A case study of re-design for 3D printing: proposal to replace metallic fastening elements in an orthopedic corset with 3D printed PLA850 substitutes

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Abstract: Medicine is implementing revolutionary techniques like 3D printing in customized patient care. This enables tailor-made manufacturing with high productivity and low cost. In this work, the possibility of replacing the metal closures of an orthopedic corset using 3D printing has been studied. For the redesign, a multi-criteria decision analysis method is carried out. A design of experiments of nine specimens on the final prototype has been realized to determinate the most optimal printing parameters. The printing parameters analysed have been: infill density, infill pattern and printing speed. These specimens were subjected to a non-standardized bending test. From the experimental results, a triangular infill pattern, 100% infill density and 100 mm/s in printing speed provide the best bending strength values.

Keywords: Fused Deposition Modelling, Biomedical 3D-printing, Additive manufacturing, Polylactic acid.

1. Introduction

Medicine is experiencing important advances thanks to the use of revolutionary new techniques, such as additive manufacturing (AM) or 3D printing. AM produces objects by adding material, layer by layer, from a 3D digital model. This technique is leading medicine in numerous areas such as [1]: dentistry [2], engineered tissue [3] and organs models [4], surgical instruments [5], implants [6], prostheses [7], orthoses [8] and drug formulations [9].

One of the sectors where AM will have the greatest potential in the coming years is the orthopedic sector: lightweight, customised and cost-effective elements can be manufactured using AM. In the literature we can find works related to the manufacture of different orthoses and prostheses: lower-limb prosthesis sockets [10]; wrist orthosis [11], ear prosthesis [12], robotic arm prosthesis [13], among many other applications.

One of the most common orthoses in orthopedic is the lumbar-back orthosis or corset [14]. A corset allows patients with scoliosis to correct the curvature of the back. It is usually made of polypropylene but includes metal closures that increase its weight, cost, and delivery time as they are manufactured by external companies. The authors propose the replacement of these metal closures with components manufactured by AM.

One of the most widely used AM techniques today is fused deposition modelling (FDM). There are several reasons for this [15]: FDM printers are a cost-effective solution; a multitude of printing materials are available, at affordable prices; short learning curve; a wealth of information is available on the web.
The operation of this type of printer is simple: a thermoplastic filament is melted and extruded through a nozzle; a moving head containing the nozzle moves in the XY plane, depositing the material on top of previous layers to form the desired part.

There are a multitude of materials for 3D printing [16]: polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polyethylene terephthalate (PETG), high impact polystyrene (HIPS), polycarbonate (PC), among others. The use of polylactic acid is a polymer that has the advantage of being biodegradable as it is obtained from renewable resources such as sugar beets and corn. It has a high stiffness and hardness compared to other petroleum-based polymers. Its disadvantages are that it is a brittle material [17].

The present work consists of the redesign of the metal closures of an orthopedic corset with the aim of replacing it with components manufactured by 3D printing, using PLA 850 as raw material. For this purpose, the multistage redesign process proposed by Salonitis and Al Zarban [18] has been followed. The technical experts who were advising us during the work pointed out that the most responsible part of the set works in flexion. Therefore, before printing the final prototype, a small experimental test was carried out to determine which values of infill density, infill pattern and printing speed were the most suitable to obtain parts with better bending behaviour.

2. Redesign process
The redesign process was carried out following the method proposed by Salonitis and Al Zarban [18] (figure 1). A total of five stages were carried out until the final design was achieved with continuous revisions with the aim of achieving a fully functional model.

![Figure 1. Redesign process followed (elaborated from [18]).](image)

2.1. Analysis of specifications
The starting point of this work is the need in a production process of a company dedicated to the manufacture of orthopedic corsets for patients with scoliosis. This need consists of lightening the weight of the corset.

The orthopedic corset consists of two polypropylene parts, one front and one back as shown in figure 2. These parts are custom-made according to the needs of the patients. These two parts are joined by means of metallic connecting elements, manufactured by external companies dedicated to the modelling of parts. Since it is not possible to lighten the weight of the front and back parts, the steel connecting elements are redesigned.

To carry out the work, a ‘Creality Ender 3’ 3D printer was used to print parts of up to 220 × 220 × 250 mm using FDM technology. PLA 850 was used as a material because it is easy to extrude. The printing parameters selected in the study were the infill pattern, infill density and the printing speed. To analyse the values that provide the best bending strength, a three-parameter DOE with three levels was carried out. The printing parameters were: layer height equal to 0.20 mm; extrusion temperature equal to 200 ºC, hot bed temperature equal to 50 ºC.
2.2. Initial concept

The original joining elements are made up of four parts assembled as shown in figure 2. ‘Part 1’ is a joining element between the other components. ‘Part 2’ is an assembly of two different parts, both of which are joined together. ‘Part 3’ consists of holes distributed circularly with the aim of gradually increasing the opening of the corset, making the patient more and more upright. Finally, ‘part 4’ is assembled to the rest of the components to give stability to the corset. Figure 3 shows the assembly process between all the parts.

| Stage | Errors | Modifications |
|-------|--------|---------------|
| #1: Recreation of original parts | Printing error in the central hole due to poorly solidified filament. Lateral holes with dimensional errors due to error in printing parameters. | Increase the internal diameters to take into account the inaccuracy of the printer. Use of M4 hexagonal screws to join the parts. |
| #2 | Design error in considering the hexagonal hole of 7 mm radius, which is the same size as the screws. Problems in making the connection between the two elements. | Redesign for adjustment with play. Redesign part 1 so that the hexagonal head of the screw fits perfectly. |
| #3 | Poor quality of the anti-return hexagon, due to limitations of the technique. | Replace the hexagonal anti-return geometry with a circular anti-return geometry. |
2.3. Interpretation of results
In the manufacture of the parts, similarity to the original parts was maintained as far as possible. The FDM 3D printing technique offers many benefits, but also some limitations inherent to the technique, resulting in continuous revisions and improvements that have been made in successive stages (tables 1-4).

Table 2. Re-design stage for part 2.

| Part 2: | Stage | Errors | Modifications |
|--------|-------|--------|---------------|
|  #1: Recreation of original parts | Inaccuracies in the circular surface of the shaft due to the use of very small diameters with very reduced thicknesses. Design error in the assembly of parts 2.1. and 2.2. | Modify the original design by reducing the width of the base of the part so that the part 2.2. can fit and rotate correctly. Increase the outside diameter of the vertical part of the part to increase the thickness of the circular shaft and avoid dimensional inaccuracies. Extending the safety margin to allow the part to rotate. Modify the diameters of all bores to 4/4.25 mm diameter. Reduce the flap and the hinge axis (flat and horizontal part). |
|  #2 | Error in the internal diameter due to printing quality errors. Error in part rotation 2.1. and 2.2. due to inaccuracies in the 3D printing technique. | |

Table 3. Re-design stage for part 3.

| Part 3: | Stage | Errors | Modifications |
|--------|-------|--------|---------------|
|  #1: Recreation of original parts | Error in the distribution of the circular pattern of clamping holes. Error in the vertical element of hight 10 mm rising above the horizontal surface. | Establish a circular pattern in the distribution of the clamping holes. Eliminate the vertical element after its printing is incompatible, carrying out a general redesign of the parts. Modify the diameters of the shaft/hexagon bore fit. |
|  #2 | Use M4 hexagon socket head screws as anchors between different connecting elements. Error when printing the holes for the hexagonal screw heads with too much play. | |
|  #3 | The part is not completely symmetrical; however, it does not represent a functional disadvantage in the service life of the model. | Redesign the part with symmetry axis. Modify the bore diameters of the part to 4/4.25 mm diameter. Increase the thickness of the part. Replace circular anti-returns with hexagonal anti-returns. |

2.4. Design evaluation
According to experts, the part that must withstand the most stress is part 4. Therefore, non-standardised bending tests (Figure 4) were carried out on a specimen to determine the maximum bending capacity of part 4. The non-standardised bending test carried out consisted of inserting a blank with a through hole
at one end into the jaw chuck of a manual lathe. On the other hand, the specimen to be tested is placed in the turret, as if it were a tool. Both parts are connected by means of a dynamometer. Once this is done, the carriage hand wheel is operated, so that the end of the specimen attached to the tool post moves away from the workpiece holder and the specimen begins to flex. The dynamometer records the maximum force value reached. From this value, the maximum bending moment that the specimen can withstand before breakage is calculated.

![Figure 4. Non-standardised bending test.](image)

### Table 4. Re-design stage for part 4.

| Stage                              | Errors                                                                 | Modifications                                                                 |
|------------------------------------|------------------------------------------------------------------------|-------------------------------------------------------------------------------|
| #1: Recreation of original parts   | In the centre of the cantilevered part, the part has a 10 mm high vertical projection with a joining function. This element was printed correctly, with a diameter of 8.5 mm, which is sufficient for the fit of this part with part 2.2. Error in the assembly of part 3-4, leaving a lot of space underneath. Design error when fitting the holes in part 4 with the thread of the hexagonal head screws fitted in part 3. | Increase the hole diameters to ensure that the screws pass through the holes in part 4. |
| #2                                 | Error in the rotation of part 3 and 4 due to a small gap between the bottom end of the cantilever of part 4 and the outside of part 3. Error in the design by overhanging the base by 10 mm. | Increase the distance of the cantilever joint hole to the horizontal base with Y dimension 0 mm. Reduce the vertical height of the cantilever, thus facilitating the attachment of both parts 3 and 4 to the final corset. Modify the bore diameters of the parts to 4/4.25 mm diameter. Reduce the thickness of the part. Redesign the part to be 15 mm shorter and 5 mm narrower. Replace circular anti-returns with hexagonal anti-returns. Reinforcement with angle strips. |
To test the specimen, a design of experiments (DOE) was carried out using the Taguchi 3-level method with 3 factors. The following factors are considered as printing factors: infill density, infill pattern and printing speed. For the infill density, the studied levels are: 60%, 80% and 100%; for the infill pattern, the studied levels are: triangular, cubic and hexagonal; and for the printing speed, the studied levels are: 60, 80 and 100 mm/s.

Figure 5. Bending test specimen

| Infill Density (%) | Infill Pattern   | Printing Speed (mm/s) | Bending Moment (N · m) |
|--------------------|------------------|-----------------------|------------------------|
| 60                 | Triangular       | 60                    | 4.4                    |
| 60                 | Cubic            | 80                    | 5.1                    |
| 60                 | Hexagonal        | 100                   | 4.6                    |
| 80                 | Triangular       | 80                    | 3.9                    |
| 80                 | Cubic            | 100                   | 5.7                    |
| 80                 | Hexagonal        | 60                    | 5.2                    |
| 100                | Triangular       | 100                   | 7.3                    |
| 100                | Cubic            | 60                    | 6.5                    |
| 100                | Hexagonal        | 80                    | 6.7                    |

2.5. Final design

Figure 6 shows the assembly of the final model. Figure 7 shows the parts printed in PLA850.

Figure 6. Final model assembly.
3. Results and conclusion

Many companies are currently investing time and resources in the redesign of metal parts with the aim of replacing them with 3D printed parts. In this work, the redesign Methodology developed by Salonitis and Al Zarban [10] has been applied to try to replace the metal closures of an orthopedic corset with one made of PLA 850 using fused filament deposition modelling (FDM).

The methodology followed consists of several stages. Once the final design was reached, a non-standardised bending test was carried out on the part of the assembly with the greatest responsibility, to determinate the most suitable printing parameters: infill density equal to 100%, triangular pattern, and printing speed equal to 100 mm/s.

The 3D printed fastening elements were successfully tested on a real corset for a child with scoliosis problems. Based on these results, it can be affirmed that the metal closure of a corset can be replaced by a 3D printed closure, with the following advantages: lower weight; lower price; possibility of being manufactured on demand in the orthopedic workshop without the need to resort to third companies; customisation of the closure to adapt it to the size of the patient.

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