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Re-design of a component of a lower-limb robotic exoskeleton for integrating sensing capacity and enhancing multi-material direct additive manufacturing

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\textbf{Abstract:} The quest for the materialisation of advanced products is expanding the need for intelligent components and devices. One of the fields of application for such products is the medical technology industry, in which many value-added products could benefit from extending its embedded functionalities. To this regard, the obtention of such products via Additive Manufacturing Technologies would be very beneficial, providing that the design requirements could be met in a seamless and direct manner. In this context, the present article develops and analyses three design iterations of a component of a lower-limb robotic exoskeleton for integrating sensing capacity on it via multi-material direct additive manufacturing. In subsequent steps, the component geometry is optimised for additive direct manufacturing, and different functionalities are incorporated (padding for comfort and circuitry for sensing). For each iteration, the design is validated by means of finite element analysis and the main manufacturing parameters are assessed to compare the different times and costs yield. The third redesign incorporates three different materials (ABS, TPU and PE+Cu), but still it is possible to 3D printed with a two extruder-head FDM 3D printer. The design and manufacturing results obtained could be implemented in further biomedical products or other parts requiring advanced functionalities.

\textbf{Keywords:} Fused Deposition Modelling, Multi-material, Design, Sensor, Exoskeleton.

1. Introduction

Multi-material additive manufacturing (AM) makes possible to manufacture directly parts incorporating several materials, enhancing to custom-build heterogeneous, functionally graded components [1]. The possibility of 3D Printing parts utilising different materials in the same manufacturing process operation will probably be critical to leverage the AM full potential which remains unleashed today. By materialising this, the benefits yield by the freedom of creation could be combined with the elimination of the requirements of some post-processing phases (e.g.: colouring, assembling), so obtaining multifunctional objects with high potential savings in production times and prices which could entirely disrupt the current global supply chains [2].
Technology-wise, there are different approaches that are currently being under development. For example, in the search for a high dimensional accuracy, several remarkable devices have been developed for obtaining parts based on Stereolithography (SL) means [3-5]. Apart from these, other technology approaches are those based on multi-extruding head Fused Deposition Modelling (FDM) [6-7] or multiple material jetting [8].

FDM efforts have revealed to produce interesting outcomes in terms of materials’ properties [6] and possibilities (e.g.: mimicking of human tissues [7]). Also, the selection of the best values for each of the different printing parameters is being under scrutiny for achieving the best part properties [9].

Complementary to the technology development, other important aspects that are currently being under development are design methodologies for multi-material AM. Being the approach a mono-technology use [8] or a hybrid technology deployment [3], topology and multi-objective optimisation considering the layer-by-layer nature of the parts [10], and the adhesion levels achieved between layers, are of utmost importance to anticipate the results obtained. Also, sustainability pays a big role [11], as well as the elucidation of outcomes in high value-added products [12].

Exoskeletons are high value-added products, usually manufactured in small series and often required to be adapted to the user. The user comfort is required to be maximum, whilst it is interesting to incorporate in the designs several sensing and actuating elements [13]. All these reasons make robotic exoskeleton components an interesting case study for multi-material direct additive manufacturing.

The present study addresses the redesign of an exoskeleton component -a shank support used to attach the exoskeleton structure to the patient’s lower limb-, to incorporate specific comfort and sensing functionalities (using 3 different materials: rigid, flexible, and conductive) as well as improve its manufacturability by multi-material AM.

1.1. Design zero: initial part utilised in the ABLE Exoskeleton

The case study part of the present article is a lower-limb robotic shank support, which is used in the ABLE Exoskeleton (ABLE Human Motion, Barcelona, Spain). The role of this shank support is to join the exoskeleton to the human body below the knee of the user. The exoskeleton is attached to the shank support with the help of the three holes where bolts are tightened, and a strap is tied along the lower limb to attach the part to the body. The shank support is used on both legs, being both parts symmetrical. Figure 1 shows the part in its context.

The initial design in the present article was a proposal that had been previously redesigned with the idea of manufacturing it via Multi Jet Fusion. The application of material in the design was homogeneous in the full body and the geometry did not take full advantage from the freedom of creation that empowers the three-dimensional printing systems.

![Figure 1. Lower-limb ABLE Exoskeleton, offered by the company ABLE Human Motion with focus on the case study part.](image-url)
Also, although the part was operational in the exoskeleton, it was rigid and did not incorporate extra functionalities, e.g.: it required to be assembled with some specific padding, it failed to adapt to the leg of the user, and it did not incorporate sensing capacities.

### 2. Materials and Methods

Different multi-material AM technologies were screened to see whether each option could fit better the list of requirements for the manufacturability of the lower-limb robotic exoskeleton. Assessing the technology constraints in coalition with the part specifications, and in a search for a compromise between technological capacity, availability and cost levels, multi-material Fused Deposition Modelling (FDM) technology was selected.

The three filament materials utilised as reference for comparing the designs in the study were Acrylonitrile butadiene styrene (ABS, BCN3D, Barcelona, Spain) for the structural cage, Thermoplastic polyurethane with a 98 Shore-A (TPU, BCN3D, Barcelona, Spain) for the padding, and a conductive 3D printing filament composed of biodegradable polyester and copper (PE+Cu, Electrifi, Multi3D, Cary, NC, US) for the internal circuitry. All the filaments have a diameter of 2.85 mm and all the layer thicknesses of printed samples were set at a relatively high value of 0.35 mm. Layer thickness is inversely proportional to the printing time duration, and one of the objectives was to achieve fast prints. Also, the electrical wiring was required to be big enough to ensure proper conductivity. For comparison matters layer thickness will not affect the results, as all samples will be assessed at the same value. However, as the layer thickness should not be larger than half of the value of the nozzle diameter and so the value chosen considered the use of a 0.8 mm nozzle diameter all design iterations.

The original design of the shank support (AM manufacturable, only structural part) was iterated in 3 re-design rounds, addressing the improvement of its FDM manufacturability (production times and costs), as well as to the incorporation of soft padding (comfort) and sensing add-ons (function), while meeting the structural requirements set. In all design iterations, features such as the joint for coupling with the exoskeleton and the strap for applying tension are to be maintained.

The main physical parameters for the ABS 3D printed material used in the different redesigns of the present study have been extracted from the manufacturer’s filament files, which describe a possible outcome range of the material properties obtained in printed parts. The values chosen, which are within a conservative estimation from the manufacturers’ technical information, are summarized in Table 1.

| Material | Tensile strength [MPa] | Flexural modulus [GPa] | Max. elongation to break [%] |
|----------|------------------------|------------------------|-----------------------------|
| ABS      | 27                     | 2.75                   | 23.25                       |

### 3. Results and Discussion

3.1. Design one

Starting with a mono-material approach, the first design iteration focuses on improving the level of adaptation to the user’s leg with the use of movable sections in the part. In this case, the part incorporates three joints to make it adaptable and easier to attach it to the human body. The new design one is depicted in figure 2 and it is intended to be printed in ABS.

With the new design geometry completed, the part is laid in a construction platform of a 3D printer to evaluate the production times and therefore the new cost level. The new design is suitable for being printed with all the four sections at once in a Prusa Mini, as it can be seen in figure 3. The part is designed to be homogeneous and considered to be fully dense.

Then, a Finite Element Analysis is undertaken to validate the expected performance while in use. The contour variables of the study are a force of 400 N, according to the maximum knee torque during human gait of an average subject, situated in centre of the third section and an embedment of the coupling joint and on the strap windows. The simulations do not consider clearance in the rotating joints. In the physical reality, the strap used to attach the shank support to the lower limb, if properly adjusted,
would ensure that there is contact in all joints. This simplification is considered appropriate as the objective of the simulation is to validate a mass reduction, not to produce a minimal optimisation. The results obtained are within acceptable thresholds of 22.66 N/mm² (compared to the maximum yield strength of 3D printed ABS that it is considered of 27 N/mm²) and 14.26 mm of maximum displacement for the maximum load expected. All this information is presented in Figure 3(b) and figure 4.

**Figure 2.** Design one (first re-design) of the lower-limb robotic exoskeleton support, focusing on achieving a geometry more adaptable to the user (a) Top view (b) Front view (c) Left isometric view.

**Figure 3.** (a) Design one (first re-design) of the lower-limb robotic exoskeleton support, laid on a 3D printing FDM platform for assessing the production times with Prusa Slicer. (b) Graphical summary of the contour variables applied for the FEA analysis.

**Figure 4.** FEA of design one (a) Tension state at the maximum load expected. (b) Displacement at the maximum load expected.
3.2. Design two

Based on the results obtained in the design one, several improvements are identified to be incorporated in a second iteration. Concerning the structural capacity of the part, the geometries in the joints are redesigned to be bigger, so they can resist higher loads when in service, and with higher clearance between sides, so to avoid collisions. Also, the overall thickness could be reduced to 60% infill while meeting the maximum load requirements.

Concerning the fit to the user’s body, it is decided to increase the number of sections to 7. Also, the most important feature incorporated was the addition of soft padding in each of those sections. Finally, the allocation for the strap was redesigned to a smoother shape. The new design is presented in Figure 5.

Figure 5. Design two (second re-design) of the lower-limb robotic exoskeleton support, only with padding but enabling full flat printing (a) Top view (b) Right isometric view (c) Left isometric view.

Regarding the manufacturability, the different sections of the shank can now be manufactured totally flat in the 3D printing surface, thus facilitating the production, and decreasing the expected costs. As proceeded in the previous case, a validation FEA is conducted to make sure that the obtained values are within the admissible thresholds. In this case, the structure (ABS) is considered to be fully dense while the padding zones (TPU) are considered to be manufactured in a honeycomb structure with a density of 60% to save material and to reduce the rigidity of the contact zones with the user’s legs. The results obtained are within acceptable thresholds of 19.04 N/mm² (compared to the maximum yield strength of 3D printed ABS that it is considered of 27 N/mm² by the manufacturer) and 10.61 mm of maximum displacement for the maximum load expected.

With the new design geometry completed, the part is laid again in a construction platform of a 3D printer to evaluate the production times and therefore the new cost. The main FEA results and the lay-out of the design two in the 3D printing platform are presented in figure 6.

Figure 6. Design two (a) Displacement at the maximum load expected (b) Lay-out on a 3D printing FDM platform for assessing the production times with Prusa Slicer.
3.3. Design three

In the third iteration of the design, the focus is on enhancing sensing functionalities in the part (printing patterns with the conductive material PE+Cu), while maintaining the structural and comfort material zones (ABS and TPU). As the 3D printer to be utilised has only two extrusion heads, it is introduced as a design restriction to have only two of the materials in the same slice. In this way, it would not be necessary to have a three extrusion-heads machine but only to stop the print to change the material feed when required. The printing position will again have to be flat in the 3D printer. The padding zones (TPU) will be printed on the top side (opposite to what is done in design two) and the structural (ABS) and circuitry (PE+Cu) will be printed starting from the platform. Also, the coupling with the exoskeleton requires a printing design to be reinstalled when set to the service position (see Figure 7(a)).

From the electronic connection point of view, a simple circuitry is designed to be incorporated in the part. The basic sensor unit is a Wheatstone bridge in the centre of one of the sections of the support (see Figure 7(b)) and the connections from the corners are diverted as it is presented both in Figures 7(a) and (b) to the coupling with the exoskeleton. Apart from these functionalities, design three also integrates further changes, namely: the number of independent sections is reduced to 5, and some more material is removed from the sides of each section. Several views of the third design are presented in figure 8.

![Diagram of design three](image)

**Figure 7.** Circuitry arrangement in design three to meet the manufacturability requirements via FDM

(a) Top view in the 3D printing flat position. (b) Schematics of the Load cell in a section and conductive circuitry connections between two different sections.

![Diagram of design three](image)

**Figure 8.** Design three (second re-design) of the lower-limb robotic exoskeleton support, which incorporates padding and sensing (a) In-side view (b) Top view in the 3D printing flat position.

As proceeded in the previous cases, a validation FEA is conducted to make sure that the obtained values are within the admissible thresholds. In this case, the structure (ABS) is considered to have a 60% density, while the padding zones (TPU) are considered to be the same as in design two. The results obtained are within acceptable thresholds of 15.01 N/mm² and 5.88 mm of maximum displacement for
the maximum load expected. With the new design geometry completed, the part is laid again in a construction platform of a 3D printer to evaluate the production times and therefore the new cost.

The main FEA results and the lay-out of the design two in the 3D printing platform are presented in figure 9.

![Figure 9. Design three (a) Displacement at the maximum load expected (b) Lay-out on a 3D printing FDM platform for assessing the production times with Prusa Slicer.](image)

### 3.4. Processing times and costs

With the different design iterations information, the manufacturing results are compared and reviewed in table 2. In this case, only the direct costs of AM production have been scrutinised, as the rationale is to compare the outcomes after changing only design features and not processing parameters.

|                  | Design Zero (original) | Design One (first re-design) | Design Two (second re-design) | Design Three (third re-design) |
|------------------|------------------------|-------------------------------|-------------------------------|--------------------------------|
| Material cost [€/g] | 0.044                  | 0.044                         | 0.044                         | 0.080                          | 0.080                          | 1.599                          |
| Filament used [g] | 125.50                 | 94.28                         | 40.80                         | 11.78                          | 80.32                          | 9.17                           | 3.25                          |
| Number of slices [ut] | 635                    | 250                           | 226                           | 462                            | 80.32                          | 9.17                           | 3.25                          |
| Number of joints [ut] | 0                      | 3                             | 6                             | 4                             | 4                              | 4                              | 4                             |
| Number of sections [ut] | 1                      | 4                             | 7                             | 5                             | 5                              | 5                              | 5                             |
| Manufacturing time [h:min] | 8.06                   | 7.12                          | 4.23                          | 8.16                           | 8.16                           | 8.16                           | 8.16                          |
| Cost of each material used in manuf. [€] | 5.52                   | 4.15                          | 1.80                          | 0.94                           | 3.53                           | 0.73                           | 5.20                          |
| Total cost of materials used in the manufacturing [€] | 5.52                   | 4.15                          | 2.74                          | 9.46                           |                                 |                                |                                |

Even though the original design (design zero) was intended to be manufactured via MJF and considering that the materials cost is quite different (and much higher) for that technology, for comparison matters, it is calculated the reference cost for it as if it were to be manufactured via FDM.

In this overview, Design one achieves a time reduction of 54 min (-15.3%) and a material’s cost reduction of 1.37 € (-24.8%) from the initial case (design zero). When introducing the changes of design two, times and costs are decreased 223 min (-45.9%) and 2.78 € (-50.4%) from the initial case. Design three does not achieve cost reductions, mainly because of the cost of the conductive materials. Still the production time (8h 16min) is almost equal to that of design zero and the material costs (9.46 €) are aligned with what it would have to be for a premium functional part.
4. Conclusions
Three new designs for the lower limb shank support of the ABLE Exoskeleton were developed and analysed. Based on the simulations, all the presented designs meet the structural requirements, and could be manufactured via multi-material FDM improving the printing conditions of the original design. Concerning the manufacturing parameters, design two yields the lowest manufacturing times and costs while incorporating soft padding for enhancing user comfort. Also, design three includes soft padding and sensing add-ons, and it is possible to be manufactured by means of multi-material AM with three different materials in a 3D printing machine equipped with only two extrusion heads. Nevertheless, the real comfort level should be assessed in live testing with end users and the 3D printed circuitry performance should be analysed in detail in further testing. Next steps will be the physical development of the samples and the analysis of their performance and comfort in real usage.

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References
[1] Senthilkumar V, Velmurugan C, Balasubramanian K R and Kumaran M 2020 Additive Manufacturing Applications for Metals and Composites, in chapter: Additive Manufacturing of Multi-Material and Composite Parts (Pennsylvania: IGI Global)
[2] Minguella-Canela J, Muguruza A, Lumbierres D R, Heredia F-J, Gimeno R, Guo P, Hamilton M, Shastri K and Webb S 2017 Comparison of production strategies and degree of postponement when incorporating additive manufacturing to product supply chains Procedia Manufacturing 13 pp 746-761
[3] Muguruza A, Bonada Bo J, Gómez A, Minguella-Canela J, Fernandes J, Ramos F, Xuriguera E, Varea A and Cirera A 2017 Development of a multi-material additive manufacturing process for electronic devices. Procedia Manufacturing 13 pp 746-753
[4] Schwartz J J and Boydston A J 2019 Multimaterial actinic spatial control 3D and 4D printing Nature Communications 10 p791
[5] Khatri B, Frey M, Raouf-Fahmy A, Scharla M-V and Hanemann T 2020 Development of a Multi-Material Stereolithography 3D Printing Device Micromachines 11 p 532
[6] Singh R, Kumar R, Farina I, Colangelo F, Feo L and Fraternali F 2019 Multi-Material Additive Manufacturing of Sustainable Innovative Materials and Structures Polymers 11 p 62
[7] Fenollosa F, Goma J R, Buj-Corral I, Tejo Otero A, Minguella-Canela J, Uceda R, Valls A and Ayats M 2019 Foreseeing new multi-material FFF-Additive Manufacturing concepts meeting mimicking requirements with living tissue Procedia Manufacturing 41 pp 1063-1070
[8] Vua I Q, Bassb L B, Williams C B and Dillard D A 2018 Characterizing the effect of print orientation on interface integrity of multimaterial jetting additive manufacturing Additive Manufacturing 22 pp 447-461
[9] Yadav D, Chhabra D, Garg R K, Ahlawat A and Phogat A 2020 Optimization of FDM 3D printing process parameters for multi-material using artificial neural network Materials Today: Proceedings 21 pp 1583–1591
[10] Garcia-Domínguez A, Claver-Gil J and Sebastián-Pérez M A 2018 Propuestas para la optimización de piezas para fabricación aditiva DYNA-Ing e Industria 94 (3) pp 293-300
[11] Zhang H, Nagel J K, Al-Qas A, Gibbons E and Lee J J-Y 2018 Additive Manufacturing with Bioinspired Sustainable Product Design: A Conceptual Model Procedia Manuf 26 pp 880-891
[12] Kaspar J, Bechtel S, Häfele T, Herter F, Schneberger J, Bähre D, Griebse J, Herrmann H-G, Vielhaber M 2019 Integrated Additive Product Development for Multi-Material Parts Procedia Manufacturing 33 pp 3-10
[13] Font-Llagunes J M, Lugris U, Clos D, Alonso F J and Cuadrado J 2020 Design, control, and pilot study of a lightweight and modular robotic exoskeleton for walking assistance after spinal cord injury Journal of Mechanisms and Robotics 12 (3) p 031008
[14] 3D Hubs Knowledge Base 2021 Material Considerations PLA vs. ABS (3D HUBS B.V.) (https://www.3dhubs.com/knowledge-base/pla-vs-abs-whats-difference) accessed 19 January 2021