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COMPARATIVE STUDY REGARDING THE DESIGN OF A 3D PRINTED HIP PROSTHESIS

Silvia-Iuliana NECULA, Vasile BAȘLIU, Vasile BRIA, Marius BODOR*
"Dunarea de Jos" University of Galati, Romania
*e-mail: marius.bodor@ugal.ro

ABSTRACT

This work proposes the comparison of two models of 3D printed hip prostheses, using microscopic and chemical analysis, but also compression and bending testing. The comparison was made using a hip prosthesis designed in the Autodesk Inventor 2020 program and a model freely available on the Internet. The work includes some details about the virtual prototyping of prostheses and results from the chemical analysis of the components of the hip prostheses, carried out using an X-ray spectrometer to identify the elements contained in the PETG (polyethylene terephthalate glycol) material that was used to obtain the samples. The second method of analysis was the microscopic one and finally the samples were subjected to external forces, through bending and compression testing. This comparison aimed to demonstrate the dependence between the shape of the prosthesis and the mechanical properties of the analysed samples.

KEYWORDS: virtual design, PETG, 3D printing, XRF, optical microscopy, mechanical testing

1. Introduction

Using the technology created in recent years, researchers working in the field of biotechnology, together with doctors in the field of orthopaedics, form research groups to improve artificial implants to better meet the needs of the patients. Recently, people tend to have more orthopaedic procedures such as total hip replacement at a young age. For this reason, researchers are constantly looking for ways to optimize endoprostheses either geometrically or from the point of view of the materials used in manufacturing, in order to reduce the number of postoperative revisions required by the patient and thus increase the life span [1].

Due to the technological advances made in recent years and especially due to the growth of the additive manufacturing industry, researchers are using virtual prototyping to take the patient's femoral mould directly from the film (tomography), trying to customize the design of the hip prosthesis. In this sense, the trend is towards using software that allows the user to select the size of anatomical landmarks and then generate the shape of the implant from algorithms. Finally, the resulting design can be manufactured using additive manufacturing (AM). Additionally, recent studies of materials used in endoprosthesis manufacture attempt to regenerate bone tissue to reproduce a material that exhibits the same mechanical properties and properties as human bone tissue [2].

A femoral hip prosthesis is made of special alloys, such as titanium, to ensure the best biocompatibility. They are usually coated with hydroxyapatite to facilitate the growth of bone tissue on the prosthetic surface, resulting in better integration and complete fixation of the crown. Alternatively, the prosthesis can be cemented (typically used in patients with poor bone quality, such as elderly patients with bone demineralization) or cementless (typically used in young or active patients) [3].

The total hip prosthesis consists of three elements connected together, usually by pressing, designed to form a spherical contact that allows flexion, extension, shape, external rotation and internal rotation movements of the hip. The hip prosthesis and the surgical approach are based on the particularities of the hip morphology and the patient's medical history. Therefore, surgeons look for the best standard prosthesis for each patient and the most suitable medical treatment [4].

A 3D printing process always starts with the creation of a 3D digital model, which is the basis of the printed product [5]. Compared to traditional manufacturing options, 3D printing can turn a design into reality in just a few hours. There are also projects that require more time, but when it comes to small or medium volumes, 3D printing is definitely a much faster solution [6]. Additive manufacturing makes it easier to create new and innovative designs than traditional manufacturing processes. The very narrow angle limitations that require special tools in 3D printing are eliminated due to layers that can be easily overlapped regardless of shape [7]. 3D printing also has limitations, although significantly fewer than other processes. One of them is that 3D printed parts become weaker due to layering. Another limitation occurs with large volumes of 3D printed products, as production costs are significantly increased compared to other methods used. If the design on the printer is not well aligned, the 3D printed product may be inaccurate. CNC machines are sometimes used for precision finishing to increase the accuracy of the final product [8].

A variety of materials can be used in the 3D printing process. These include materials such as plastics, metals, ceramics and even concrete, but also less expected materials such as paper, edible materials and others [9]. They come in 3D filament, liquid resin or powder form and can be used in almost any type of 3D printer. Of course, the most commonly used are polymers and it is preferable to use specific materials for each technology [10]. The choice of material for 3D printing is very important and the success of the whole project depends on it [11].

For polymers, 3D printing offers many possibilities and can be used both for prototyping and for the creation of various landmarks and tools [12]. Materials from the polymer family include: Polyamide (PA 11) [12], Glass-filled Polyamide – used in techniques such as MJF (multi-jet fusion) in the manufacture of housings and closures [13], Polypropylene – used in techniques such as SLS (Selective Laser Sintering) and FFF/FDM (Fused Filament Manufacturing/Fused Deposition Modeling) in the production of food packaging and mechanical products that require low friction [14], Polycarbonate – Used to make supports or brackets in FFF/FDM [15], ABS – Used in FFF/FDM to create prototypes and devices [15].

Although the material used in this study is not a biocompatible one, the purpose of the work herein was satisfactorily met. This was done using two different types of designs for a hip prosthesis and the results of testing revealed the importance of this aspect when a decision comes into discussion. Results were obtained by using a virtual design environment to get the desired shape of the sample and then printing this shape and a second one, based on another design. The samples were 3D printed using the same type of polymeric filament and the testing was done by using X-ray spectroscopy, optical microscopy and mechanical testing.

2. Materials and methods

To obtain the hip prostheses, a sketch is needed along with its dimensions. After analysing the sketch, the designing can start in the chosen program. In this case Autodesk Inventor 2020 was chosen. This program allows the creation, simulation and visualization of 3D products designed with professional engineering tools. It helps create a highly accurate virtual model to validate design form and function in real life, minimizing the need for testing using physical prototypes [16].

An Artillery Sidewinder X1 3D printer (Fig. 1) was used to fabricate the physical hip prostheses. Two prototypes were created using the additive manufacturing (AM) process, based on two models of the femoral prosthesis, the first model being made in the Inventor program and denoted P1, and the second model whose file was obtained online, denoted P2 (Fig. 2). AM-based 3D printing technology is one of the most widely used in the rapid prototyping process due to its affordable cost, equipment and high potential for printing a wide range of materials.

The material used in this process was polyethylene terephthalate glycol, known as PETG, a thermoplastic polyester with excellent chemical resistance, durability and moldability when manufactured, but not compatible with the human body [17].

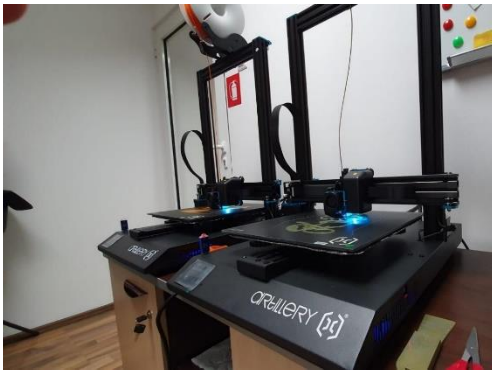

Fig. 1. *Presentation of the layout of the printer used to obtain the hip prostheses*

After the stages in Autodesc Inventor for the design of the prosthesis, in the 2D and then in 3D, the next step towards printing the prosthesis was to enter the designed prosthesis in the Curra program. This program offers the possibility to choose the position

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of printing the prosthesis, the height of the layer of the print, the thickness of the outer wall of the print and more. For the printing process, the printing temperature was chosen as 235 °C and the printing table temperature as 85 °C, for the layer height was chosen as 0.2 mm, for the initial layer height was chosen as 0.32 mm and for the line width as 0.45 mm, the wall thickness and the number of wall lines, the wall thickness being 1.35 mm and the number of lines being 3, the filling density was chosen to be 40%, the filling line distance 1.125 mm and Gyroid was chosen as the filling pattern.

Fig. 2. *The two models of hip prostheses: P1 – left; P2 – right*

For chemical analysis an X-ray spectrometer, model INNOV-X SYSTEMS, α A-4000 was used. The samples were placed, one at a time, in front of the instrument's Kapton window and the data acquisition (lasting for 30 seconds) was triggered from the instrument iPaq PDA, as presented in Figure 3.

Fig. 3. *A hip prosthesis atop the X-ray spectrometer, model INNOV-X, α A-4000, during an X-ray analyses*

The apparatus uses a standardless software based on fundamental parameter (FP) method. Fundamental parameter (FP) method is based on peak fitting for direct correlation of measured spectra and calculated element concentrations [18]. The apparatus returns the data to the user in the form of a graph represented as a function of energy between 0 – 40 [keV].

A KERN OLM 171 metallurgical microscope was used for the microscopic analysis, which belongs to the series of inverted microscopes and has an ergonomic, robust and extremely stable design. The samples were not specially prepared for this type of analyses and the construction of the instrument made the manipulation of the sample very easy.

The Instron 8850 series system is a floor-model biaxial servo-hydraulic dynamic testing system that provides axial and torsional load on the specimen in an integrated biaxial actuator. With a precision-aligned two-column frame and high rigidity, the 8850

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series meets the challenging requirements of a wide range of static and dynamic biaxial testing requirements [19]. This type of instrument was used for mechanical testing, bending and compression being the chosen possibilities.

For bending tests, the top support moved at 5 mm/min and the distance between the supports was 90 mm. To submit to external forces, the apparatus was turned on and the preparation of the test machine was awaited. After machine preparation, the P1 femoral stem was placed and bending was started. The same was done for the P2 femoral stem. Figure 4 presents the abovementioned architecture of the bending test.

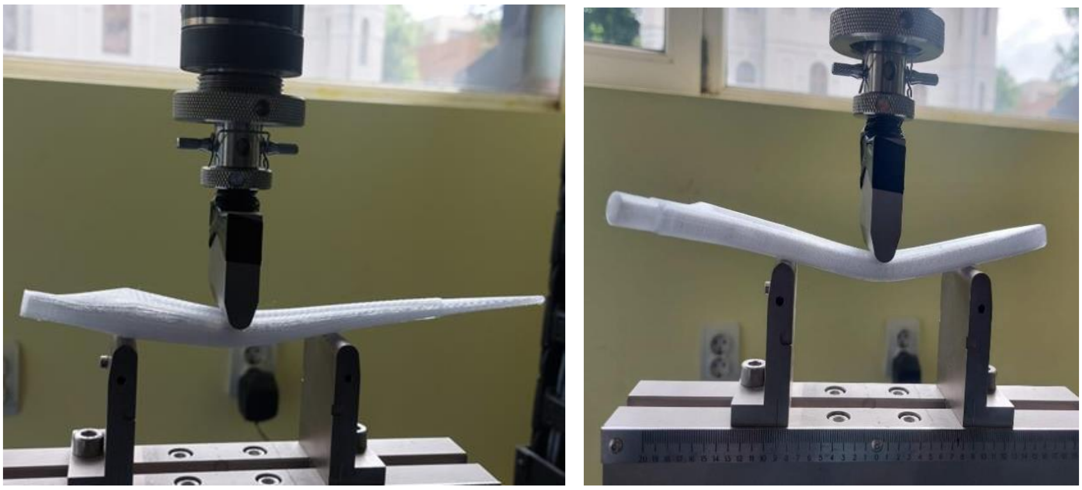

Fig. 4. *Bending test of P1 sample femoral stem – left and P2 sample femoral stem – right*

Fig. 5. *Compression test of P1 sample acetabular cup – left and P2 sample acetabular cup – right*

For compression testing, two plates were used, one for support and the second for applying force. In this case the upper arm descended by 1.3 mm/min. For testing, the P1 acetabular cup was placed on the support plate and compression testing was started, after the testing of the first cup was completed, the testing of the P2 cup was started and then continued for all the other components: the liners of P1 and P2 samples and femoral heads of P1 and P2 samples.

3. Results and discussions

3.1. X-ray fluorescence analysis

Figure 6 presents the result of the XRF analysis of the P1 and P2 femoral stems. Visibly, there are no major differences between the results of the two samples. With the help of the XRF spectrum provided by the device, it was possible to confirm the presence of chemical elements specific to the PETG material, namely: carbon, hydrogen, sulphur and oxygen. The specific energies of these elements are as follows for carbon kα = 0.28 [keV], oxygen kα = 0.53 [keV] and sulphur kα =2.3[keV] [20]. As such from the XRF spectrum it is observed that the values are reduced and are found in the specific range of the background noise of the device.

This type of analyses emphasises the identical chemical composition of both samples used for comparison. This result was expected since the same material and parameters were used for both samples and the data only stands for confirmation of this expectation.

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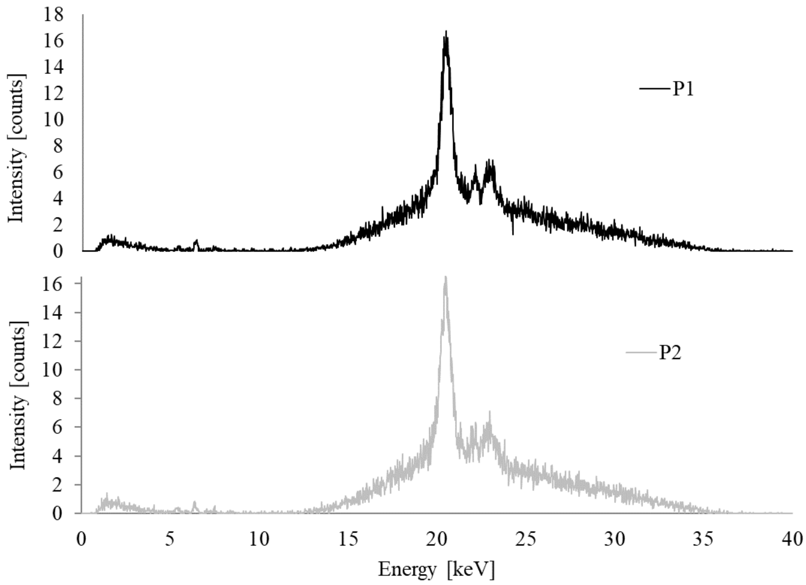

Fig. 6. *Spectra obtained through X-ray fluorescence analyses of P1 and P2 sample femoral stems*

3.2. Optical microscopy analysis

The obtained results were possible by using a 5x magnification, other magnifications being unfit to obtain proper images to compare the samples. The purpose of this type of analysis is also to confirm the similarities between the two types of samples. All samples' components were analysed and compared as seen in Figures 7-10.

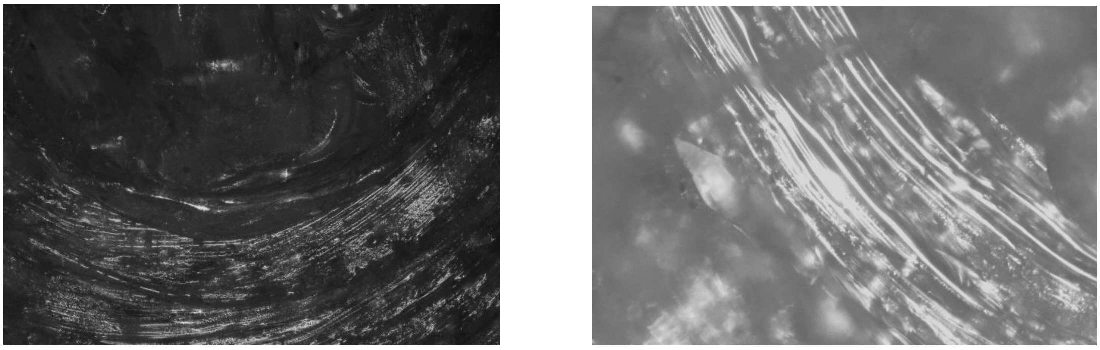

Fig. 7. *Microscopic view at 5x magnification of P1 sample acetabular cup – left and P2 sample acetabular cup – right*

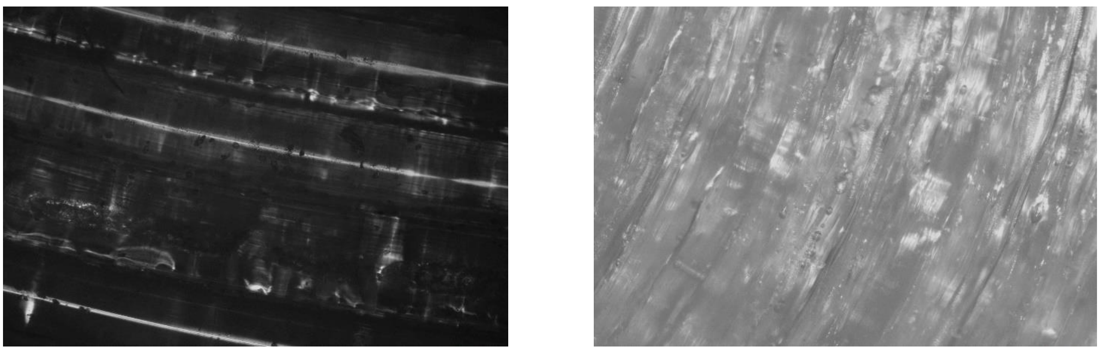

Fig. 8. *Microscopic view at 5x magnification of P1 sample liner – left and P2 sample liner – right*

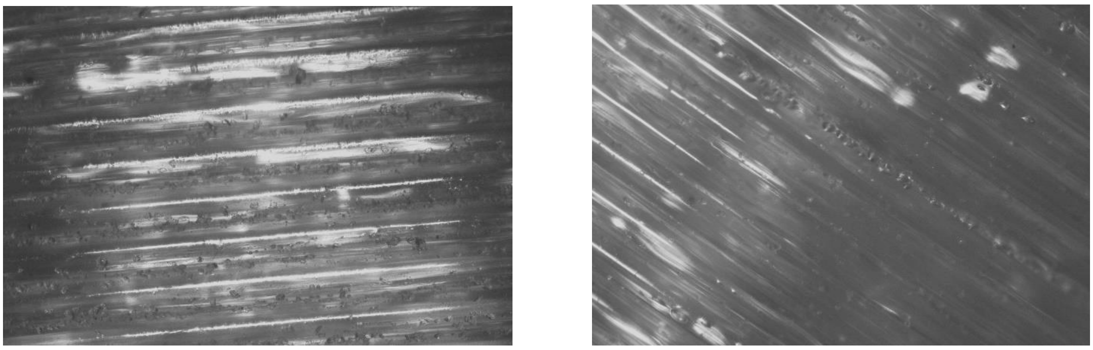

Fig. 9. *Microscopic view at 5x magnification of P1 sample femoral head – left and P2 sample femoral head – right*

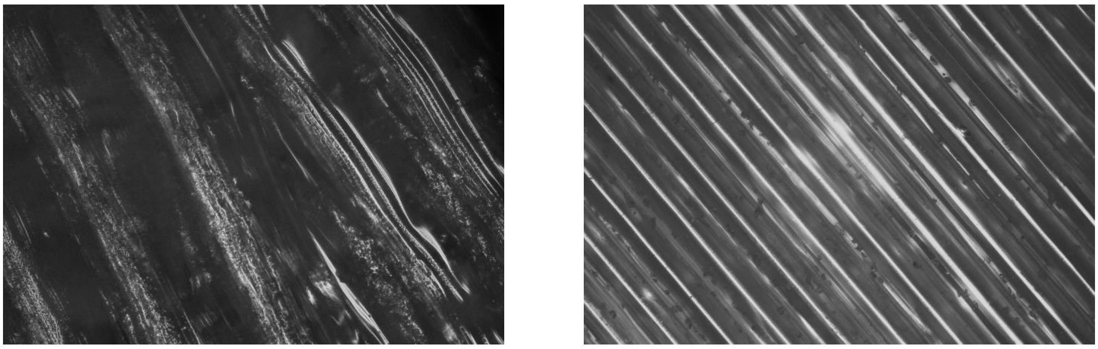

Fig. 10. *Microscopic view at 5x magnification of P1 sample femoral stem – left and P2 sample femoral stem – right*

Although the appearance of images for the same component of each sample was expected to be similar, some aspects may slightly differ due to the different angle during microscopic analysis. This is most noticeable in Figures 7 and 8, while the next two ones, Figures 9 and 10, present morphologies that look alike. Nevertheless, the morphological aspect of both samples also emphasises the common build-up that stands behind the two separate shapes used for comparison in this work.

3.3. Bending and compression testing

Using the mechanical testing device some results were obtained that finally differentiated one hip prosthesis design from the other. For this tests, first the femoral stem of P1 and P2 samples were tested from the bending point of view and then, all the other components were tested from the compression point of view and the data is presented in Figures 11-14.

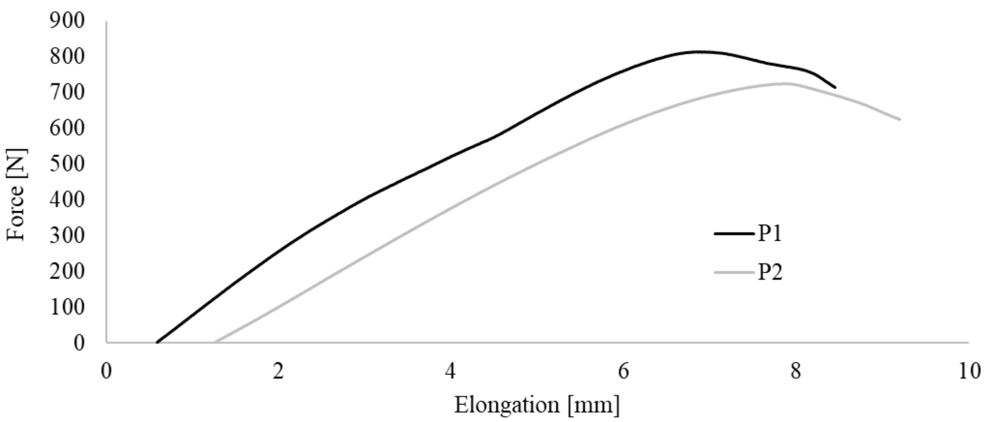

Fig. 11. *Results of the bending test for P1 and P2 samples femoral stems*

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Figure 11 presents the results of the bending test. This type of testing was chosen since this type of stress is the most probable to be encountered for femoral stems and the data presented here emphasises a small difference in favour of the P1 sample femoral stem. The trends in elongation seem similar until around 700 N of applied force, although the elongation is constantly higher for P2 compared to P1. The automatic stop-point of the test is also very close for both samples from the force and elongation point of view, with the higher force value sustained by P1, proving that this shape is more agreeable than the one of P2, when it comes to bending forces.

The next test, the compression of acetabular cups proved again in favour of P1 sample. Again, not too great, but observable differences are presented in Figure 12, this time the starting point being the same, as expected for this type of test. The higher stress sustained by P1 is observed throughout the testing time with lower strain, when compared to P2. Also, in this test, P2 sample acetabular cup sustained an abrupt rupture when reaching the highest stress.

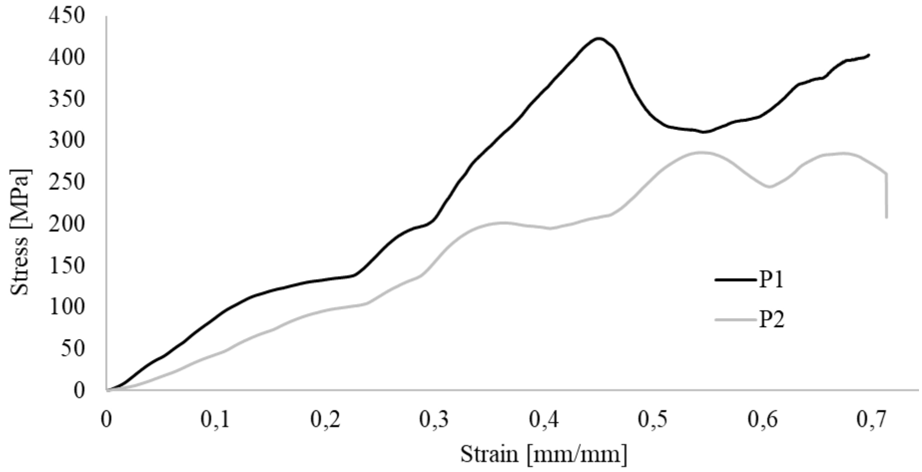

Fig. 12. *Results of the compression test for P1 and P2 samples acetabular cups*

When it comes for the comparison of data for the compression test of the liners, Figure 13 reveals an almost exact behaviour of the two tested objects, until approximately the value of 600 MPa of stress. Starting from this point, a slight difference is observed in the behaviour during testing, this time in favour of the P2 sample liner, although only from the strain point of view, since the automatic stop-point value of the force is approximately the same, namely around 1400 MPa.

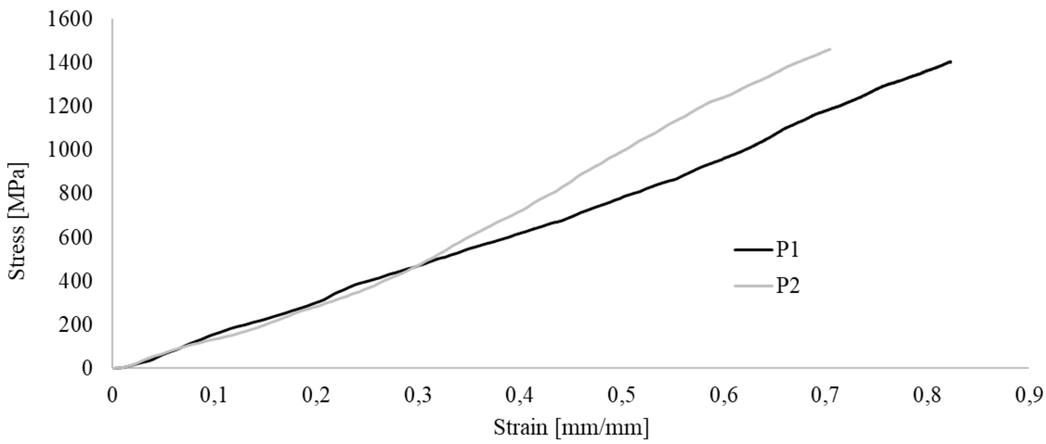

Fig. 13. *Results of the compression test for P1 and P2 samples liners*

Since the construction is almost the same, in case of the femoral heads the compression test offers almost the same data, the curves based on these data being almost overlapped, as can be observed in Figure 14.

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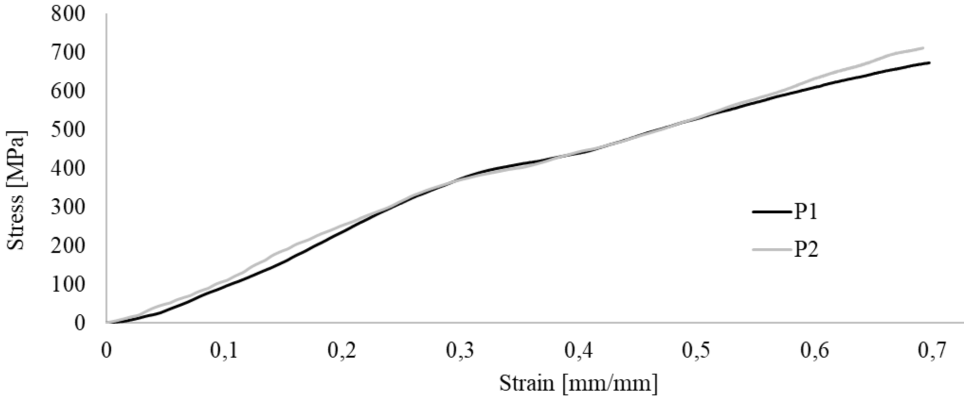

Fig. 14. *Results of the compression test for P1 and P2 samples femoral heads*

The results from the mechanical testing of all the components of the two femoral prosthesis, that were obtained in this work through 3D printing, demonstrates the advantage of the P1 sample design towards sustaining greater overall values of applied force and smaller deformation in contrast to the P2 sample design.

4. Conclusions

Virtual prototyping is now becoming increasingly important in the fields of biotechnology and medicine, as it provides the opportunity to analyse patient conditions, simulate various activities of daily life, and plan surgical interventions. The human body is an organic machine and although it has common characteristics when analysed in depth, there are many characteristics that make it unique both as an individual and as an organism and set it apart when discussing orthopaedic surgical approaches.

The obtained results demonstrate that both 3D printed prototypes were similar in chemical composition and structurally. Instead, mechanical testing demonstrated a clear, although small, advantage of the P1 hip prosthesis overall design in comparison to the P2 hip prosthesis design.

Future research directions could aim towards obtaining and testing different other designs of the hip prosthesis, using biocompatible materials.

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