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Bio-inspired redesign of a hip prosthesis stem for improving geometrical optimization time

Jaime Orellana[a]*, Teresa Palacios[b], Fernando Calle[c], José Ygnacio Pastor[a]

[a]*Universidad Politécnica de Madrid, Escuela Técnica Superior de Ingenieros de Caminos, Canales y Puertos, Departamento de Ciencia de Materiales-CIME, Calle Profesor Aranguren 3, Madrid 28040, Spain*
[b]*Universidad Politécnica de Madrid, Escuela Ténica Superior de Ingeniería y Diseño Industrial, Departamento de Ingeniería Mecánica, Química y Diseño Industrial-CIME, Ronda de Valencia 3, Madrid 28012, Spain*
[c]*Universidad Politécnica de Madrid, Escuela Técnica Superior de Ingenieros de Telecomunicación, Departamento de Ingeniería Electrónica-ISOM, Av.Complutense 30, Madrid 28040, Spain*

Abstract

It has been investigated the potential application of a bio-inspired 3D model for decreasing the time required to perform the geometrical optimization of a hip prosthesis stem. This research assumes that nature has already found the best solution for many situations, proved to be real for many cases, what has been demonstrated for the specific situation of a femur in this study. The application of bio-inspired 3D models can save up to a 35% of the time when geometrical optimizations are going to be performed.

Keywords: prosthesis ; redesign ; simulation ; bio-inspired ; time ; optimization ; geometry ; mass

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1. Main text

Every day, more advanced and complex simulations are performed with the aim of finding the optimum geometry for a given component in a particular application. However, this also means that the time required for these simulations increases, a variable of concern when a detailed solution is required and when high time consumption studies are not possible [1].

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* Jaime Orellana Barrasa. Tel.: +34-691-180-649.
E-mail address: jaime.orellana@upm.es

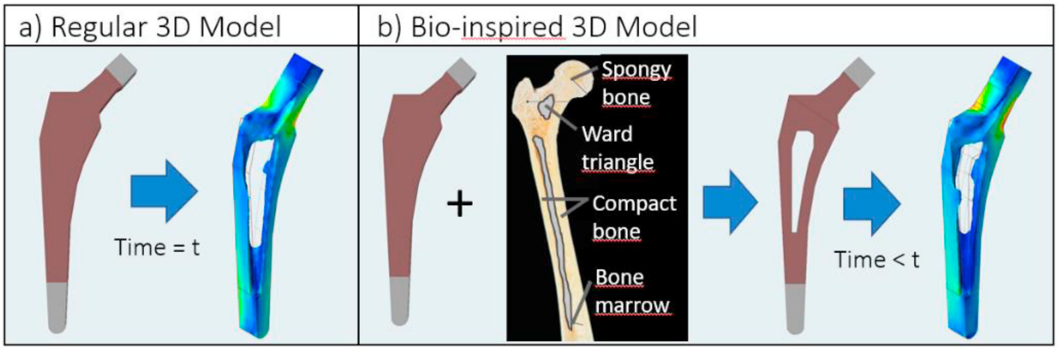

Fig. 1. Hip stem model and geometrical optimization (a) from the regular 3D model; (b) from a bio-inspired 3D model.

Finding these optimized geometries have interest, for example, on the aerospace or transportation industries where fuel consumptions can be improved if lighter components are used [2]. In this study, it has been investigated the stem of a femoral hip prosthesis, which is of great importance due to the increasing number of hip arthroplasties and the longer life of patients [3, 4]. The ideas here presented can be used on any other industries in which the reduction of the mass of the components could be obtained by redesigning the geometry of that component.

Removing material of the regular 3D model stem here studied, significantly reduces the mesh size and thus the time required for any simulation performed, like a geometrical optimization in this case. This idea has been represented in Fig. 1. The material manually removed from the regular 3D model should be carefully selected so that the final solution will not differ from the optimum one. In addition, this process of removing material must take a small amount of time compared with the total time saved on the geometrical optimization to make these bio-inspired models useful.

If we assume that the final geometry solution of our regular 3D Model is going to be similar to the one on the nature which is going to be substituted (the upper part of the femur is going to be substituted with a hip stem, in this case), we can easily find which parts of the regular 3D model can be removed without compromising the result. This assumption has been proved to be real in several cases [5–7], and therefore, this study wants to get a comprehensive understanding on how to use nature geometries to improve geometrical optimization times. Moreover, we also have proved that the final solution with the regular 3D model of the stem has similarities with the real femur, adding one more example to list of best solutions already obtained by nature for a given application.

2. Modeling and Simulation

2.1. Femur Bone

A 3D model with the main femur dimension has been created on Evolve software (SolidThinking) with a simple truncated cone, to have a better understanding of the influence of the bio-inspired 3D model of the stem on the geometrical optimization process. The osteotomy of the major trochanter has been imitated, and only the upper half of the femur has been considered Fig. 2.a.

2.2. Hip Stem

A regular 3D model of a commercial hip stem (Renovis A400 Tappered Cementless) has been created with the software Evolve (SolidThinking).

Then, it has been reshaped the regular 3D model on Inspire software (SolidThinking) to include the bone marrow cavity of the femur and this way, getting the bio-inspired 3D model (Fig. 1.b). Other possible bio-inspired shapes to include on the 3D model could have been the Ward triangle (a radiolucent area in the neck of the femur surrounded by principal and secondary stresses). The Ward triangle hasn't been included, as it is localized in a small area on the neck of the femur, and thus the risk of misplacing the Ward triangle and remove critical material (the material that

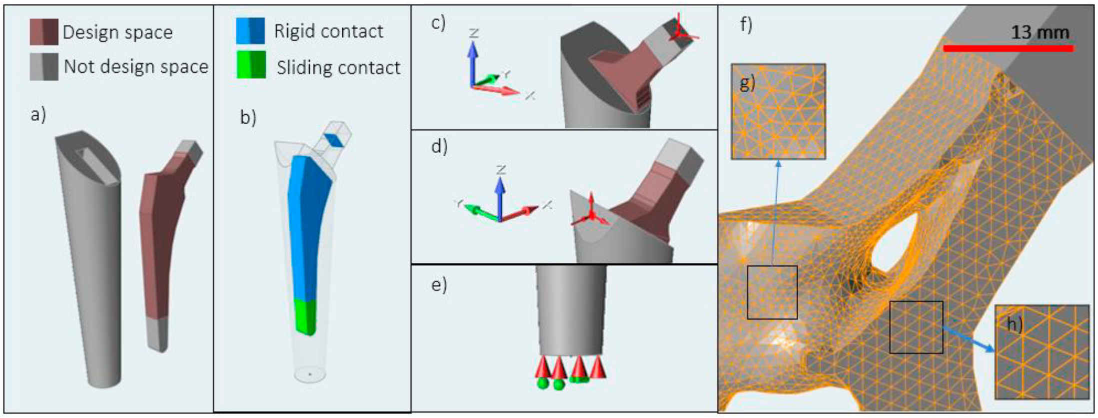

Fig. 2. (a) design space; (b) contacts; (c) body weight forces; (d) abductor forces; (e) supports; (f) mesh example and (g)(h) mesh details.

would be obtained on the optimum solution) is too high. Moreover, the amount of material associated to the Ward triangle is so small, that for this research it doesn't justify the risk of adding it to the bio-inspired 3D model and lose optimization on the final solution obtained.

The geometrical optimization and the simulations performed on the solutions obtained after the optimization process have been done on Inspire (SolidThinking).

The regular 3D model of the stem and the simplified bone model have been exported from Evolve (SolidThinking) to Inspire (SolidThinking) where they have been built together and all the constraints, material properties for the bone and for the hip stem, connections and forces between the femur and the hip stem model have been applied. After this, the geometrical optimization has been performed on the hip stem, driven by the objective of minimizing the mass of the stem.

Once the geometrical optimization has been performed on the regular 3D model, the result has been compared with the shape of the natural human femur. This has been done to check the viability of using a bio-inspired 3D model of the femur based on the assumption that nature already has found a solution close to the optimum one with the femur shape.

2.3. Materials

The bone for the femur model has been simulated as a cortical isotropic bone material and the femoral stem as the titanium alloy Ti6Al4V, suitable for the additive manufacturing of orhtopaedic components [8–12]. The material properties for both the bone and the stem are shown in Table 1.

Table 1. Material properties

Material	**E (GPa)**	**Poisson coefficient**	**Density (kg/m^3)**	**Yield strength (MPa)**
Cortical bone	19	0,35	1,9	150
Ti-6Al-4V	115	0,35	4,45	786

2.4. Design space

The design space, the volume of the stem in which the geometry redesign can be performed, has been all the hip stem, except for two specific areas (Fig. 2.a). These specific areas of the hip stem in which the geometrical redesign has not been performed have been:

- The tip of the stem, which has been considered as a fully dense material.
- The Mors-Tapper junction of the stem, thus the junction between the stem and the head is ensured on the final solution.

2.5. Interface constraints

Interface constraints between the stem and the bone have been applied to the model. The tip of the femur has been simulated as a sliding contact with no friction, whereas the upper part of the femur has been constrained as a fully bonded contact, a rigid contact, as it can be seen on Fig. 2.b. [13].

2.6. Forces and movement constraints

Forces due to body weight and the abductor during the gait cycle have been considered, as it can be seen in Fig. 2.c and Fig 2.d. As it is known, during the gait cycle, the forces due to the body weight and due to the abductor change depending on the moment of the cycle considered [14]. Considering all the possible force results for both the body weight and the abductor on the femur would be highly time-consuming for any simulation and studying only one moment of the gait cycle would be not representative. A good compromise between performance and the solution obtained have been found with three load cases obtained during different positions on the gait cycle. These three load cases chosen have been considered all together to ensure that the final geometry withstands the complete walking action. The values of these forces can be found in Table 2. Gravity forces due to the weight of the prosthesis have been considered neglectable compared with the forces due to the body weight and the abductor. Similarly, other forces due to body parts (muscles, tendons…) have been neglected for the results here presented as they barely affect the final geometry.

Four supports have been applied to the bottom of the femur, as shown in Fig. 2.e.

Table 2. Forces applied for each load case. F.body = Force due to body weight; F.abd = Force due to the abductor.

Load case	**F.body.x (*N*)**	**F.body.y (*N*)**	**F.body.z (*N*)**	**F.abd.x (*N*)**	**F.abd.y (*N*)**	**F.abd.z (*N*)**
1	-2500	-700	-300	900	600	100
2	-2000	-900	-600	800	600	-100
3	-2200	-600	-200	500	300	-200

2.7. Safety factor

A minimum safety factor of 2 has been imposed for the final solutions. This value is related to the fatigue resistance of the stem and it has been used before in the literature [13, 15]

2.8. Minimum thickness

A thickness constraint of 4,0 mm, 4,5 mm, 5 mm, 7,5mm, 10 mm and 15 mm have been applied for both the regular 3D model and the bio-inspired 3D model. This constraint can be understood as a limit for the software to know how precise the geometrical optimization must be. The smaller the minimum thickness (MT) constraint, the more precise it is going to be the geometrical optimization, as the software will be able to remove material up to that MT value.

The MT constraint value should be as high as possible, in order to keep the run time as low as possible but being careful of maintaining a good enough resolution on the solutions. The value of 5mm has been used for the regular 3D model and bio-inspired 3D model for a more in deep comparison, as 5 mm presented the best compromise between time (Fig. 5) and structural significance of the final solution. (Fig. 3)

2.9. Time calculation

The time required to perform all the geometrical optimizations has been obtained from the software timer. Three optimizations have been performed for each model, and then the average time and the standard deviation have been calculated. Errors smaller to 1% on the standard deviation have been neglected.

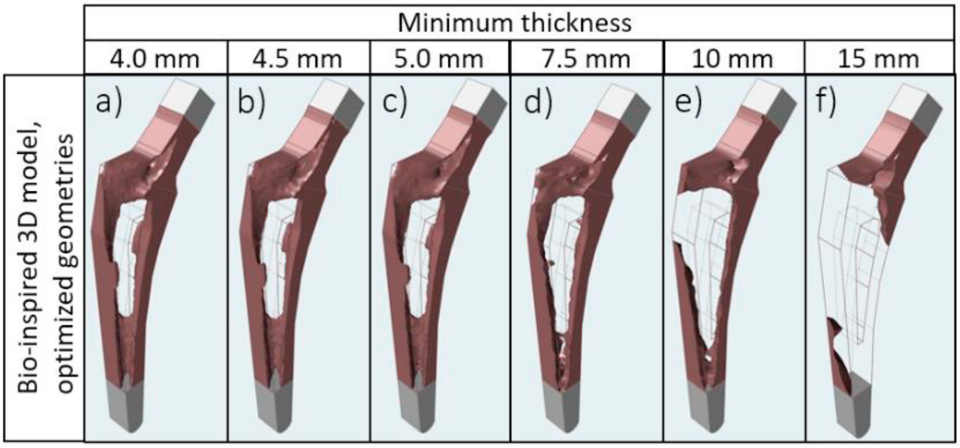

Fig. 3. Optimized geometries for each minimum thickness studied on the bio-inspired 3D model.

2.10. Mesh size and type

A tetrahedral mesh has been automatically created by Inspire software. The same mesh generation algorithm has been used for every model. In Fig 2.f-h. it is shown an example of the mesh obtained in one of the models studied.

2.11. Software and hardware

All the modeling, geometrical optimizations, and analysis have been performed on the same computer (MSI GS73 7RE Stealth Pro Intel Core i7), 16Gb RAM, i7, Geoforce GTX 1050 Ti, with a controlled CPU/GPU temperature and with 20% of its maximum memory applied to the simulations, to ensure that all simulations have been done on the same conditions. Applying 100 % of the memory had the risk of interference with any background application.

The software used for doing the 3D modeling has been Evolve (SolidThinking) and for the simulation Inspire (SolidThinking), being both software installed in a Windows10 OS.

2.12. Comparison between solutions

To compare the final geometry of the solutions obtained, some specific zones of the final geometry in each stem have been chosen for these comparison purposes. The chosen zones have been:

- The hole on the hip stem related with the Ward triangle area of the femur.
- The material removed on the upper-left size of the stem, related to the cancellous bone of the femur.
- The bone marrow cavity.

Also, control variables (Shear Stress, Von Misses Stress and mass) have been used for these comparison purposes between the regular 3D model and the bio-inspired 3D model. After the geometry optimization has been performed to each model, the Von Misses Stress and the Shear Stress have been calculated. Mass has been obtained directly for the software after the geometry optimization.

The time required for each geometry optimization has been obtained from the clock inside the simulation software Inspire (SolidThinking).

3. Results

The time calculations for the regular 3D model and a MT of 5mm had an average value of 241 s, meanwhile for the bio-inspired 3D model and the same MT had an average value of 155 s. Therefore, a time reduction of 35 % has been achieved just by adding the bone marrow cavity to the regular 3D model.

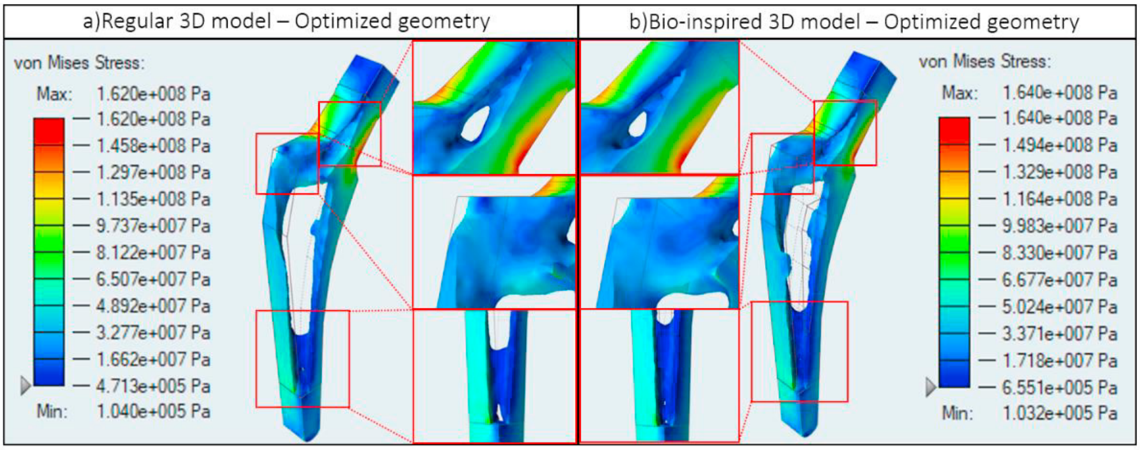

Fig. 4. Geometry comparisons between optimized geometries with minimum thickness of 5mm (a) regular 3D model; (b).bio-inspired 3D model.

3.1. Geometry

The geometry obtained after the simulation of the regular 3D model and of the bio-inspired 3D model (for a 5mm thickness constraint) can be seen in Fig. 4, where only small differences are observed, regarding the Ward triangle, the bone marrow and the upper-left zone of the hip stem.

3.2. Control variables

The maximum Von Mises Stress and the maximum Shear Stress, as well as the final mass of the final geometries (with a MT constraint of 5mm) of the hip stem for both the regular 3D model and the bio-inspired 3D model have shown insignificant variation when compared. The summary of the results for comparison purposes can be observed in Table 3. In Fig 4 can be seen the Max.Shear Stress on the optimized geometries.

Table 3. Control variables for the final geometries of the 3D models obtained with a 5mm minimum thickness constraint

Control variable	Regular 3D model	Bio´-inspired 3D model	Difference (%)
Initial mass (kg)	0,180	0,153	-15,0
Final mass (kg)	0,096	0,102	+6,3
Mass reduction respect regular model (%)	46,7%	43,3%	-3,4%
Max. Von Misses Stress (MPa)	84	84	+0,0
Max. Shear Stress (MPa)	162	164	+1,2
Time required for the geometrical optimization (s)	241	155	-35,6

3.3. Time saved with other minimum thickness constraints

The time saved between the regular 3D model and the bio-inspired 3D model has been investigated with other MT constraints. This is an important parameter related to the time required for any geometrical optimization and thus, its comprehension is mandatory to understand the potential extrapolation of these results to other models. The results obtained, have been summarized in Fig. 5. The standard deviation on the time for all the cases has been below 3%.

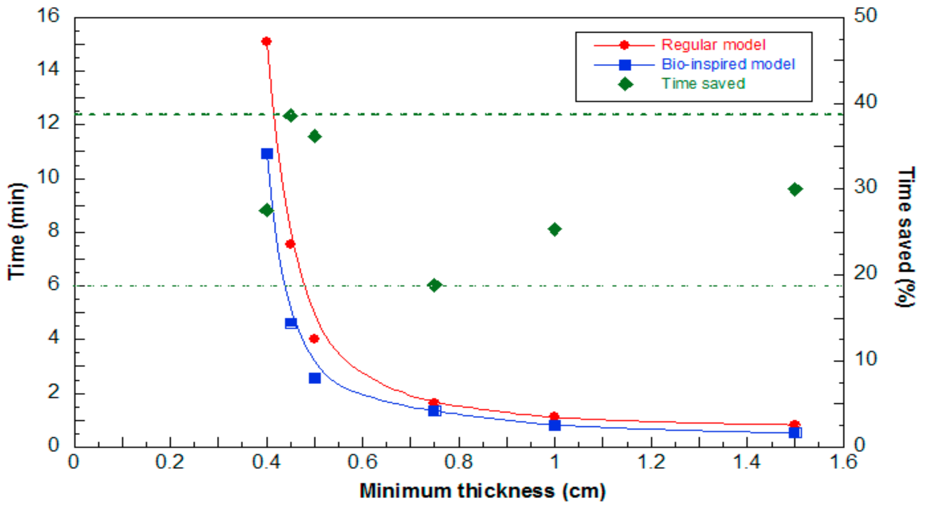

Fig. 5. Time dependency on the minimum thickness constraint applied on the models for doing the geometrical optimization.

4. Discussion

Regarding the geometry of the solutions, the use of a bio-inspired model maintains the solution in good agreement with the regular 3D model solution. The solutions obtained in this research for the geometrical optimization are comparable to others on the literature [16].

Regarding the control variables, none of them exhibit significant changes.

Once the bio-inspired and the regular models have been proven comparable, a time reduction up to a 35 % is achieved when the bio-inspired model is used (under a 5mm MT constraint) without compromising the solutions.

This time reduction has been proved for several MT constraints, where time reductions between 20% to 40%. This confirms the potential of bio-inspired models not only for the stem geometry optimization but for other models which will need other MT constraints. On Fig. 5, the time required for doing the geometrical optimization is highly dependent on the MT constraint and thus it should be carefully chosen for the component that is going to be optimized. For the hip stem studied, it has been found that the best value for the MT was at 5mm, where the time required is reasonable, while obtaining solutions like those with a MT value of 4,5mm and 4,0mm, much more time-consuming.

It is also interesting to note that only with a 15 % of volume reduction on the bio-inspired 3D model, a 35 % of time reduction is reached, what suggests the potential of these bio-inspired 3D models for being used also in those cases in which only small amounts of material can be manually removed from the regular 3D model.

However, an extra 6% of mass has been obtained when the bio-inspired 3D model has been used, compared with the final from the regular 3D model. This shows that the material removed should be carefully selected and saves using a bio-inspired 3D model, can have some drawbacks regarding the optimization degree reached on the final solution (directly measured from the mass of our model, as decreasing the mass has been our objective).

5. Conclusions

We have proved that the optimal solution for the optimal redesign of a hip prosthesis stem driven by the objective of minimizing the mass is like the natural bone femur shape.

These solutions are also like some already described in the literature [16],even though the objective for reaching the final solutions haven’t been the same.

We have found that the amount of time saved by using a bio-inspired 3D model vary in a range of 20% up to a 40% percentage, depending on the MT used and with a good enough reproducibility under the conditions here described, what leads to the use of bio-inspired 3D models with other components that will need to use other MT.

For these reasons, we suggest that bio-inspired 3D models should be used for reducing the calculation times when a geometrical optimization is going to be performed, but being careful of not removing critical material, material that will lead to a non-optimum solution.

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