3D Printed Human Foot Splint, Designed from MRI of the *Luffa Cylindrica* Dried Fruit

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Abstract: This article presents a method to design a splint from the MRI (Magnetic Resonance Imaging) of the dried fruit of a tropical plant called *Luffa (Luffa cylindrica* (L.) M.Roem), which shows the possibility of using synthetic forms in Nature to reproduce and apply them in the development of products, a concept known as bio-design. This fruit –similar to a cucumber-, when dried it becomes a fibrous and imbricated structure that confers interesting stiffness and lightness properties, which were used to design a splint for a human foot, different from the conventional plaster, through a reverse engineering process. Such structure was copied, with the help of a 7T MRI scanner (Magnetic Resonator of seven Tesla *Varian*). The images of the *Luffa* processed with the OSIRIX® and AMIRA® programs then converted to the STL (STereo Lithography) format for manipulated with CAD / CAM (Computer-Aided Design / Computer-Aided Manufacturing) programs. The results have been successful since it was possible to print by FDM (Fused Deposition Modeling) a scale model of the splint in ABS (Acrylonitrile butadiene styrene), from a module that extracted from the MRI, which tested in a model of a human foot.

1 INTRODUCTION

The bio-design represents an alternative to produce orthopedic products such as splints - and in general, for any product type, because the traditional ones made from bandages covered with plaster, are uncomfortable and somewhat heavy for the user, in addition to producing itching and bad smell, to mention the most representative inconveniences. On the other hand, the current development of NT (New Technologies), has given a great boost to creativity and proposition of better designs that were once unimaginable: from X-rays to scanners and from bandages to smart textiles, the Technological advance, (it goes without saying), has become a valuable tool –together with the inspiration in Nature- of generating new concepts, forms, processes, materials and techniques.

Bio-design, as the name implies, combines the science of biology with industrial design, that is, the application of biological principles in the search for solutions to design problems, principles that – according to Michael Pawlyn- are backed "from a 3.8 billion year research and development period" (Pawlyn, 2011). However, since these solutions do not always appear at first sight, that is, by direct observation, it is necessary to do an abstraction work to be able to reach them.

Based on this, a review of certain existing structures in nature (both organic and inorganic) was made to find that way that could solve the design of the splint raised, bearing in mind the drawbacks of the

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plaster splints mentioned above, in order to propose a design that was comfortable, light and with sufficient ventilation to avoid bad smell and itching; in addition –of course- to protect and help the healing of the affected limb of the patient.

Thus, the focus was on the *Luffa* (family *Cucurbitáceae*), whose fruit –once dry- acquires a peculiar structural order, which can fully cover a surface without increasing the mass, which gives it firmness, rigidity, and lightweight. It is a plant of tropical origin that belongs to the same family of pumpkins that gives an oblong green fruit similar to a cucumber, only larger; It is commonly known as *smooth loofah*, *sponge gourd* or *vegetable sponge* (PROTA, 2018), since when drying –and without a shell- it takes on a matted straw like appearance similar to that of a bath sponge, which is why it is usually used in body or object cleaning. The dried fruit in question has proven to have interesting mechanical properties (Chen, Shi, Gorb, & Li, 2014, Shen, Min Xie, Huang, Zhou, & Ruan, 2012), that prove its resistance and resilience that its peculiar structure confers, (apart from its chemical components); this is why it was ideal for designing the splint. It should be clarified that in this investigation, its chemical-organic composition is not specifically addressed, but rather, the analysis of the form.

Now, it was one thing to find the ideal biological organism and another to replicate it. Given its peculiar structure –fibrous and tangled- it would have been somewhat complicated to achieve it, so that the next step was to find a way to copy it as faithfully as possible, so the magnetic resonator was thought for, through a reverse engineering process, obtain an exact duplicate of the fruit and that in the end, it would be modeled with CAD / CAM programs.

The use of MRI is widely known and used in the medical area, where it acquires its highest expression (Backstrom, Nazari, Gu, & Jakola, 2018), (Bouchet, Pastore, Brun, & Ballarin, 2015), although not only limited to it, but also for other types of investigations (Cole-Hamilton, Ka-ye, Chudek, & Hunter, 1995, Ghisalberti & Godfrey, 1998). On the other hand, the treatment of computerized images is very widespread, what was previously done with radiographs, today we work with the Computed Tomography, the MRI or the Ultrasound, through specialized software from which not only images can be obtained every increasingly accurate, useful for diagnosis, but can reach three-dimensionality, (Al Jabbari, Abu Saleh, Patel, Igo, & Rear-don, 2016, Ehricke, Hauser, Nägele, Schult, & Klose, 2018, Bezinque et al., 2018), which significantly improves the knowledge, analysis and understanding of the object of study, be it the human anatomy or some organic or inorganic specimen.

On the other hand we have splints, an external device used to immobilize parts of the body in order to help in its healing or correction, in case of fractures or orthopedic treatments; splints are made of various materials such as aluminum, fabric, wood, plastic or plaster (Pal, 2016), but first of all it must be resistant. The most used material is plaster based on bandages. Plaster is uncomfortable and heavy, in addition to causing discomfort to patients such as sores, itch and bad smell by "encapsulating" the affected part. This article is focused on designing a splint for human foot, which avoids the aforementioned inconveniences.

Unlike the splint designed by Jake Evill (Jake Evill cited by Kim & Jeong, 2015), the structure proposed here was not created from a generative design program after scanning the contours of the human limb in 3D, but it was achieved from the tessellation of a module extracted from the dried fruit of the *Luffa*.

One of the main contributions of this work is that you can take advantage of the qualities of a biological structure to design a splint more efficient than the traditional ones made with plaster, since significant improvements related to comfort, ventilation, weight and the amount of material required, to name a few. And that through an inverse engineering process, the exact replication of said structure is possible using MRI technology. The design process presented can be used to create diverse products based on the same principle.

2 MATERIALS AND METHODS

2.1 The Organic Specimen

The process diagram that was followed to model the splint is shown in Figure 1. Five samples from different parts of the same specimen of the *Luffa* fruit of approx. 27 cm^3 and an average weight of 10 g. submerged in a gelatinous solution. The gelatinous solution prepared with 5 parts of grenetina (15 g) per liter of water, which was poured into 5 cylindrical glass containers 5.5 cm in diameter by 13 cm high with capacity 295 ml (10 oz); in each one a sample of the fruit was submerged, and at room temperature until they took the firm consistency, then keep them in refrigeration. This preparation was done because

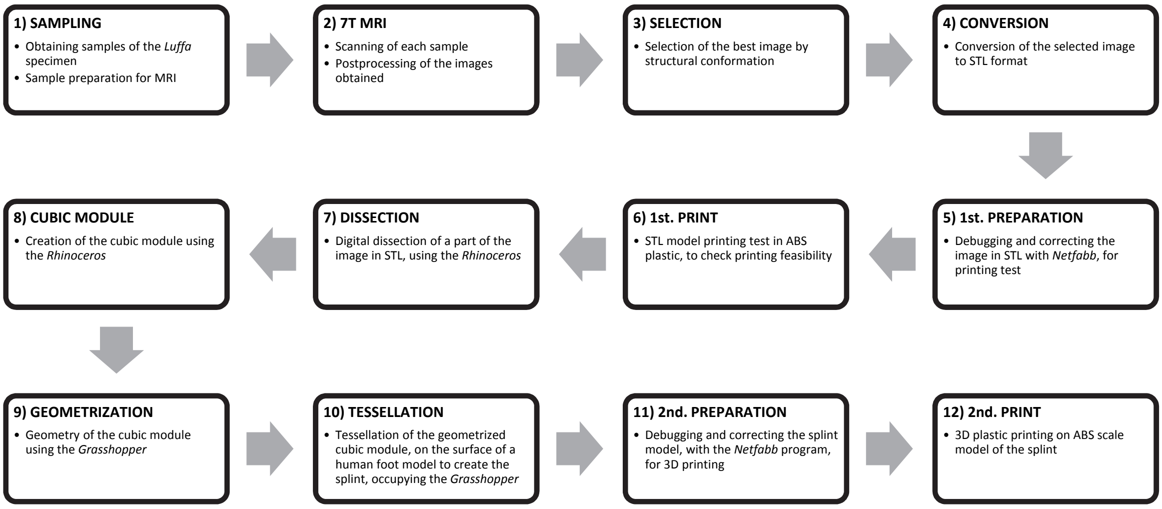

Figure 1: Process diagram for splint modeling.

the scan that produces a resonator requires a contrast volume so that it can detect the sample since it would not register something if it was introduced as is.

2.2 Magnetic Resonance Imaging

For this project a 7T MRI was used; each sample scanned with a standard sequence weighted in T1 type Gradient-Echo in three-dimensional acquisition (GE3D), with the parameters: TR 4 ms, TE 2.3 ms, FA 20^{o}, FOV 60x60 mm, MAT 256x256, slice 0.39 mm and Avg. 10 (Fig. 2). The studies acquired were exported in DICOM format for post-processing.

2.3 The Software and 3D Printing

The MRI software consists basically of the OSIRIX® and AMIRA® programs, used in order to post-process MRI (semi-automatic segmentation), generating the *Luffa* model by polygonal approaches and exported to STL format. The STL were processes with *Rhinoceros®* CAD / CAM, its *Grasshopper™* plug-in, *Netfabb®* by Autodesk and Stratasys *Dimension Elite™*, thread fusion printer. The printing material was thermoplastic ABS.

3 RESULTS AND DISCUSSION

An image obtained by a scanner such as the MRI is made up of a point-cloud. The point-cloud is a set of data collected by the scanner using the means in three-dimensional structures. These points constitute vertices in a three-dimensional coordinate field, so they can be interpreted in a graphic format such as the

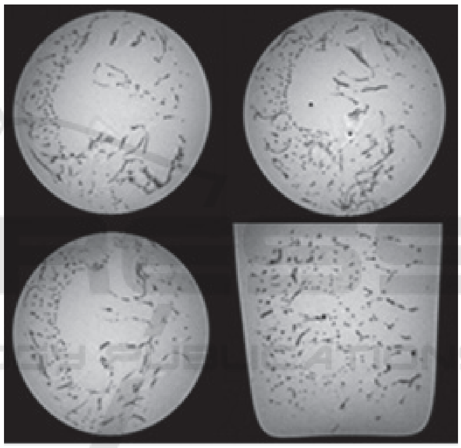

Figure 2: GE3D acquired in the 7T MRI scanner, without post-processing.

STL the digital model is made up of multiple polygons, which makes easy manipulate information –as if it will be a physical object- in some program such as *Rhinoceros®* (Fig. 3).

One of the images in STL was processed. First it was increased by 1200% its size and debugging in the *Netfabb®.* Next was printed in 3D (Fig. 4). As 3rd step, verify its materialization and check its structure's behavior. The experiments worked quite well, so the project continued, dissecting the virtual sample to create a cubic module of approximately 15.6 cm^3 (Fig. 5), with which the splint structure could be formed.

Figure 3: STL digital model of the *Luffa* sample.

Figure 4: 3D printing test on ABS plastic.

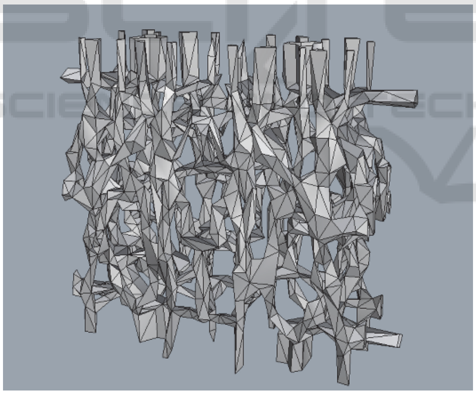

Figure 5: Dissected cubic module of the selected sample.

The dissected cubic module was made using symmetry in the 3D planes, a section of the virtual sample. In the splint modeling, was used the *Grasshopper*™ visual programming language that is part of the *Rhinoceros*® program; this plug-in works based on graphic algorithms called 'variables' with which they can model and create shapes, through a set of instructions called "definition".

To be able to work the cubic module, it was necessary to convert it to geometric figures through the *Grasshopper*™ program, since images made based on geometric figures are easier to handle due to their low "weight", than those made of polygons. So a "definition" was created for this purpose (Fig. 6) that linked the "points" through cylinders coupled with spheres, the result of which is seen in Figure 7. A second "definition" (Fig. 8) was created to tessellate the geometrized cubic module on the surface of a virtual model of average human foot to generate the splint.

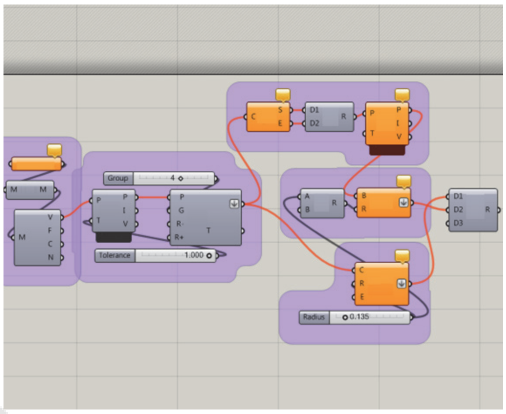

Figure 6: "Definition" to geometrize the cubic module.

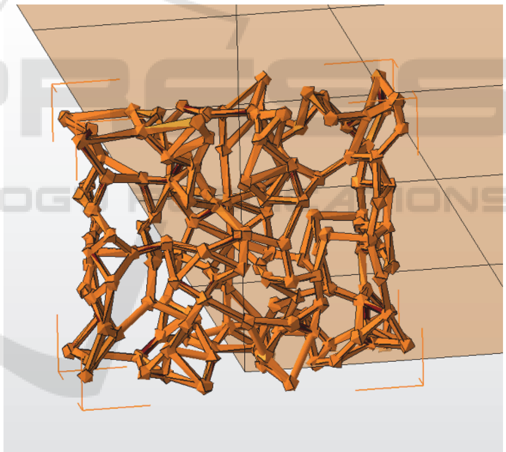

Figure 7: Geometrical cubic module.

"A tessellation is a special pattern, as it is formed by different modules that splice together, according to different symmetry principles, without overlapping or leaving empty spaces" (Roncoroni Osio, 2017, p. 229).

Several dissected cubic modules accommodated to determine which of them best covered the surface (the distribution surface was the form of the human foot), the optimum being 30 modules on the x-axis by 15 on the y-axis (fig. 9). It was observed that two factors influence the formation of the splint a) the dissected cubic module size and b) the size of the distribution surface. For smaller modules, the mesh

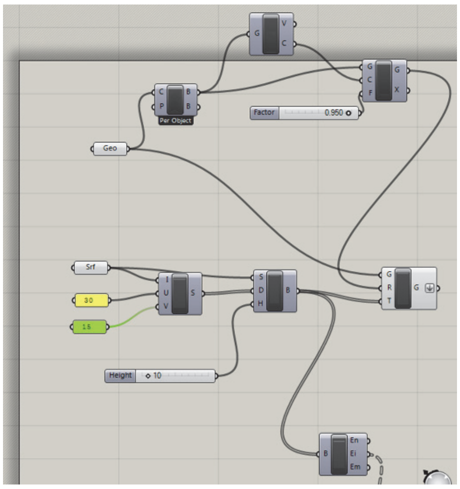

Figure 8: Second "definition" to tessellate the cubic module.

becomes more closed and compact; on the contrary if it is enlarged it becomes more open. The same goes for the surface; more modules create a larger size of the model and less for smaller. It is important to mention that the surface where the module is tessellated must be "closed".

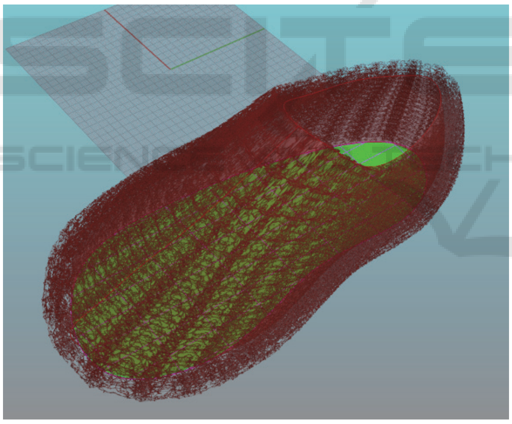

Figure 9: Result of the tessellation of the cubic module on the foot model.

Next, it was exported to the *Netfabb®* program to correct the file and prepare the model for ABS printing, using the FDM process. Since the printer used has a print volume of 8 in^3, it was necessary to reduce the dimensions of the splint by proportional scaling so that the formal properties of the cubic module was not lost so that it entered the printing tray, in addition divided in half to appreciate the thickness and arrangement it would acquire (fig. 10). The printing process took 72 h, plus the removal of soluble support material.

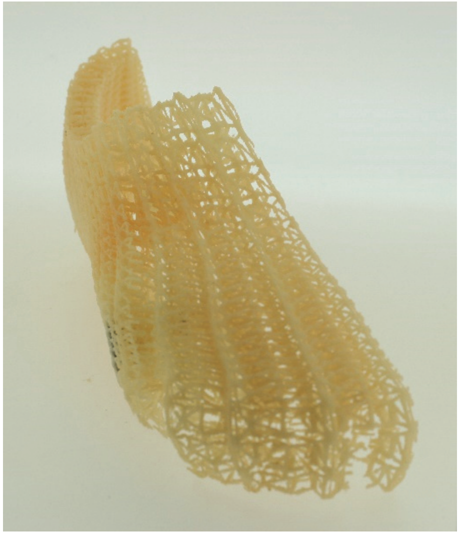

Figure 10: The First model of the foot splint, printed in ABS plastic.

The results of this first phase were successful, since the task of replicating the structure of the organism as well as its application in the design of the splint was achieved.

However, the work does not end here; it will continue to improve in one case and resolve in another, certain aspects such as the system of attachment and coupling to the member, the final material, the copy of the user's anthropometry and the processing time. It is very important to compare the three-dimensional model against the model printed by FDM, since the first one exhibits a different behavior from the second, especially due to the printing trajectories of the filament, so that stress analysis and resistance tests will also be done.

4 CONCLUSIONS

Bio-design, in conjunction with the NT –particularly the MRI and 3D printing - is a good alternative in product development, as demonstrated in this project. Relying on principles backed by millions of years of testing, in the great laboratory that is Nature, becomes a great advantage when it comes to solving design problems. Although the use of MRI is associated with the medical area, it can be used equally for other research; in this case it was used to obtain an exact reproduction of the structure of a biological organism, which otherwise would have been complicated to achieve: the dried fruit of the *Luffa*. Its peculiar structure gives it interesting mechanical properties that make it resistant to deformation, which is why it was thought that this advantage could be used to design a splint for the human foot, which improves on the traditional ones made of coated bandages with plaster This research can serve as a basis for creating diverse and varied bio-designed products, not only from the medical area, but also from other fields and specialties of human activity.

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