improve the performance of the robot in order to be able to accomplish many human activities. However, these aims are found to be contradicting, especially when talking about hydraulically powered humanoid robots. In such robots, high stresses are introduced. Consequently, high strength mechanical parts are essential in order to bear the important applied pressure (more than 150 bar). Thus, high duty metals were elected by most researchers in order to develop hydraulic powered humanoid robots. Despite, this solution generates critical problems. First, the developed hydraulic humanoid robots have heavier masses than that of the human of the same size. This will obviously reduce the capabilities of the robot to achieve the human activities such as walking and manipulation. Second, the manufacturing of such robots will be more difficult due to the complex machining process. Consequently, the robot will have a complex design inherently inducing a high price. Examples of hydraulic humanoid robots include CB robot (92 kg in weight and 1.58 m in height), CB-i robot (85 kg in weight and 1.55 m in height) [5], Atlas robot (180 kg in weight and 1.88 m in height) [6] and the underdevelopment HYDROïD, the first hydraulic integrated robot.This induces still open questions, in order to achieve the development of lightweight hydraulic humanoid robots, with high strength and optimal energy efficiency. To initiate that, the employment of the modern composite materials is selected as promising solution for HYDROïD robot's foot, due to its important role in the walking activity of humanoid robots. However, conventional methods of composite materials have limitations as to the manufacturing of complex parts. This drawback is tackled thanks to the 3D printing technology of composite material which has been introduced recently.

In this paper, the sandwich material theory is applied to best describe the robot's foot. This is explained in section 2, along with the parameters of the sandwich panels. Furthermore, the description of the robot's foot parameters required for the design process is given in section 3. Meanwhile, the optimization process is triggered and performed in section 4. Then, the results of the optimization process are appreciated to fulfill the new optimized design, which is detailed in section 5. Finally, the conclusion and perspectives of this work are given in section 6.

2. Sandwich Model Parameters

Table 1. Different Sandwich Model Parameters

Parameter	Unit	Definition
L	m	Foot Length
b	m	Foot width
h	m	Foot Thickness
M	kg	Foot Mass
D	$N.m^2$	Bending Rigidity
E	N/m^2	Young Modulus
R	N/m^2	tensile Strength
P_r	€	Price of the foot
ν	-	Core Thickness ratio

In order to best describe HYDROïD robot's foot proposed solution, the theory of sandwich material is used. Sandwich material consists of a low density core, with stiff skins that offer a considerable achievement for weight saving, in applications where the main loads are bending. The considered sandwich panel consists of the fiber with thermoplastic blend skin laminates with nylon core. The fiber can be carbon, glass or Kevlar. These materials are specified by the manufacturer of the composite 3D printer.

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The calculations are carried out according to the basic design formula of the sandwich material theory, and applied on the properties of the used composite materials. The main parameters of the sandwich panel are related to geometric and mechanical aspects. The geometric parameters include mainly the dimensions: the length L, the width b and the thickness h, and the mass M, while the mechanical parameters consist of the bending rigidity D, the Young modulus E and the tensile strength R. Thus, the optimization process would take into account the geometric and the mechanical parameters. Finally, the price P_r will be included in the optimization process as it is an effective factor. The main achievement is to reach the optimum core thickness ratio v (which is the ratio of the core thickness to the total sandwich thickness h) under the desired application and load cases. All the parameters are summarized in table 1.

3. HYDROïD Foot Description

3.1. Comparison of Possible Models of HYDROïD Foot

The design of the HYDROïD foot consist of 3 main parts: the heel, the central part and the toes. In general, four main models of the foot are proposed [7]. First, the plate foot, where no degree of freedom exists between the three parts. Second, the flexible foot, where a passive joint exits at the toe level. Third, the active foot, where one active joint exists at the toe, and finally the flexible active foot where,in addition to the active joint, one passive joint is added between the heel and the central part. A comparison between the four types concerning the energy consumption and normal contact force is shown in table 2.

Table 2. Comparison of different types of foot models concerning the energy consumption and the normal contact

Foot Model	Total energy consumed	Normal Contact
Plate Foot	Reference	-
Flexible Foot	10%	+
Active Foot	25%	- -
Flexible Active Foot	25%	+ +

Table 2 shows that the hybrid model, with flexibility and active joint, has a 25% advantage in the consumption of the energy, as the active foot, and has a very good normal contact force.

3.2. HYDROïD foot parameters

The current design of the HYDROïD foot is an active foot. It is manufactured of aluminum with a total mass of 0.95 *kg*. The impact at the heel still exists which has a disadvantage in the normal contact force. Fig1 shows the design of the actual foot.

The looked for foot would be divided into 3 parts: flexible heel, central part and active toe. The central part would be 3D printed from composite material, with a length of 290 *mm*, a width of 100 *mm* and a thickness of 15 *mm*. It is also supposed to show a mass reduction of 70 %, with 3 times higher strength. The heel would be 3D printed from flexible shock absorbing material, which will reduce the impacts in the foot. The toe would be active as the actual design.

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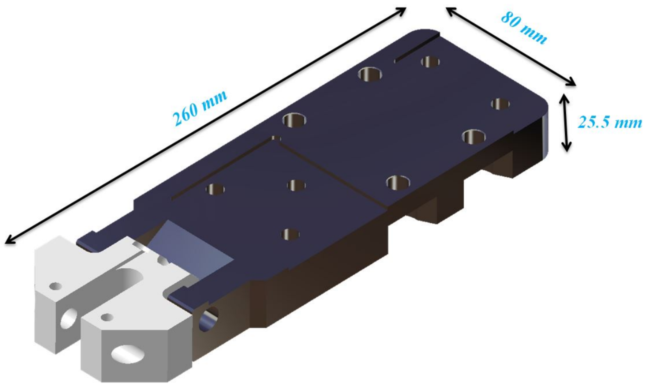

Figure 1. Actual Foot Design Dimensions

4. Optimization Process

4.1. Least-Weight Method

4.1.1. Introducion

The optimization process is carried out to specify the optimum core and skin thicknesses, which give the least weight with the highest rigidity. This is done using the theory of the least weight for a given bending rigidity [8]. Using this theory, an optimum choice of the core thickness ratio v is given by Eq.1

$$v^2 = \frac{1 - \frac{\rho_c}{\rho_s}}{1 - \frac{E_c}{E_s}}. \tag{1}$$

Where ρ_c and ρ_s are the core and the skin material densities (in kg/m^3) respectively, E_C and E_s are the core and the skin young modulus (in N/m^2) respectively. Then for a given bending rigidity D (in $N.m^2$), the sandwich optimal thickness is stated by Eq.2:

$$h^3 = \frac{12\,D}{bE_f}. \tag{2}$$

where D is the bending rigidity, b is the width (in m) and E_f is the bending modulus of the sandwich material. E_f is function of E_C and E_s and is calculated using Eq.3:

$$E_f = v^3 E_C + (1 - v^3) E_s. \tag{3}$$

Results are obtained using a range of bending rigidity from 400 $N.m^2$ to 1600 $N.m^2$, for the different types of the fiber laminate composite of the skin material.

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4.1.2. Simulations

To identify the optimum thickness of the sandwich material, Eq.2 is simulated on MATLAB for different values of bending rigidity. Fig2 shows the variation of thickness of the sandwich panel, as a function of the rigidity for each type of the composite laminate. According to the curves, for a given value of rigidity, carbon fiber shows the least thickness, while glass fiber shows the highest thickness.

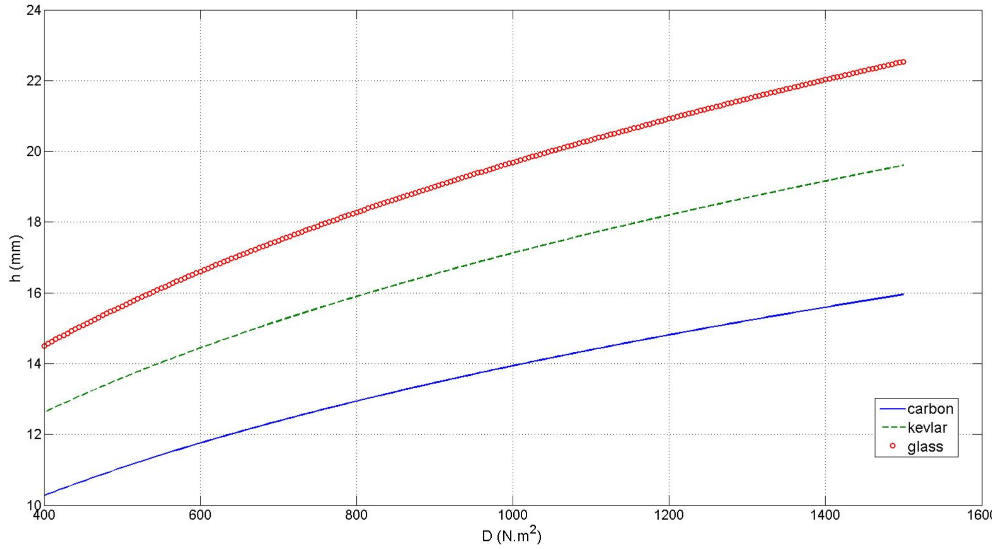

Figure 2. Variation of the thickness function of bending rigidity for carbon, glass and Kevlar composite

The mass variations are also simulated using equation Eq.4:

$$M = bhL(\nu\rho_c + (1 - \nu)\rho_s). \tag{4}$$

where M is the mass of the sandwich panel (in kg). The results are shown in Fig 3. Carbon fiber shows best results concerning the mass, where for a given rigidity, the carbon fiber composite has the least mass while the glass fiber has the highest one.

Concerning the core thickness ratio ν, equation Eq.1 shows that carbon fiber has ν=0.5, Kevlar has ν=0.36, while glass fiber has ν=0.6. Table 1 gives different parameters for a chosen thickness h=15 mm.

It is obviously shown in Table 3 that carbon fiber has the highest rigidity to mass ratio, while glass fiber has the lowest one.

4.2. Optimization Cost Function

4.2.1. Introduction

The objective of the second method is to carry out an optimization process based on a cost function F. This function includes the bending rigidity D, the mass of the foot M_{foot} and the price P_r in €. All these parameters vary function of the core thickness ratio ν.(such as $D = \frac{bh^3}{12}(E_c\nu^3 + E_s(1 - \nu^3)$,

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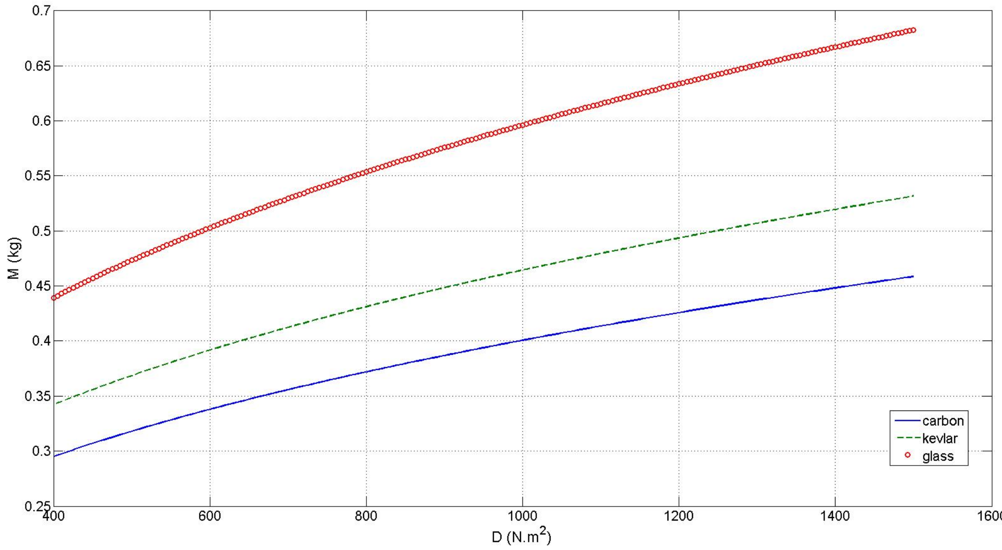

Figure 3. Variation of the mass of composite as function of bending rigidity for carbon, glass and Kevlar

Table 3. Comparison of different sandwich material parameters (the core thickness c, the skin thickness t with $h = 2t + c$, the mass of the foot M_{foot} and the bending rigidity D) for different types of fibers for a given thickness for least weight method

Composite Type	M_{foot} (kg)	t (mm)	c (mm)	D $(N.m^2)$	D/M $(N.m^2/kg)$
Carbon fiber	0.431	3.75	7.5	1250	2900
Kevlar	0.407	5	5.25	675	1658
Glass fiber	0.415	3	9	445	1072

$M_{foot} = bhL(\rho_c \nu + \rho_s(1 - \nu))$, $P_r = bhL(P_{rc}\nu + P_{rs}(1 - \nu))$ where P_{rs} and P_{rc} are the skin and the core price respectively per unit volume).

The aim is to specify the optimal core thickness ratio ν which maximize the optimization cost function F, with the constrained dimensions L, b and h. The cost function F has to be maximized since one needs to increase bending rigidity while minimizing the foot's mass as well as the price. The expression of the cost function F is given by equation Eq.5:

$$F = \frac{D}{M_{foot} P_r}. \tag{5}$$

This function is evaluated for the different types of the fibers of the composite laminate skin, and the optimum ν^* for each type is identified.

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4.2.2. Optimisation results

In order to calculate the optimal core thickness ratio ν^*, cost function F variations are simulated using MATLAB. The function F is calculated for different values of ν and results are plotted for each type of the used composite fiber laminates (shown in Figure 4).

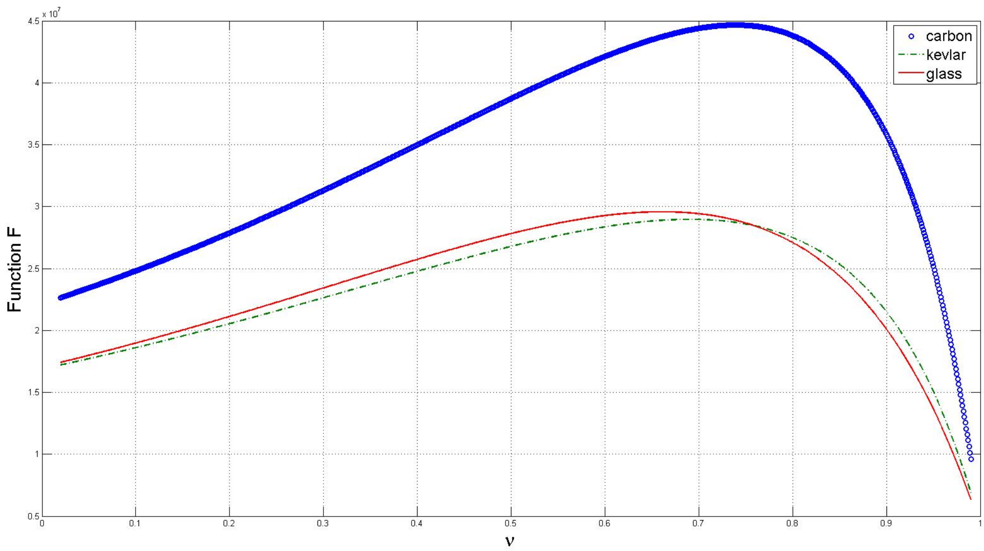

Figure 4. Variation of the cost function F with the core thickness ν ratio for carbon, glass and Kevlar composite

The three curves show the optimum value of ν^*, at which F has its maximum value F^*. The optimum core thickness ratio for carbon fiber is $\nu_c^* = 0.74$, where for Kevlar the optimum core thickness ratio is $\nu_k^* = 0.68$ and for glass fiber is $\nu_g^* = 0.65$. Carbon fiber reinforced composite skin shows the maximum optimization value for F, where Kevlar and glass have approximately the same values. Table 4 gives a comparison between the different geometric and mechanical parameters for each type of the fiber composite, at the optimum core thickness ratios ν_c^*, ν_k^* and ν_g^* respectively.

Table 4. Comparison of different sandwich material parameters for different types of fibers at optimum core thickness ratio ν^*

Composite Type	M_{foot} (kg)	t (mm)	c (mm)	D $(N.m^2)$	D/M_{foot} $(N.m^2/kg)$
Carbon fiber	0.265	2	11	860	3245
Kevlar	0.25	2.5	10	500	2000
Glass fiber	0.3	2.6	9.8	412	1373

Carbon fiber composite shows the highest rigidity, while glass fiber has the lowest rigidity. Generally, the three types of composites have small difference concerning the masses and the core and skin thicknesses. The main difference is mainly in the bending rigidity, where carbon fiber composite has at least double

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the rigidity of that of glass fiber and Kevlar composites. In addition, the carbon fiber composite has the highest bending rigidity to mass ratio, while glass fiber has the lowest bending rigidity to mass ratio.

4.3. Comparison of the optimization methods

The comparison of the two optimization methods shows a large difference in bending rigidity to mass ratio of the HYDROïD robot foot. For the same thickness h = 15 mm, the optimization function method gives higher rigidity to mass ratio results for the three types of the fiber composite than the least-weight method. This is due to introducing the price factor. Meanwhile, the optimization function method gives more reasonable results concerning the skin and the core thicknesses. In addition, in both methods, carbon fiber shows the highest bending rigidity to mass ratio.

5. Results

The new optimized design is a deformable flexible active foot.The central part is 3D printed, from carbon fiber composite skin and nylon core, with a thickness h = 15 mm and a core thickness ratio $v = 0.75$, as has been reached with the optimization cost function method. The heel is formed of a 3D printed rubber like flexible elastic material, integrated with the central part. That permits the new design to absorb the impacts during walking. Fig.5 shows the CAD design (A) and the 3D printed optimized HYDROïD foot (B). The new foot is 70% lighter than the current one with a mass of 0.265 kg. The ankle mechanism,

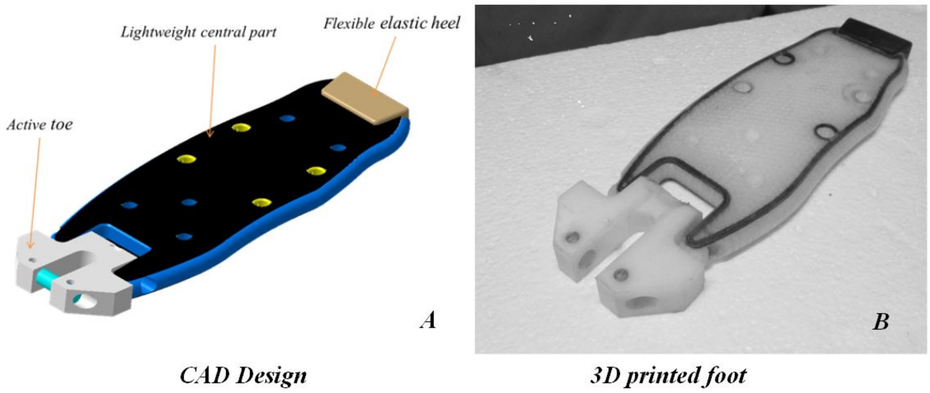

Figure 5. The CAD design (A) and the 3D printed optimized HYDROïD foot (B)

with an actual mass of 1.9 kg, is thus reduced to 1.215 kg, which gives about 35% reduction of mass on the current whole ankle mechanism. This has two main advantages. The first advantage concerns the rotational kinetic energy K_{rot} consumed during the swinging phase of the ankle. The kinetic energy is stated as:

$$K_{rot} = \frac{I_a \omega^2}{2}. \quad (6)$$

where I_a is the inertia (in $kg.m^2$) and ω is the rotational velocity of the ankle (in rad/sec). Thus, according to Eq.6 when the ankle's mass M_a is optimized 35%, the inertia I_a is is reduced linearly with the mass, and thus the energy consumed is reduced 35%. The second advantage deals with the natural frequency of the ankle which is stated as following:

$$\omega_n = \sqrt{\frac{K}{M_a}}. \quad (7)$$

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Where K (in $N.m$) is the stiffness of the ankle mechanism around a given axis of motion namely pitch or yaw. When M_a is increased by 35% then ω_n is increased by 25%, this is according to Eq.7 considered for the same stiffness value of the ankle and by reducing the mass M_a by 35%. This would allow for better control of the ankle since the mass reduction diminishes the phase shift and improves the time response of the mechanism. In other hand, for thin skins, the tensile strength can be calculated as following [8]:

$$R = \frac{1}{2}\sqrt[\frac{1}{3}]{E_s E_c^2}. \tag{8}$$

Using Eq.8, the new design is 3 times stronger at bending than the old design. This is considered as additional advantage for the optimized HYDROïD foot proposed in this paper.

6. Conclusion

In this paper, the new optimized design of HYDROïD foot has been presented and discussed. At first, several possible models of the foot are compared, and the flexible active foot has been chosen for the design. Meanwhile, two optimization methods have been used to determine the geometric and mechanical parameters of the new design. Then, the new design is implemented, and several advantages concerning the energy consumption and the natural frequency have been discussed. For the future work, the proposed solution for the foot will be assembled to the ankle mechanism and a set of experimental performance analyses will be carried out before a full integration on the HYDROïD humanoid robot. Also, the same principle will be applied on other parts of the robot.

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