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Additively Manufactured Textiles and parametric modelling by generative algorithms in orthopaedic applications

Abstract

Purpose - The purpose of this work is to implement a new process aimed at the design and production of orthopaedic devices fully manufacturable by Additive Manufacturing. In this context, the use of generative algorithms for parametric modelling of Additively Manufactured Textiles has been also investigated and new modelling solutions have been proposed.

Design/methodology/approach - A new method for the design of customised elbow orthoses has been implemented. In particular, to better customise the elbow orthosis, a generative algorithm for parametric modelling and creation of a flexible structure, typical of an Additively Manufactured Textile, has been developed.

Findings – To test the developed modelling algorithm, a case study based on the design and production of an elbow orthosis made by Selective Laser Sintering was investigated. Obtained results have demonstrated that the implemented algorithm overcomes many drawbacks typical of the traditional CAD modelling approaches. The parametric CAD model of the orthosis obtained through the new approach is characterized by a flexible structure with no deformations or mismatches and has been effectively used to produce the prototype through AM technologies.

Originality/value - Obtained results present innovative elements of originality in the CAD modelling sector, which can contribute to solving problems related to modelling for Additive Manufacturing in different application fields.

Keywords: Additive Manufacturing, Additively Manufactured Textiles, Generative Algorithms, Elbow orthosis, CAD modelling

1. Introduction

In recent years, there has been a significant improvement in Additive Manufacturing (AM) technology [Bikas *et al.*, 2015] and many researchers have explored its application in different fields, like engineering and medicine [Javaid and Haleem, 2017, Singh and Ramakrishna, 2017].

In this last field, AM represents a very flexible and effective solution that, especially for orthopaedic applications, allows designing customised devices with different shape, size and functionality. AM technology, in fact, allows fabricating very complex shaped prototypes with a variety of materials [Singh *et al.*, 2017, Eyers and Potter, 2017]. These features of AM technology can be exploited in the orthopaedic field to make customised prostheses and orthoses.

Orthoses are external medical devices used in the treatment of some pathologies to correct functional diseases that, unlike the prostheses, do not replace any missing anatomic parts [Cerniglia *et al.*, 2012, Ingrassia *et al.*, 2017]. Usually, these devices limit the relative movements in a joint affected, for example, by trauma, arthrosis, ligament tears or that has been subjected to surgery. For patients with disabilities that cause functional limitations, orthoses are also employed to apply forces on the body for biomechanical needs so to help patients to move the diseased limbs, e.g. during walking [Ingrassia *et al.*, 2018].

Similar to other orthopaedic devices, orthoses can be prefabricated or customised. The prefabricated ones are less expensive and readily available on the market. Customised orthoses, instead, adapt better to the patient's body than the prefabricated ones and can ensure higher performances [Chen *et al.*, 2016].

Customised orthoses usually have more complex shapes than the prefabricated ones and, for this reason, AM represents the most suitable technology to produce them. For this kind of applications, AM allows creating complex shapes in a short time, with lower costs than manual fabrication [Huang *et al.*, 2013, Gao *et al.*, 2015] and very good surface finish, if the process parameters are suitably chosen [Ingrassia *et al.*, 2017].

In the literature, there are different works related to wrist [Paterson *et al.*, 2014], foot [Fantini *et al.*, 2017] and hip orthoses [Munhoz *et al.*, 2016], but there is not much information about customised elbow orthoses completely manufactured through AM. For this reason, this work focuses on the design of a new customised elbow orthosis. For this purpose, a new modelling approach based on generative algorithms and on the use of the Additively Manufactured Textiles (AMT) technology [Lussenburg *et al.*, 2014] has been proposed.

The present work was divided into four main steps. The first step consists of the 3D acquisition and CAD modelling of the patient's arm. In the second step, the structural parts of the customised orthosis were modelled. During the third step, the non-structural parts were designed using a flexible structure in order to better customise the device. The CAD modelling of these parts was achieved using conventional software and generative algorithms implemented in an *ad hoc* manner. In the fourth step, the prototype of the orthosis was manufactured using a Selective Laser Sintering (SLS) process.

2. Methods

The main requirements in the design of customised orthoses are functionality, ergonomics and aesthetics. In order to design a highly functional, customised and ergonomic device, the real shape of the patient's arm was reconstructed through a reverse engineering based approach.

2.1 CAD modelling of elbow orthosis

The first step comprised the 3D acquisition process and the subsequent CAD modelling of the patient's arm.

Considering that it is quite difficult to keep stable the position of the patient's arm during the whole acquisition process, it was decided to reproduce a copy of it using a plaster cast that was subsequently digitally acquired through the ZScanner 800 by ZCorporation. In this way, a very accurate CAD model of the arm was obtained (Figure 1).

Different CAD models of the arm were created to reproduce three different positions by varying the value of the elbow flexion angle, **in order to be able to observe the real deformations of the arm, and in particular of the elbow area, during extension and flexion movements.**

After the CAD models of the arm were created, the structural parts of the orthosis were modelled.

In order to meet the ergonomics and wearability requirements, the frame of the structural parts of the orthosis were created by applying a 2 mm offset to the reconstructed surfaces of the arm. In this way, a small clearance between the arm and the orthosis was ensured. **This value of offset is usually adopted to realize customised orthoses.**

Moreover, two longitudinal openings were made along the internal side of the orthosis so as to facilitate its wearing and to increase its fitness.

The relative rotation between the arm and the forearm during the extension and flexion movements was ensured by using a hinge mechanism.

After the structural parts of the orthosis were modelled, they were assembled into the final CAD model of the orthosis using the SolidWorks software (Figure 2).

2.2 CAD modelling of AMT flexible structures

Regarding the aesthetic requirement, it was decided to use AMT technology to create some flexible structures [Bloomfield and Borstrock, 2018] that, in addition to making the orthosis more aesthetically pleasing, allowed a greater adaptability of the orthosis to the arm during movements.

Of course, AMT technology is still an evolving field and many research activities are being developed to improve the 3D modelling of these structures. Some authors have mainly concentrated on the development of efficient modelling strategies for the creation of 3D CAD models of AM textiles [Bingham *et al.*, 2007]. Other authors have focused on the mechanical characterization of the AM textiles and their possible use in complex structures [Johnson *et al.*, 2011].

Although there are many reasons for the wide spreading of these novel complex structures, the lack of efficient approaches for their 3D modelling limits their applications.

There are indeed some issues regarding the 3D modelling of complex AM textiles using conventional software [Melnikova *et al.*, 2014, Gürcüm *et al.*, 2018].

In fact, even if it is possible to model planar or simple net-shape AMT structures, modelling of more complex net-shape AMT models can be very problematic and can give incorrect connection among the linking elements as shown in Figure 3 [Bingham and Hague, 2013].

Another drawback in the CAD modelling of AMT structures with conventional software is the possible deformation of the linking elements in case of irregular surfaces (Figure 4) [Bingham *et al.* 2007].

Also, the 3D CAD modelling of quite simple net-shape AMT structures can have drawbacks. In many cases, in addition to maintaining the connecting elements' separation (to ensure their relative movement), it is necessary to correctly map these elements onto the surface, also according to the surface normals (Figure 5), and this could be difficult to do using traditional CAD software.

Finally, many difficulties can arise when trying to combine the linking elements in AMT structures which have very complex shapes. In these cases, the requirement is not the creation of a simple array of connecting elements, but the automated creation of a uniformly distributed series of several elements that must be accurately mapped onto complex (double-curved) surfaces.

In this work, AMT structures were used to provide the non-structural parts of a customised elbow orthosis. These AMT parts were modelled using two different approaches: in the first, a standard CAD software was used; in the second, a generative algorithm [Krish, 2011, Khabazi, 2010] was used.

This second approach was developed to overcome the problems encountered during the CAD modelling of the AMT structures with conventional software.

2.2.1 CAD modelling of flexible structure by commercial software

In the first method, the flexible structures of the orthosis were modelled using the commercial software Rhinoceros. In particular, the Paneling Tools plug-in was used. This plug-in allows the panelization of surfaces and polysurfaces by creating patterns.

Initially, it was decided to test the plug-in by modelling a flexible structure consisting of a network of rings. The 3D basic module of the network is shown in Figure 6 (left).

To create the panelization of the basic module on the surface, the "ptPanel3DCustom" function was used. This function creates several copies of the basic module at predefined points of a grid (Figure 6 – right).

Figure 7 shows the structure created and adapted to the surface of a part of the orthosis.

However, the modelling of a flexible structure using this approach showed some drawbacks mainly due to the deformations of the rings of the basic module after the panelization on the surface. As shown in Figure 8, in many cases, wide variations of the diameter of the rings were detected.

In some cases, a diameter reduction of around 40-50% was calculated. Moreover, in addition to these deformations, there were also misalignments among the rings of different modules (Figure 9).

The above-mentioned modelling problems, besides representing a drawback from the aesthetic point of view, could generate some problems during the manufacturing phase and could also affect the strength of the structure.

2.2.2 CAD modelling flexible structure by generative algorithm

To overcome the drawbacks of the modelling of the flexible structure with Rhinoceros, a new modelling approach based on generative algorithms has been proposed. In particular, the new algorithm was developed using Grasshopper, a graphical algorithm editor that can be used as a plug-in of Rhinoceros. The Grasshopper development environment is based on function blocks (Figure 10) that can be arranged and linked to setup different features and algorithms.

The developed algorithm allows the creation of flexible structures made of different basic modules (for example rings) that are perfectly mapped onto any surface with no deformation and/or misalignment.

The algorithm consists of three main features that allow the:

- 3D parametric modelling of a basic module;
- definition of a grid of points on a surface;
- paneling of the basic module on the surface.

To compare the results obtainable with the new approach, the developed algorithm was tested by modelling the same flexible structure previously created with the commercial software.

Initially, the basic module was modelled. In particular, a group of three connected rings (Figure 11) was modelled.

To obtain a very robust 3D model of the basic module, the relative positions of the three rings were parameterized depending on the main input parameters, like the diameters of the toroid and of the transversal circular section. In this way, if the user needs to change the main dimensions of the rings, they always remain connected to each other with no problems of mismatch or geometry interference.

The grids of points needed to map the basic module onto the surfaces of the orthosis were defined through the "Surface Distance" function, which allows the creation of grids of points on a surface by dividing it along two parameterization directions (U and V). To ensure the correct interconnection of the rings when the diameters are changed by users, the distances between the points along U and V directions were parameterized according to the diameters of the toroid and of the transversal circular section.

To panelize the basic module on the surfaces, the "Orient to Grid" function was used, which allows the user to orient and map an object relative to a grid on a surface (Figure 12).

The developed modelling algorithm allowed obtaining a flexible structure perfectly adapted to the surface of the orthosis and linked to its structural parts.

Figure 13 shows some details of the flexible structure modelled through the new algorithm. It can be seen that there is no deformation, misalignment or interference among the rings.

Figure 14 shows two AMT structures modelled with the conventional software and the new modelling approach. It can be seen the high quality of the models created with the new algorithm.

The final CAD model of the orthosis made through the new algorithm is shown in Figure 15.

3. Prototype manufacturing by Additive Manufacturing

After the CAD model of the designed orthosis was completed, a prototype of the device was produced in PA 2200 using an SLS 3D printer. PA 2200 is a fine white powder based on

polyamide, used for the manufacture of products with high surface quality and very good thermal and mechanical characteristics [Singh *et al.*, 2017, Pitarresi *et al.*, 2015]. Specifically, the EOS FORMIGA P100 printer (Figure 16) was used, which allows the production of small series and customised products with complex geometries.

Figures 17 and 18 show some images of the prototype from which it is possible to observe the good surface finish obtained with this AM technology.

4. Conclusions

In this work, a new method for the design of customised orthopaedic devices completely manufacturable by AM is presented. The newly developed approach was tested by designing a customised elbow orthosis.

A classical reverse engineering approach was used to digitalize the patient's arm to custom the orthosis.

To enhance the aesthetic appeal, it was decided to use the Additively Manufactured Textiles technology. This also allowed the creation of some flexible structures to better customise the elbow orthosis and, at the same time, to improve the wearability of the orthosis.

Initially, a commercial CAD software was used to model the structural parts of the orthosis and its flexible structures. The conventional modelling approach has shown some drawbacks mainly due to the deformations and misalignments of the AMT structures. To overcome these problems, a new modelling approach based on generative algorithms was developed.

The obtained results have shown that this generative algorithm is a very good modelling tool that allows the user to create very complex AMT structures with no deformation and/or misalignment.

The CAD model of the orthosis created with the new tool was subsequently used to produce a prototype of the elbow orthosis by means of the SLS technology. A fully functional prototype having a good surface finish was obtained.

The developed procedure could be used effectively for the designing of other kinds of customised devices for orthopaedic applications.

References

- Bikas, H., Stavropoulos, P., Chrysosouris, G., (2015) "Additive manufacturing methods and modelling approaches: a critical review", *Int J Adv Manuf Technol* DOI 10.1007/s00170-015-7576-2.
- Bingham, G.A., Hague, R.J.M., (2013), "Efficient three dimensional modelling of additive manufactured textiles", *Rapid Prototyping Journal*, 19 (4), 14pp.
- Bingham, G.A., Hague, R.J.M., Tuck, C.J., Long, A.C., Crookston, J.J. and Sherburn, M.N. (2007), "Rapid Manufactured Textiles" *International Journal of Computer Integrated Manufacture*, Volume 20, Issue 1, pp96-105
- Bloomfield, M., Borstrock, S., (2018), "Modeclix. The additively manufactured adaptable textile", *Materials Today Communications* 16 (2018) 212–216.
- Cerniglia, D., Ingrassia, T., D'Acquisto, L., Saporito, M., Tumino, D., (2012), "Contact between the components of a knee prosthesis: Numerical and experimental study", *Frattura ed Integrità Strutturale* 6, 56-68 DOI: 10.3221/IGF-ESIS.22.07.
- Chen, R.K., Jin, Y., Wensman, J., Shih, A., (2016), "Additive manufacturing of custom orthoses and prostheses—A review", *Additive Manufacturing* 12 77–89
- Eyers, D.R., Potter, A.T., (2017), "Industrial Additive Manufacturing: A manufacturing systems perspective", *Computers in Industry* 92 208–218.
- Fantini M, De Crescenzo F, Brognara L, Baldini N, (2017), "Design and Rapid Manufacturing of a customized foot orthosis: a first methodological study", *Springer International Publishing AG Advances on Mechanics, Design Engineering and Manufacturing, Lecture Notes in Mechanical Engineering*, DOI 10.1007/978-3-319-45781-9_46.
- Gao, W., Zhang, Y., Ramanujan, D., Ramanian, K., Chen, Y., Williams, C.B., Wang, C.C.L., Shin, Y.C., Zhang, S., Zavattieri, P.D., (2015), "The status, challenges, and future of additive manufacturing in engineering", *Computer-Aided Design* 69 65–89.
- Gürcüm, B.H., Börklü, H.R., Sezer, K. and Eren, O., (2018), "Implementing 3D Printed Structures as the Newest Textile Form", *J Fashion Technol Textile Eng*, S4 DOI: 10.4172/2329-9568.S4-019.
- Huang, S.H., Liu, P., Mokasdar, A., Hou, L., (2013), "Additive manufacturing and its societal impact: a literature review", *Int J Adv Manuf Technol* 67:1191–1203 DOI 10.1007/s00170-012-4558-5.
- Ingrassia, T., Nigrelli, V., Ricotta, V., Tartamella, C., (2017), "Process parameters influence in additive manufacturing", *Springer International Publishing AG Advances on Mechanics, Design Engineering and Manufacturing, Lecture Notes in Mechanical Engineering*, DOI 10.1007/978-3-319-45781-9_27.

- Ingrassia, T., Nalbone, L., Nigrelli, V., Ricotta, V., Pisciotto, D., (2018), "Biomechanical analysis of the humeral tray positioning in reverse shoulder arthroplasty design", International Journal on Interactive Design and Manufacturing, Volume 12, Issue 2, Pages 651-661.
- Ingrassia, T., Nalbone, L., Nigrelli, V., Pisciotto, D., Ricotta, V., (2017), "Influence of the metaphysis positioning in a new reverse shoulder prosthesis", Springer International Publishing AG Advances on Mechanics, Design Engineering and Manufacturing, Lecture Notes in Mechanical Engineering, DOI 10.1007/978-3-319-45781-9_47.
- Javaid, M., Haleem, A., (2017), "Additive manufacturing applications in medical cases: A review literature based", Alexandria Journal of Medicine.
- Johnson, A.J., Bingham, G.A. and Wimpenny, D., (2011), "Additive Manufactured Textiles for High - Performance Stab resistant Applications" – 12th RDPM conference, Lancaster, England.
- Krish, S., (2011), "A practical generative design method", Journal Computer-Aided Design Volume 43 Issue 1, Pages 88-100 .
- Lussenburg, K., Van der Velden, N., Doubrovski, Z., Geraedts, J., Karana, E., (2014), "Designing with 3D Printed Textiles", Proceedings of 5th International Conference on Additive Technologies, pp 74-81.
- Melnikova, R., Ehrmann, A., Finsterbusch, K., (2014), "3D printing of textile-based structures by Fused Deposition Modelling (FDM) with different polymer materials", IOP Conference Series Materials Science and Engineering 62(1):012018 DOI: 10.1088/1757-899X/62/1/012018.
- Munhoz, R., Da Costa Moraes, C.A., Tanaka, H., Kunkel, M.E., (2016), "A digital approach for design and fabrication by rapid prototyping of orthosis for developmental dysplasia of the hip", Research on Biomedical Engineering, Volume 32, Number 1, p. 63-73, DOI 10.1590/2446-4740.00316.
- Paterson, A.M., Donnison, E., Bibb, R.J., Campbell, R.I., (2014), "Computer-aided design to support fabrication of wrist splints using 3D printing: A feasibility study", Hand Therapy 19(4):102-113 DOI 10.1177/1758998314544802.
- Pitarresi G., Tumino D., Mancuso A. (2015), "Thermo-Mechanical Behaviour of Flax-Fibre Reinforced Epoxy Laminates for Industrial Applications", MATERIALS, vol. 8, p. 7371-7388, ISSN: 1996-1944, doi: 10.3390/ma8115384.
- Singh, S., Ramakrishna, S., (2017), "Biomedical applications of additive manufacturing: Present and future", Current Opinion in Biomedical Engineering, 2:105–115.
- Singh, S., Ramakrishna, S., Singh, R., (2017), "Material issues in additive manufacturing: A review", Journal of Manufacturing Processes 25 185–200.
- ZUBIN KHABAZI, (2010), "ALGORITMI GENERATIVI con GRASSHOPPER".

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CAD Model of the arm

240x152mm (96 x 96 DPI)

Assembled CAD model of the designed elbow orthosis

149x64mm (96 x 96 DPI)

Wrong connection of the linking elements in a hemispherical AMT structure

84x68mm (96 x 96 DPI)

Deformation of the linking elements

157x74mm (96 x 96 DPI)

Example of normal direction and mapping of a chain of rings

187x44mm (96 x 96 DPI)

Basic module to repeat (Left) - Grid of points (Right)

288x79mm (96 x 96 DPI)

CAD model of the flexible structure by Rhinoceros

269x146mm (96 x 96 DPI)

Deformations of the rings of the flexible structure using a commercial software

289x80mm (96 x 96 DPI)

Misalignments of the rings of the flexible structure

143x79mm (96 x 96 DPI)

Example of function blocks diagram in Grasshopper

342x135mm (96 x 96 DPI)

Basic module (on the left) and block diagram of the 3D parametric modelling function (on the right)

172x87mm (96 x 96 DPI)

Example of the flexible structure modelled by the algorithm

305x150mm (96 x 96 DPI)

Details of the flexible structure
200x100mm (96 x 96 DPI)

Generative Algorithm Conventional software

Comparison between the results obtained with the two modelling approaches

206x120mm (96 x 96 DPI)

CAD model of the elbow orthosis
154x51mm (96 x 96 DPI)

FORMIGA P100 3D printer

60x88mm (96 x 96 DPI)

Final prototype

266x99mm (150 x 150 DPI)

Final prototype worn by the patient

102x99mm (150 x 150 DPI)