CHARACTERIZATION OF BIOMODELS MANUFACTURED VIA CNC MILLING

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Abstract. *Medicine has greatly evolved in the last century, a great part result from the cooperation with engineering. One of those results is the biomodels: physical models made to represent parts of the human anatomy. They became possible thanks to the medical imaging technologies, such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI), which creates volumetric data that can be converted to be manipulated in CAD (Computer-Aided Design) softwares. Later, the CAD file will be used in CAM (Computer-Aided Manufacturing) software, where a toolpath strategy can be created for the intended automated manufacturing process. Biomodels are a useful resource because they provide a visual and a tactile perception that are not possible using CT and MRI images. Main applications for biomodels are surgical planning and simulation, to help the doctor communication with the patient and the design and manufacturing of custom prosthesis and implants, especially for craniofacial and maxillofacial surgery. Studies indicates that their usage reduce the time of recovery and complications, producing better aesthetic results. The most used manufacturing process for biomodels is the Rapid Prototyping (RP), an automated and easy to program method based on layer-by-layer addition of material. These characteristics allow the reproduction of complex shapes and internal structures, with single piece manufacturing capability, favorable to the production of biomodels. Nevertheless, this technology has limitations in materials available and it is still expensive and not available in large scale, mostly on developing countries. Considering the facts described above, it would be interesting to investigate alternative manufacturing processes to produce biomodels. An interesting choice, among the processes widely available in industry, is CNC (Computer Numerical Controlled) Machining, as it is also an automated manufacturing process capable of producing single pieces, but is better understood than RP and can use a wider range of materials. This paper has the objective to characterize biomodels manufactured via CNC milling, through the study of two facial injuries with different geometry complexity. Six biomodels were manufactured in a three axes milling machine using three different materials: Nylon, MDF and Polyurethane foam. Their precision was evaluated using Three-dimensional laser scanning. Time, cost, ease of fabrication and application characteristics were evaluated. For the cases studied, with simple geometries, the CNC manufactured biomodels presented good precision, comparable with the best ones produced by conventional RP. CNC Milling has shown itself a fast and affordable method to produce biomodels. The obtained models were considered satisfactory for different applications, but more complex geometry cases must be yet analyzed.*

Keywords: *keyword Biomodels, CNC Machining, Milling, 3D Scanning, Rapid Prototyping.*

1. INTRODUCTION

Computed Tomography (CT) and Magnetic Resonance (MRI) are two of the most useful technologies currently employed in medicine, since they provide volumetric data in the form of virtual images, allowing precise diagnosis and aiding surgical planning. Nevertheless, for more complex cases, such as facial bone defects, D’Urso *et al.* (1998) state that there is a significant difference between the three-dimensional image on the screen and the moment of surgery itself. For this reason, another tool, easier to visualize and manipulate, is necessary.

With the improvement of Computer-aided Design (CAD) and Computer-aided Manufacturing (CAM) systems, it is possible to manufacture physical models of the human anatomy, known as biomodels. According to Volpato *et al.* (2007), the process of creating a biomodel starts with CT or MRI images, presenting the internal structures of the patient in the form of a series of slices. Those images are manipulated in a system for medical images treatment, where the relevant structure is separated and a 3D model is generated in the computer. This model can be manipulated in CAD software, and later CAM software can be used to generate a toolpath strategy for a manufacturing process.

Typically, biomodels are utilized in surgical planning and simulation, helping the communication between doctors and patients, and the design of custom implants and prosthesis (Choi and Samavedan, 2002). The use of custom implants and prosthesis is becoming of great interest lately, as its defenders claims that they reduce surgery time, produces better aesthetics results and reduces the risk of infection and rejections (Bertol, 2008)

Due to the complexity and singularity of the human anatomy, an automated process is needed to manufacture biomodels, where presently the most utilized method is Rapid Prototyping (RP). RP can be defined as a manufacturing process through the adding of material in the form of consecutive plane layers, allowing the production of physical components in three dimensions, with information obtained directly from the geometric model generated in the CAD system, in a fast, automated and totally flexible way (Volpato *et al.*, 2007). These characteristics make the RP a technology capable of reproducing complex geometries with considerable precision and with simple programming.

The increasing number of accidents involving means of transportation and the practice of radical sports is reflecting in an increasing demand for medical products, among those are the biomodels. Therefore it is possible that Rapid Prototyping centers have difficulties to meet the demand for biomodels. This is most likely to happen in developing countries, where this technology remains too expensive and less available. Such fact is a motivation to investigate alternative methods for biomodels manufacturing.

Machining is a considerably known mechanical fabrication method, consisting of a number of different processes (ex. turning, milling, boring, etc.), based in the removal of material to generate the intended piece. With the development made in industry after the half of the XX century, more precise components were necessary, too complex to be produced by conventional machining. To suppress this need, CNC (Computer Numerical Control) was created.

The limitations in CNC mechanical machining come from the geometry of the tool and the number of axes. The tool has a limited reach on the piece and represents a complication in the moment of programming. Additionally, most of the times more than one tool is needed and also the piece of raw material has to be re-oriented on the milling machine to manufacture the other side of the piece, resulting in a larger number of interventions in the process. Some CNC machines have automatic tool changers (ATC) and additional axes, which increases the flexibility of the process, but increase equipment cost and programming complexity.

Among the machining processes one of the most versatile is milling by the fact that the tool used (the mill) can present itself under the most diverse shapes (LdSM, 2009). A mill is composed by multiple cutting edges, each one removing a small part of material in each revolution of the tool. Generally, CNC milling machines have three axes of movement, conferring good geometry reproduction capability. Also, the technologies applied in motion control provide reliable precision. Furthermore, the quantity of different types of material available for milling is considerably greater compared to RP, thus a material can be selected based on cost, desirable properties and appearance. Lastly, the recent advances in High Speed Machine (HSM) are permitting greater cut and feed speeds, what results in a reduction in time and cost of manufacturing.

Despite CNC milling has some disadvantages in comparison with rapid prototyping, this process is one of the most potential alternatives for the production of biomodels, as both are automated processes capable of producing prototypes and milling having some advantages of its own. Moreover, it must be considered that CNC milling machines are more available and this technology is better understood then RP. For this reason, it would be interesting to study the characteristics of biomodels produced by CNC milling, determining if such alternative can be considered reliable. The evaluation will be performed through a series of test representing service applications and a precision verification, employing three-dimensional laser scanning.

Three-dimensional (3D) laser scanning is a non contact digitizing system, largely employed in reverse engineering. Although there are 3D laser scanning technologies based on different principles and with different capabilities, the one used in this work is based on the conoscopic holography principle and measures only geometric data, in three axes (X,Y,Z).

In this system, a laser probe measures the distance between an object and the probe (the Z coordinate) by emitting a laser point on the surface of the object and detecting the reflected light. The probe acquires data (points) at a given rate, and when fixed to CNC machine, the position data of the machine (X and Y coordinates) can be crossed with the distance data of the probe. As part of the system, a set of changeable lens are used, each one having an individual precision and range of data acquisition. Additional factors that can produce errors or even prevent the laser scanning process are the object color, opacity and the presence of adverse geometrical features, such as sharp edges.

Geometrically, the data are processed as coordinates in the three-dimensional space (X, Y, Z). A surface scan may return thousand of points, accordingly to the size of the analyzed area and the distance between points used. This group of thousands of points is called “point cloud” and after computational manipulation it allows to generate curves, meshes, surfaces and 3D solids compatibles with CAD/CAM systems (Silva, 2006), and can also be used in dimensional analysis.

2. MATERIALS AND METHODS

For this study, a skull with facial bone defect was reproduced. The virtual model of the patient’s skull was obtained from a computed tomography. Each bi-dimensional slice of the CT was joined and processed with the software InVesalius. A 3D virtual model of the patient’s skull was generated. The obtained file format is compatible with CAD and CAM software. The process is illustrated in Fig. 1.

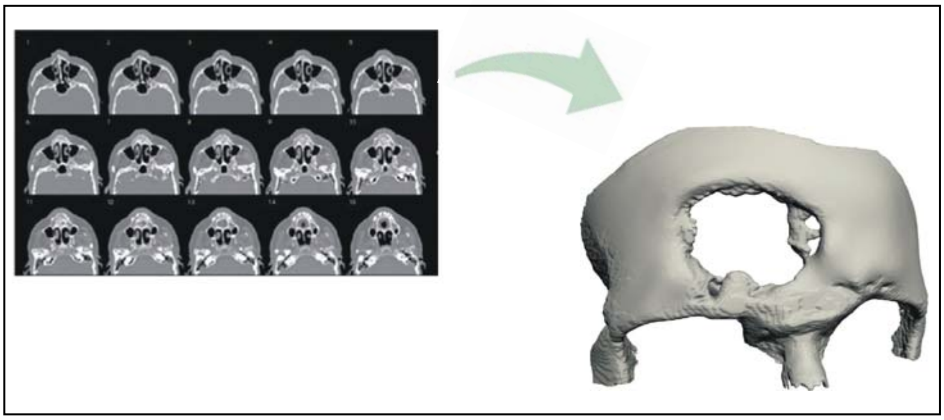

Figure 1: 3D virtual model generated from computed tomography 2D slices.

2.1. Biomodels manufacturing

To manufacture the biomodels, a three axes CNC milling machine Digimill 3D was used. This equipment belongs to the Laboratory of Design and Materials Selection (LdSM) of the Federal University of Rio Grande do Sul (UFRGS). In order to better evaluate CNC machined biomodels, three different materials were milled: MDF (Medium Density Fiberboard), polyurethane (PU) foam (with 120g/cm³ density) and Nylon. Both MDF and PU were chosen because they are commonly utilized in machined prototypes. In addition, MDF has a low cost and is widely available, while PU has better machinability, permitting high cut and feed speeds. Nylon on the other hand, was chosen since it is a polymer with a large number of applications, as it has good appearance and mechanical strength.

Each block of material was submitted to a face milling operation, in order to adjust its dimensions, then to one roughing and one finishing operation on the superior and inferior face of the block, making a total of one adjustment and four shaping operations per block of material. For the roughing operations, an end mill with 6mm diameter was used. For the finishing operations, a ball nose mill with 4mm diameter was used.

All toolpath strategies were generated in the software Edge CAM, with the following milling parameters: stepover 40%, cut increment 1mm (MDF and Nylon roughing), cut increment 2mm (Polyurethane roughing), cusp height 0.05mm (constant cusp finishing), feedrate 2000mm/min, plunge speed 800mm/min, spindle 12000rpm.

After the production, each biomodel was detached from the block of material, and the supporting structures were manually removed in a post-finishing step.

2.2. Dimensional analysis

With all three biomodels finished, their precision was evaluated, each one having the frontal area digitized by 3D laser scanning. The equipment used was a ConoProbe 1000 attached to the Digimill 3D CNC machine and equipped with a 150mm lens, which has a precision of 0.035mm. In order to obtain an adequate resolution, the distance between points was set to 0.1mm.

The point clouds were treated in the software Geomagic Studio, where objects not related to the analysis and misplaced points created by errors were removed. Later, each treated point cloud dimensional error was analyzed in the software Geomagic Qualify, having the CAD file obtained from the CT as the reference.

2.3. Application analysis

For the service applications analysis, two different situations were simulated, trying to replicate the surgeon procedure when manipulating the biomodel: the easiness to cut the models and the possibility to make marks.

The first situation analyzed was the easiness of cutting the material. Considering that, during surgical planning, the surgeon usually removes from the biomodel the affected areas that will be removed in the surgery. In order to analyze the easiness to cut the studied materials (MDF, PU and Nylon), three specimens for each material were cut with manual and electrical saws, with transversal area of 55x20mm, and the demanded time was measured.

Making sketches and annotations in the biomodel are also typical procedures in surgical planning. In this work, the possibility to mark the different materials with pencil and pen was qualitatively analyzed.

3. RESULTS AND DISCUSSION

3.1. Biomodels manufacturing

The three biomodels manufactured for this study are presented in Fig. 2, below.

Figure 2: Biomodels manufactured via CNC milling.
Left: Nylon, Right: MDF, Bottom: PU

With the intention of analyzing the easiness of fabrication from CNC machining for the production of biomodels, some data related to the process itself were recorded. Table 1 contains information about production characteristics.

Table 1 – Production characteristics.

	Milling Time	Total Time	Raw Material Cost
MDF	2h 15min	4h 15min	R$ 3.00
PU	1h 15min	2h 55min	R$ 5.00
Nylon	2h 15min	4h 15min	R$ 97.00

Since the PU is the material with the best machinability among the three tested, it allowed a greater feed rate, therefore presented the smallest milling time, while MDF and Nylon utilized the same milling parameters, resulting in nearly one additional hour of processing. As the other times are essentially the same for all material (programming, tool changing, etc.), PU remained also with the smallest total time.

Considering the cost of raw material, MDF was the most affordable; this can be explained by the fact that it is largely used in industry, what causes a reduction in price. The PU foam is also largely applied, but the components used to produce it are a little more expensive, resulting in a price increase in relation to the MDF. Nylon, in contrast, is a material with greater responsibility, therefore, is significantly more expensive.

All materials demanded the same quantity of operator interventions, as it is determined by the process itself. The first intervention is the setup, where the block and the roughing tool are fixed and the program is set to start; the second intervention is the tool change, where the finishing tool is fixed. The system must then be reset with the roughing tool placed one more time, but this time with the opposite face of the block facing up and later, the fourth intervention is a repetition of the second. The final intervention consists in removing the block of material from the machine, manually detaching the milled piece from the block and removing the supporting structures. All these interventions must be done carefully, as they can produce errors in the piece dimension and damage to the tool or machine, but as a consequence of this extra care more time and more skilful handling are demanded to this process.

3.1. Dimensional analysis

The following graphics (Figs. 3 to 5) were obtained in the software Geomagic Qualify. They present in colors the negative (blue tons) and positive (yellow and red tons) dimensional deviations between the analyzed biomodel and the virtual model generated in the tomography, with a resolution of 0.05mm. The nominal error considered was ±0.05mm (green areas). Some statistical information is also presented in the graphics, such as: maximum positive and negative deviation points, average positive and negative deviation and standard deviation.

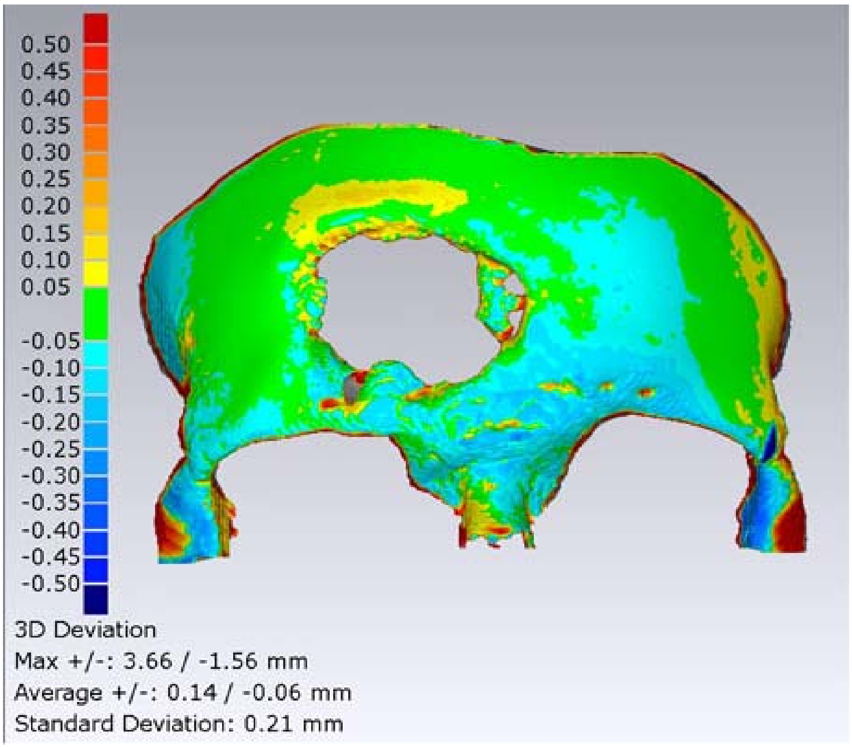

Figure 3: Color graphic presenting the precision of the MDF biomodel.

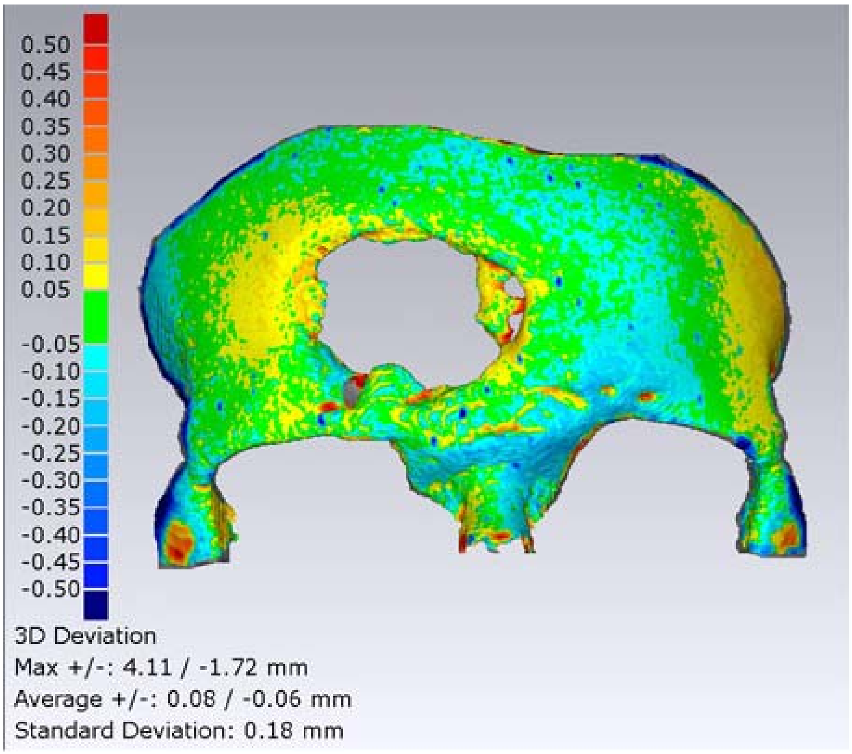

Figure 4: Color graphic presenting the precision of the PU biomodel.

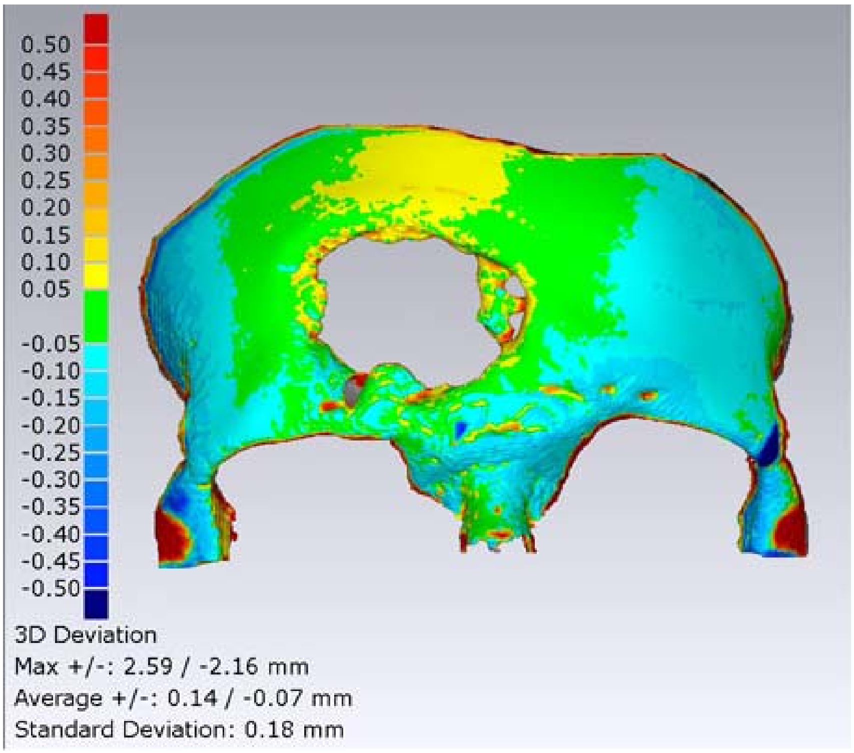

Figure 5: Color graphic presenting the precision of the Nylon biomodel.

From the graphics obtained, one noticeable characteristic is that all biomodels produced present points of maximum deviation with great values, always greater than 1.5mm. Some of the points of great deviation are located in the area of the defect, as these regions are located in areas of difficult access or contain details exceedingly complex to reproduce. This suggests that a greater care should be taken when using biomodels manufactured via CNC milling to the design of custom implants, as points of large imprecision can be present in the area of interest.

Other common characteristic is that all biomodels are more imprecise in the positive direction; this is perceptible when analyzing the average deviations, as the positive is always greater than the negative. It can be explained by the fact that the CAM algorithm prefers leaving uncut material that should be removed rather than cutting material that should not be removed. This algorithm is used by default to leave some material to a next tool cut, until the specified precision is reached.

The biomodel manufactured in MDF presented the greater standard deviation, 0.21mm, and as this data presents one of the most important information about precision, this model was considered the least precise among the ones studied. Nevertheless, this model also presented the smallest negative deviation, an advantage for this model. The graphic displays other good characteristic of this model: the area around the defect is almost completely in green, what means a good precision near the most important part of the model.

The biomodel manufactured in PU was considered the most precise among the ones produced, as both it and the Nylon models have the smallest standard deviation, 0.18mm, and this model presented the best average behavior, with 0.08mm positive and 0.06mm negative average deviation. The disadvantage of his model is that it presented the greatest maximum positive deviation and depending on where it is located, this detail can compromise the model usefulness. It is also notable in the graphic the porous aspect of the PU foam.

The biomodel manufactured in Nylon presented a singular trait: the positive and negative maximum deviations are quite similar, while the other two have the positive deviation notably greater than the negative. Associated with this, this model presented the greatest negative and the smallest positive maximum deviations, while all other statistical characteristics are comparable to the MDF model.

3.2. Application analysis

3.2.1. Cutting easiness

The easiness to cut the materials of the biomodels was related to the time taken to cut each specimen. Table 2 summarizes the time used to cut each investigated material, using a manual and an electrical saw.

Table 2: Times demanded to cut the specimens for each different material (in seconds).

Specimen	MDF		PU		Nylon	
	Manual saw	Electrical saw	Manual saw	Electrical saw	Manual saw	Electrical saw
1	23s	42s	6s	9s	42s	not possible
2	17s	39s	3s	9s	38s	not possible
3	14s	30s	2s	7s	32s	not possible
Average	18s	37s	3.67s	8.33s	37.33s	-

Table 2 presents the results of the cutting tests. The time to cut the PU specimens was the lowest, followed by MDF and Nylon, which presented the highest cutting time. These results indicate that models manufactures in PU are easier to cut, what facilitate the task of the surgeon to remove undesirable areas of the biomodel and consequently makes the surgical planning easier.

Besides presenting difficulties to cut the material manually, the Nylon melted when the attempt to cut it with the electrical saw was made. The friction made by the tool caused a localized melting of the material that adhered to the saw when it cooled and returned to the solid state. This inconvenience made it impossible to finish this operation.

3.2.2. Marking possibility

The qualitative evaluation of the possibility to make marks on the biomodel of different materials was performed using a ballpoint pen, a marker and a pencil. The results are illustrated in Fig. 6.

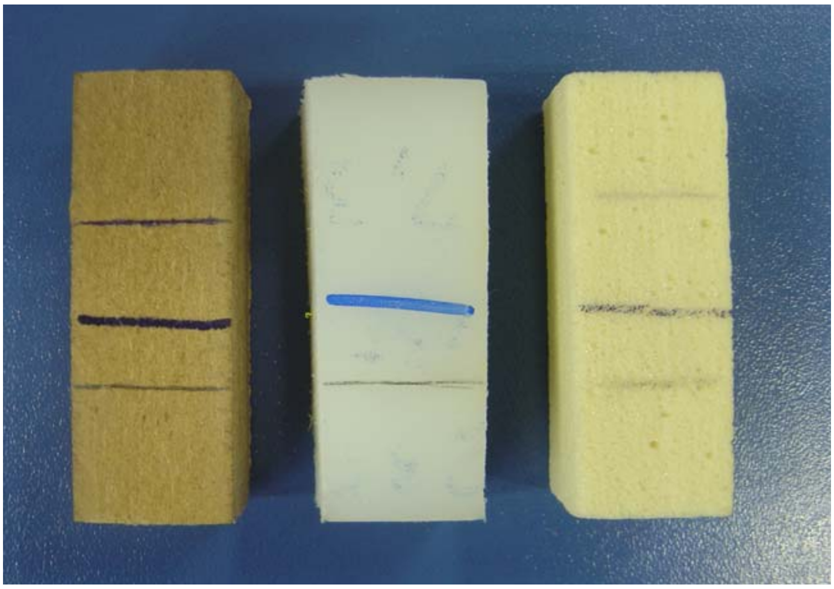

Figure 6: Marking tests made on the studied materials: MDF, Nylon and PU, respectively.
Marks from top to bottom: pen, marker and pencil.

All the marks made on the MDF are perfectly visible, what means that, in the cases when the surgeon make marks on the model to indicate the surgical procedure, no difficulties will be found on marking this material and identifying the marked regions. The marks made on Nylon were visible, except for the ballpoint pen. The marks made on PU, on the other hand, are hardly identified, as the porosity of its surface does not allow an adequate marking.

4. CONCLUSIONS

This study evaluated the characteristics of biomodels produced by CNC milling to determine if such process can be reliable. The results indicate that the CNC milling of biomodels to help in surgical planning and prosthesis design is a potential alternative, considering precision and applicability.

Three different materials were evaluated in terms of precision and service applications. In the dimensional precision verification, performed using a 3D laser scanning, it was found that CNC milled biomodels are fairly precise, having the worst average deviation of 0.14mm (Nylon and MDF) and worst standard deviation of 0.21mm (MDF). In this analysis, the PU biomodel was considered the best suitable, with the best averages and therefore, the most precise. An important consideration is that all biomodels manufactured via CNC milling presented large maximum deviations, so caution must be taken in determining if such deviations are not located in an area important to the desired application.

The service application evaluation indicated that, among the tested materials, MDF fulfills the requirements to be used as biomodel due to its marking possibility and cutting easiness. Nylon presented acceptable marking possibility, although it presents resistance in cutting, characteristic which can difficult the surgical planning. Polyurethane foam, on the other hand, presented the greatest cutting easiness, however the marks made on its surface are not easily identified.

Further studies should be made considering more materials and other aspects such as possible sterilization techniques and the machining of more complex geometries.

5. ACKNOWLEDGEMENTS

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