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Additive manufacturing of PLA to mimic the thrust force of mandibular bone during drilling

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Abstract

Edentulism is a condition that results in the partial or total loss of teeth. It may lead to problems during chewing and be a cause of self-isolation and low self-esteem. Edentulism can be resolved both with removable prostheses (dentures) and fixed implants, with the latter being more efficient. The installation of a fixed implant involves a real surgical operation in which the jaw/mandibular bone is drilled through a special drill. One of the main cautions the surgeon must have during the operation is not to sever the nerves during the drilling. Given the composition of the bone is different in each person, the drilling thrust force is variable and controlling its movement can sometimes be complicated. Therefore, being able to test the operation on a dummy may reduce the number of errors. Additive manufacturing with its high degree of customization and ability to produce objects with almost no geometrical limitations could provide the required features to realize the dummy. In this work, the drilling properties of samples made in PLA through Fused Filament Fabrication (FFF) were studied. The samples were designed to mimic the composition of the bone. Specifically, a thin, hard, and denser outer layer and a 25% internal filling were adopted. The samples were drilled with a dental drill properly connected to a collaborative robot.

Keywords: Additive Manufacturing, Fused Filament Fabrication (FFF), PLA, drilling, bone.

1. Introduction

Edentulism is a condition that results in the partial or total loss of teeth. In most cases, it is related to aging, and it can cause various problems such as decreased bone density and chewing difficulty [1].

Dental implantology is the set of techniques aimed at solving the problems caused by edentulism through the installation of dental implants. Dental implants can be removable or fixed. The removable implants, or dentures, however, do not allow to reach the same level of efficiency as the fixed ones [2]. Fixed implants consist of two parts. The first part, called the implant body, consists of a threaded root screwed inside the bone. The actual prosthesis, with anatomical geometry, is then anchored to it [3]. The typical dimensions of the implant bodies are 6-15 mm in length and 3.5-6 mm in diameter. The installation typically takes place in 3 steps: preliminary drilling, hole enlargement, and fixing. During these phases, the dentist must pay special attention to two aspects: not to sever the nerve [4] and to keep the temperature of the bone low to avoid necrosis [5]. Regarding the temperature, it is possible to keep it low through an interruption of the operation every 5-10 s and with a continuous cooling by saline solution at room temperature. The not severing of the bone nerve, on the other hand, is more related to the skill of the dentist who must be able to stop at the right moment. An additional degree of difficulty is introduced by the structure of the bone itself. In fact, the bone is characterized by an external hard shell made by compacted bone lamellae and by an internal infill made by lamellas

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arranged in a porous structure. The shell and infill bone are called cortical and trabecular bone, respectively [6]. The trabecular bone takes most of the volume, the cortical bone forms only a thin outer layer. The quality of the bone tissue and the percentages of cortical and trabecular bones depend on age, position along the jaw, and health. Studies report that the percentage volume of the bone is around 18-23 % [7] and that the thickness of the cortical bone ranges between 1.6-2 mm in the healthy zone while in the edentulous areas can reduce up to 1 mm [8].

During the preliminary drilling phase, a force of around 10-15 N is required to drill the cortical bone, while the trabecular bone requires a lower force, around 5-6 N [9-11].

As mentioned earlier, this complexity can make it difficult for the dentist to perform the operation successfully. Having the opportunity to try the operation previously on a dummy may increase the chances of success. In this light, additive manufacturing could provide the required characteristics. Its high level of customization, the ability to realize complex geometries, and the rapidity of part production [12], make these technologies ideal for manufacturing dummies. Amongst the different 3D technologies, Fused Filament Fabrication (FFF) is the most used to build training models due to its low costs and production time. Moreover, it can manufacture models with acceptable haptic feedback despite a lower accuracy compared to other technologies [13]. One of the most used FFF materials is PLA, a biodegradable and non-toxic material. Its drilling properties, however, are more studied when it is used as matrix for composite materials [14, 15] rather than in its natural form.

In this work, we studied the possibility of 3D printing dummies with a response similar to the one of the bones during drilling. Specifically, PLA samples were made using Fused Filament Fabrication (FFF) technology. The samples present a solid outer layer and an inner infill with reduced filling to mimic the two types of bone. Finally, they were drilled with a dental drill properly attached to a collaborative robot.

2. Materials and methods

2.1. Samples fabrication

The samples were fabricated through Fused Filament Fabrication with an Ultimaker 3 extended printer. The used material is PLA, and the geometry consists of a 30x10x12 mm prism. The samples were printed with a print core AA0.4, a nozzle temperature of 190 °C, and a layer thickness of 0.4mm. C (cortical) samples, T (trabecular) samples, and C+T samples were fabricated. C samples consist of only the vertical walls and the top surface, leaving the inside empty. T samples present only the bottom surface and the infill, specifically a 25% infill with a linear filling strategy. C+T samples present all the external surfaces combined with the internal infill. The 3 types of samples and their characteristics are visible in Figure 1 and Table 1, respectively. The external surfaces are 1.2 mm thick for every sample. 6 samples for each type were printed.

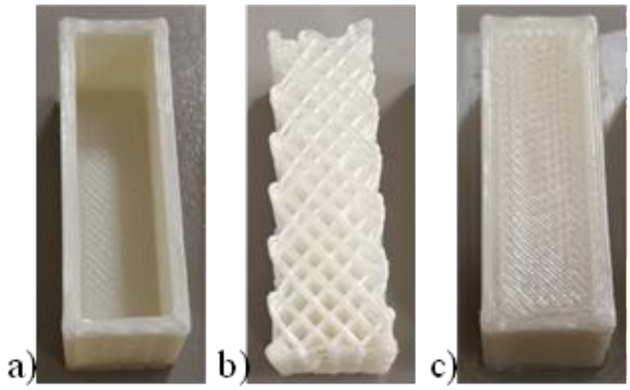

Fig. 1: Sample types: a) C sample, b) T sample, c) T+C sample.

Table 1. Samples characteristics.

Sample	Shell	Infill [%]
C (cortical)	Yes	0
T (trabecular)	No	25
C+T	Yes	25

2.2. Dental drill

The drill used for the drilling tests is a DEC 100 dental drill equipped with an INTRA matic 20 CB handpiece. The drilling tip had a 2.2 mm diameter. The drill was operated at the maximum allowed speed.

2.3. Collaborative robot

The force needed to drill the samples was measured with a Sawyer robot by Rethink Robotics. The Sawyer is a collaborative robot and presents joints equipped with force sensors. The max payload is 4 kg and the nominal repeatability in positioning is ± 0.1 mm.

2.4. Drilling procedure

The samples were fixed with a clamp. The drill was attached to the robot with a specially designed and 3d printed connector. Two holes were drilled on each sample. The holes were drilled at a speed of 5 mm/s. The drilling depth was set at 10 mm. Two different cooling systems were investigated, compressed air and water. Air was applied through the use of a compressor, while water through a squeeze bottle. Three samples of each type were tested for every cooling system, for a total of 6 drilling for every combination (sample type and cooling system). The experimental set-up is visible in Figure 2.

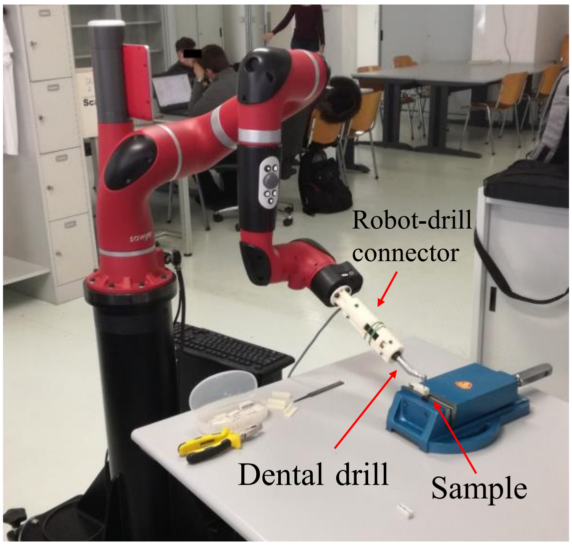

Fig. 2: Experimental set-up.

3. Results and Discussion

The typical force and displacement curves are reported in Figure 3.

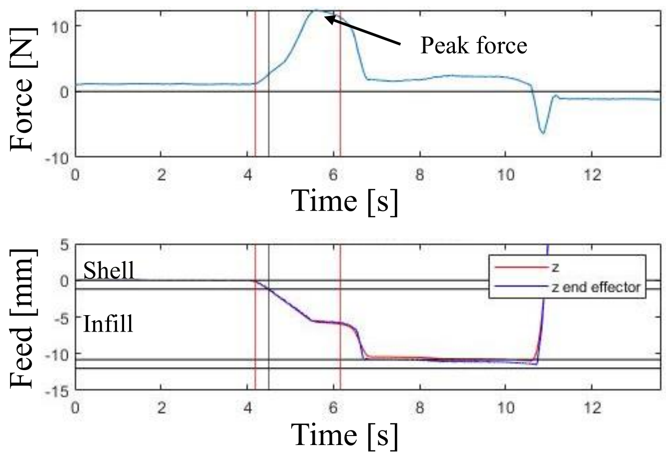

Fig. 3. Example of force and displacement measurements during the drilling of a C+T sample.

The values of the peak force are reported in Figure 4.

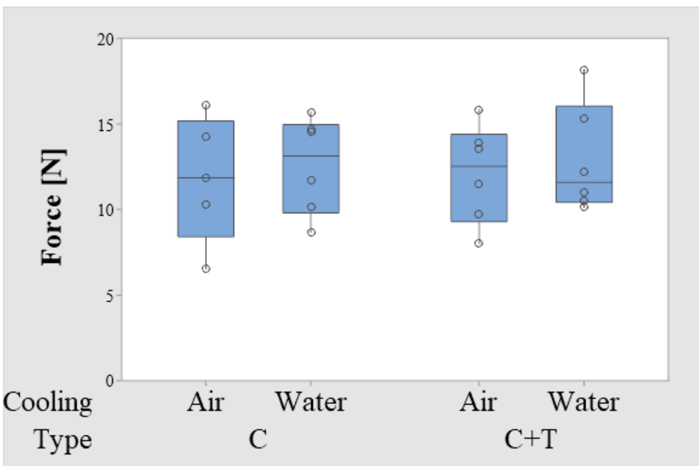

Fig. 4: Values of force obtained from the drilling of the top surfaces of the C and C+T samples.

The results of the peak force range from 7 to 18 N with the mean for every type of test between 11 and 13 N. These values are perfectly in line with the values found in literature for the drilling of the cortical bone (10-15 N [9-11]).

The cooling system seems to not have any influence on the peak force required to drill the top surface. This allows to choose the cooling system considered best for the purpose. In view of reproducing the real surgical operation, water seems the most suitable.

The similar results between the two specimen types, then, show that the presence or absence of the infill does not affect the strength necessary to drill the shell. In this way, for future specimen optimization, shell and infill can be treated as two separate variables.

As for the infill, the 25 % infill was found to be too mild to perform the drilling. Specifically, the diameters of the obtained holes generated by the grid were too large. The drill tip, as soon as it made contact with the sample, slipped into a hole of the grid due to the low rigidity of the system and the drilling was not carried out. This phenomenon does occur also in the C+T samples. Therefore, it was impossible to record a drilling force for the infill structure. A higher infill percentage or a more distributed and random strategy should be used for future investigations.

Finally, the robot used for the drilling resulted to be not rigid enough the precisely measure the position of the tip during drilling. As it is possible to see in Figure 3, the recorded force values do not align as well as they should with the measured displacements. The forces are thus misaligned with the geometry of the sample, and, for example, the force peak is found shifted forward in time, where the force value should be lower since the tip should be in the infill zone. This is due to the presence of springs in the joints of the robot that introduce a little delay in the movement.

4. Conclusion

Teeth loss is a condition that can negatively affect a person's lifestyle. To deal with this problem, dental prostheses anchored to the jaw bones through threaded structures are often used. In this type of operation, the dentist must pay particular attention during the drilling phase. This phase is especially delicate because it is necessary to keep under control the temperature, to avoid necrosis, and there is the risk of cutting the bone nerve. to increase the likelihood of success, the dentist would benefit from being able to try the operation on a dummy first. In this perspective, additive manufacturing offers a great opportunity, given its high degree of customization and the possibility to easily realize complex structures.

In this work, different types of samples were made to emulate the different types of bone present in the jaws. Specifically, C specimens were made to emulate cortical bone, T specimens were made to emulate trabecular bone and C+T specimens were made to emulate the entire behavior of bone. The samples were fabricated in PLA through FFF and drilled with a dental drill connected to a collaborative robot.

The results show that, with respect to the shell drilling force, corresponding to the cortical bone, the values are in line with those found in the literature. In fact, the means settle in the range of 11-13 N.

Regarding the plateau force, corresponding to the drilling of the trabecular bone, it was not possible to measure it due to the chosen filling strategy that left holes too wide for the tip used.

The robot used for recording the forces and displacements was found to be too flexible for a correct measurement of the position in relation to the geometry of the specimen and the recorded force.

Finally, this work lays a good basis for the fabrication of a dummy with properties similar to the jaws bone. Future works will focus on optimizing the specimen through the use of new filling strategies and the study of different materials.

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