Automatic CAD Modeling of Ventilation Holes for 3D Printed Wrist Orthoses

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Abstract. The present paper presents the study of a semi-automatic CAD technique for the generation of ventilation holes on ABS AM-manufactured arm orthoses. A lighter device, good air and water transpiration and an increased patient's comfort are the main advantages achievable by introducing openings on plastic casts. The proposed procedure relies on the adaptation of a reference pattern of holes, obtained integrating both structural and functional aspects, to each patient's cast. The adaptation procedure maps the original pattern, respecting its proportions, on each target orthosis, thanks to a set of reference points automatically extracted. The generation of holes is performed relying on an advanced CAD environment (i.e. Siemens NX), where a series of CAD modeling operations, based on the data extracted by the mapping algorithm, have been studied and tested. The whole procedure has been tested on 5 orthoses to validate its efficacy.

Keywords: CAD, Orthosis Modeling, Cast Modeling, Personalized Medicine.
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1 INTRODUCTION

The recent growth in performances and availability of Additive Manufacturing (AM) and Reverse Engineering (RE) technologies [2,8] has fostered the development of innovative medical therapies and brought groundbreaking improvements to traditional practices. In the last 10 years, AM and RE have enhanced the quality of treatment, helped establish highest safety margins for patients and played a fundamental role in the development of cutting-edge medical practices. Personalized medicine, specifically, was revolutionized by these technologies, as they can be effectively applied to the medical field to: i) acquire information on patient anatomy; ii) design CAD models based on specific anatomical reference; iii) manufacture parts with sufficient accuracy for several medical applications. Ultimately, AM&RE have empowered medics with the possibility of tailoring each treatment to the specific patient's needs. Modeling and fabrication of specific tools, the development of training medical simulators for complex surgical operations, and the production of medical implants modelled directly on the anatomy of the patients are some examples of possible applications.

In this framework, one of the most studied thread of research is the development of 3D printed casts, as an alternative to the traditional plaster of Paris, to be used to immobilize injured body regions. Specifically, most of the literature deals with the development of algorithms and CAD-based procedures to design forearm casts to treat wrist fractures [7,4,10], which are among the most common injuries.

Lightness, good ventilation to skin and muscles, an improved thermal comfort, and water resistance are the advantages that stand out comparing plastic casts to traditional ones. In order to assure these strengths, however, it is essential to design an orthosis with openings on the shell. Indeed, a well-designed pattern of holes allows for a well-distributed water and airflow to the arm, hence contributing to the wettability of the device. Moreover, a significant weight reduction is possible only removing all the unnecessary material. Obviously, the integrity and safety of the device must not be prejudiced in any way. As a result, the development of a reliable procedure to generate a pattern respecting both medical and structural constraints is essential to pursue the general goal of designing an effective 3D printed cast.

Different techniques to generate the openings have been proposed in the literature:

- Random or regular repetition of a "seed" feature; several features can be used as template to be repeated - e.g. cylindrical holes or spheres [7].
- Surface patterns defined on the original surface geometry. In this case, the general shape of the pattern depends on the considered surface. Occasionally, it is possible to integrate geometrical constraints or functional requirements to produce more effective patterns. As an example, Zhang et al. present in [10] a method based on a Hollowed Voronoi Tessellation to compute a pattern that optimizes the thermal flow to the injured arm.
- Topology Optimization (TO) approaches; they usually deal with the problem from a purely structural perspective: various algorithms can be used to determine the pattern offering the best static or dynamic response to the loads faced by the orthosis. As a result, material is removed from the areas that less contribute to the mechanical performance of the orthosis (e.g. [1]).

While the generation of a purely geometry-based pattern of regular shapes can be considered as the most straightforward approach (several CAD systems offer dedicated tools to obtain a pattern of features), the generation of a tailored pattern, i.e. based on functional requirements, can guarantee more benefits to the patient. On the other hand, both surface pattern-based and TO methods entail severe difficulties to be carried out effectively. In fact, using such approaches, each case should be analyzed and simulated individually by means of finite element analysis (FEA) or other numerical methods that are time-consuming and difficult to automatize. This is exacerbated by the necessity of imposing manufacturing/medical/structural constraints each time an analysis is performed. As a result, the effectiveness of patient-specific approaches would be weakened by a series of conservative hypotheses that must be imposed to assure appropriate orthosis strength, or more in general compliance to functional requirements. The authors of this work have already marginally addressed the problem of defining a valid and effective procedure for the generation of holes on custom orthoses [3]. This study proposes a first TO based solution to produce a valid hollowing pattern that, however, is limited in efficacy since it relies on manual operations to be applied on each newly generated orthosis.

To overcome the above-mentioned drawbacks, this paper proposes the design of a new reference pattern obtained by integrating various aspects (mechanical strength, medical guidelines [6], ventilation optimization, comfort and replicability) and on its adaptation to each specific anatomy without the need of performing numerical analyses for each single patient. To this purpose, a customized automatic algorithm to adapt the reference pattern on the surface of each cast is also proposed. The starting point of the developed procedure consists of orthoses designed following the procedure proposed by the authors in [3]. However, the method has general validity for all orthoses consisting of two halves, lying on the back and frontal part of the hand-wrist-arm district, on which reference points can be extracted as described below in the *adaptation phase*.

2 REFERENCE PATTERN

2.1 Definition of the reference pattern: medical and structural considerations

The reference pattern has been determined through a process of synthesis of various aspects, discussed in the following. The pattern should be clinically sound: it should maximize the quality of the treatment, patient's comfort and reduce typical cast-related problems – e.g. rashes and compartment syndrome. Moreover, areas sensitive to rubbing and compression should be left uncovered. Regions that require particular attention (see Figure 1) are:

i) styloid process of the ulna – this area should be left open to prevent cutaneous lesions and severe discomfort;

ii) the internal wrist area – this area needs to be protected the most in case of wrist fractures;

iii) center line of both internal and external halves - a surface portion along the centerline that should be left solid to preserve a continuous ribbing structure.

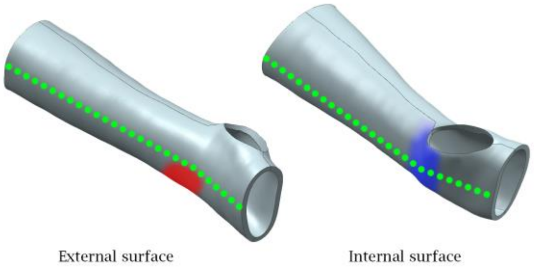


Figure 1: Relevant arm areas. Red – styloid process of the ulna. Blue – Internal wrist area. Green – center line.

The holes should evenly cover the surface of the cast to allow proper ventilation, possibility to wash and to scratch the arm, which are perceived as primary concerns by end users. Therefore, a minimum holes area of ~1cm^2 should be granted. Moreover, the pattern should guarantee the integrity of the device and its compliance w.r.t. the loads induced by regular use. Other structural aspects that need to be considered are the preservation of a minimum thickness in every direction and the removal of stress concentrations points, which results in the generation of a smooth set of curves for the generation of holes, characterized by large fillet radiuses. Since in the present work the final orthosis will be 3D printed by using a Fused Deposition Modeling (FDM) process, the minimum thickness is stated equal to 4 mm. Finally, an additional functional aspect needs to be considered in case the orthoses are generated using the approach provided in [3]. In fact, three zip ties are applied near the knuckles, the elbow, and in a central region, to keep the two halves of the orthosis together. Such areas need to be left untouched by the hole pattern in order to avoid possible complications. The integration of thermal comfort analyses as a parameter in the definition of the reference pattern is another requirement that could be considered; however, in this work, such aspect has not been included yet.

As previously mentioned, TO can help in the identification of a general pattern maximizing the structural response of the device. In this study, a TO performed within Solidthinking Inspire has been used to obtain a starting solution for the generation of the reference pattern on an orthosis modeled on a 50^{th} percentile 10-years-old male arm (Total Arm length of 643mm [11]). Load conditions used for the TO are in Figure 2.

Due to the unpredictability of possible external and accidental loads, this study takes into consideration only the loads that can be traced back to the patient itself. Considering the wrist joint, four movements can be identified (see Figure 3): flexion-extension and radial-ulnar deviations. Following the approach proposed in [4], literature values have been used to estimate maximum torques that healthy people usually produce. Four different load conditions, one for each wrist movement, were considered. Wrist torques, due to wrist joint movements (depicted in Figure 3) have been expressed as forces applied on the front face of the orthosis (different areas depending on the direction – see Figure 2 where a value of 0.1m has been used as distance).

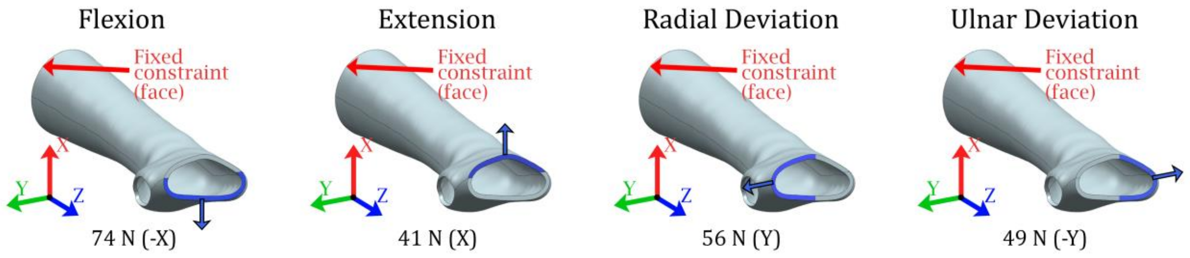


Figure 2: Loads configuration used in the study.

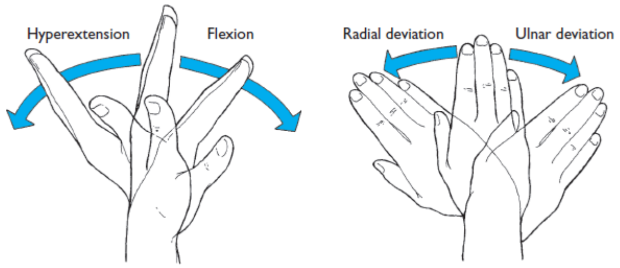


Figure 3: Wrist joint movements [6].

In all cases, the orthosis is constrained at the elbow with a fixed constraint essentially reproducing a clamped beam condition. All the choices were made trying to use a conservative approach: both the absence of the arm and the chosen constraints contribute to the definition of a condition more severe than the real one. The TO is performed with the two halves of the orthoses joined in the area where the zip ties are applied to reproduce the closing system; face-to-face contacts are considered on the other surfaces. The material used is ABS plastic. The analysis was carried out maximizing the stiffness/mass ratio of the object. The result obtained during this preliminary analysis is in Figure 4. The obtained pattern, although valid from a structural point of view, was subsequently manually edited to meet all the requirements discussed before. The result is visible in Figure 5. Since the reference pattern was obtained by adding material w.r.t. the model in Figure

4, its weight is obviously greater than the optimized one. On the other hand, the designed pattern assures full compliance with all the aspects imposed by the application.

Several differences can be observed comparing Figure 4 and Figure 5: evidently, the TO pattern has been heavily altered in order to consider all the previously described aspects (medical constraints, fabrication constraints, minimal level of regularity to assure its repeatability with an automatic procedure). The deviation from the orthosis model of Figure 4 is also justified by the philosophy followed in this study: the TO pattern is obtained studying a single, although representative, anatomy; its original efficacy and compliance to the structural needs of the device would still be hindered when applied on a different anatomy. As a result, the TO pattern of Figure 4 must be considered only as a general indication, i.e. a starting point.

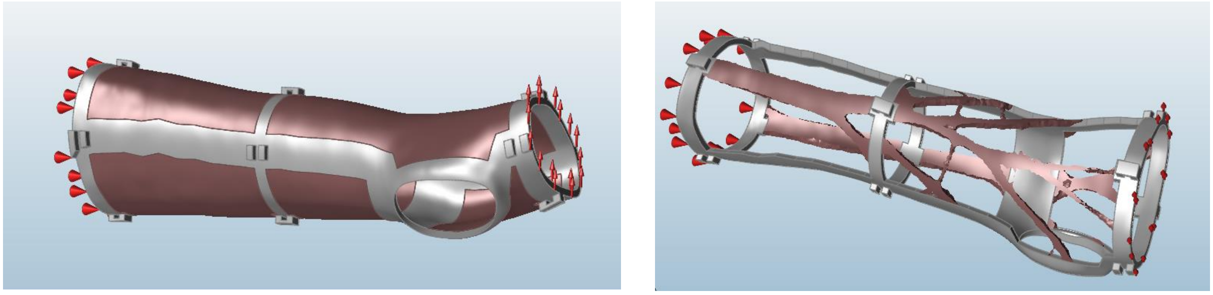


Figure 4: Topology Optimization procedure performed in Inspire Solidthinking; a) definition of the design space regions; b) final result obtained in one load configuration.

Figure 5: Final configuration of the reference pattern to be validated. The pattern is the result of manual modeling operations performed using the TO model as reference.

2.2 FE analyses

The reference pattern depicted in Figure 5 has been manually redrawn on two orthoses (named "Large" and "Small"), representative of the entire size spectrum of anatomies considered in this study. The Large orthosis is characterized by a length of ~400mm and a maximum diameter at the elbow region of ~90mm corresponding to a 95th percentile 14-years-old male arm. The Small orthosis is ~195mm long and has a maximum diameter of ~65mm, taking the dimensions of a 5th percentile 5-years-old male arm as general reference [11]. On the two newly designed orthoses, FE simulations were carried out to test the mechanical validity of the generated geometries on both sides of the spectrum.

The results obtained are summarized in Table 1; the worst condition (Flexion load – Small orthosis) is depicted in Figure 6: a maximum von Mises stress value of 25.3 MPa is observed. Such value is compatible with the yield stress of 3D printed ABS (26 MPa along ZX axis of the FDM printer [12]). Displacement values are tolerable even in worst cases, especially considering that the simulated configuration is far from the real one on this specific aspect.

Load Configuration	***Large Orthosis***		***Small Orthosis***	
	Stress (Von Mises) [MPa]	*Displacement [mm]*	*Stress (Von Mises) [MPa]*	*Displacement [mm]*
Flexion	20.2	4.4	25.3	4.3
Radial Deviation	11.7	2.0	13.9	2.2
Ulnar Deviation	8.8	2.1	13.9	2.2
Extensions	7.5	1.6	11.6	1.8

Table 1: Validation of the pattern - FE analyses results.

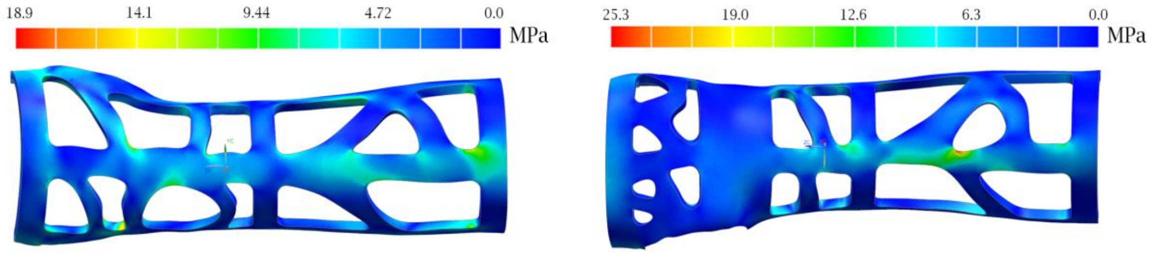


Figure 6: FE analysis (von Mises stress map) results for the Small orthosis, under the Flexion load (internal and external surface).

3 ADAPTATION STRATEGY

Once the structural and functional aspects of the ventilation pattern are outlined and its strength is tested, a strategy to automatically adapt it on any new orthosis has been developed.

After a preliminary phase of simplification of the reference orthosis holes pattern (see Section 3.1), the adaptation strategy consists of two phases: a) definition of a set of key points used to guide the creation of the holes, extracted from the scanning of the patient's arm; b) perforation of the CAD model using curves generated from the obtained key points. Both tasks (a) and (b) are completely automatized.

3.1 Pattern simplification

Before proceeding with the extraction of key points used to define the shape of the holes on a new orthosis, a simplification process of the hole pattern on the reference orthosis is required. The main aim of such a process is the generation of a simplified pattern that can be automatically scalable and replicable on each new case by modeling 3D polygons. Specifically, as visually described in Figure 7, the structure in Figure 5 is manually divided into 12 main zones (6 dorsal and 6 palmar). Subsequently, each zone undergoes a process of stylization of the holes, which are described by polygons rather that curves. The vertices of such polygons (see Figure 7) are used as points to be automatically mapped to each individual case, as described in the next paragraph.

The simplified pattern of Figure 7 is the result of a series of attempts to identify a pattern based on the minimum number of highly reliable key points. In fact, the whole procedure needs to minimize error occurrences in the identification of key points on different anatomies. As a result, the simplification of the geometry is a tradeoff between the model described in Figure 5 and the need of a model less error-prone in term of model reconstruction. As previously stated, the need for an optimized structure is supplanted by safety and repeatability needs.

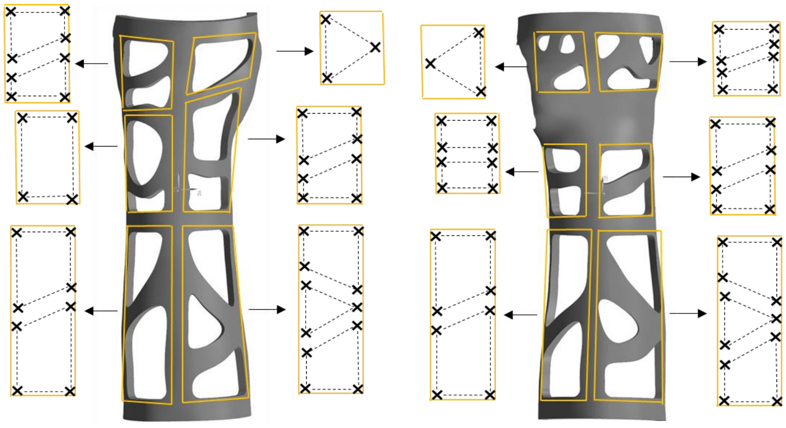


Figure 7: Simplification and stylization of the obtained pattern to ease the adaptation process. Points to be mapped on a new orthosis are cross-marked.

3.2 Key points extraction

As already mentioned, the development of an automatic procedure is supported by the availability of a number of repeatable references in the designed orthosis. In particular, the position of the scanned arm and the geometric features created are required to be kept constant. Due to the conceived architecture, the main direction of the arm has to be approximately aligned with the Z axis, while the Y axis is required to be oriented with the upper side of the hand (see Figure 8).

In this work the above mentioned references are known since the extracted features are automatically computed through the software presented in [3] and summarized below.

The software essentially performs the following operations; first, it automatically recognizes the main directions (*d1* and *d2*) of the scanned arm by means of the Douglas–Peucker algorithm [5] (see Figure 8(a) for a visual example). Then, following the direction of the hand (*d2* in Figure 8(a)), it retrieves a number of sections of the arm (named "*internal profiles*"). The sampling density for these profiles has been set to 4 mm, in the attempt to optimize both the required accuracy as well as the smoothness of the procedure, and the accuracy of the generated surface (Figure 8(b)). Internal sections are then offset (defining the so-called "*external profiles*") of 4 mm to create the thickness of the orthosis (Figure 8(c)). As already mentioned, the chosen value is a good compromise to allow both a good strength of the orthosis and a reasonable time for the subsequent manufacturing process. Finally, the profiles to make the housings for the zip-ties closing system are extracted, with an input from the user regarding their positioning (Figure 8(c)).

Subsequently, three lines (Figure 8(d)) are automatically extracted and used in the CAD modelling procedure to delimit the two main shells and to make the zip-ties housings. In particular, the points characterized by maximum and minimum values along the Y direction are selected from each internal section to define two lines (*Line1* and *Line2* in the Figure 4(d)). Another line, *Line3*, defines the position of the dorsal and palmar zip-ties housings and is calculated as passing through the point of each section with a maximum value along the X direction.

In addition to the references provided to define the positions of the zip-ties housings and the opening lines of the orthosis, two additional planes parallel to the main sectioning direction (Figure

8(a)) are extracted at a distance of +/- 10 mm from the intersection point between *d1* and *d2* (red point in Figure 8(a)). These planes are used to delimit the area of the wrist to be preserved on the palmar half of the orthosis as this area is the most prone to impacts. For this area, a value of 20 mm along the Z direction was chosen; such a value assures a full protection to the wrist even in the worst case i.e. the orthosis of a male of 14 years old, at the 95th percentile.

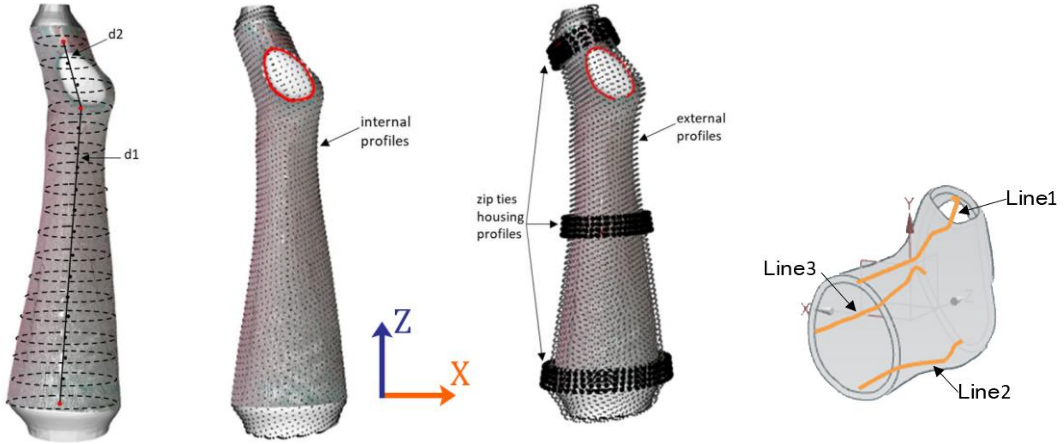


Figure 8: a) Example of cutting direction automated computation procedure with the Douglas–Peucker algorithm; b) example of automatic extraction of *internal profiles* and c) example of automatic extraction of *external profiles*, along with information relative to shape and position of zip-tie housing spaces and to the opening space for the thumb finger (in red); d) Example of the lines defining the cut for the medical device application (*Lines 1* and *2*) and the reference to build zip ties housing (*Lines 1,2* and *3*) automatically computed from the software.

Accordingly, with the above described features, it is possible to define on a new orthosis the same twelve zones (six palmar and six dorsal – yellow in Figure 9(b)) also defined for the reference pattern. As already said, such areas are used to map the reference simplified ventilation pattern, previously identified.

To this aim, a mapping grid is built within each zone in order to map the simplified reference hole pattern in each zone while keeping constant the proportions and shape of the polygonal holes. This is achieved by dividing the long side of each zone always by the same number of segments; for example, the side AB of zone 2 is divided into 9 segments (Figure 9(c)). In addition, the resulting segments are measured; if the distance between two consecutive key points results less than 4 mm, distance is forced to assume such a value. The points obtained are finally stored in a text file and kept for reference for the generation of holes (phase b).

According to the way the key points are defined, they exactly lie on the *internal profiles*; consequently, they will not be in contact with the orthosis surface, which is generated through an offset of the scanned arm. Therefore, the patterns are subsequently extruded towards the target surface to intersect it, as discussed in the following paragraph.

3.3 Holes opening in the CAD model

The second phase, i.e. the perforation of the CAD model, is carried out within Siemens NX® [9]; in the present work the perforation task is integrated in the automatic cast generation procedure described in [3]. The main steps of such an automatic procedure are reported in Table 2 with reference to the dorsal part of a given orthosis; the same procedure can be obviously applied on the ventral side.

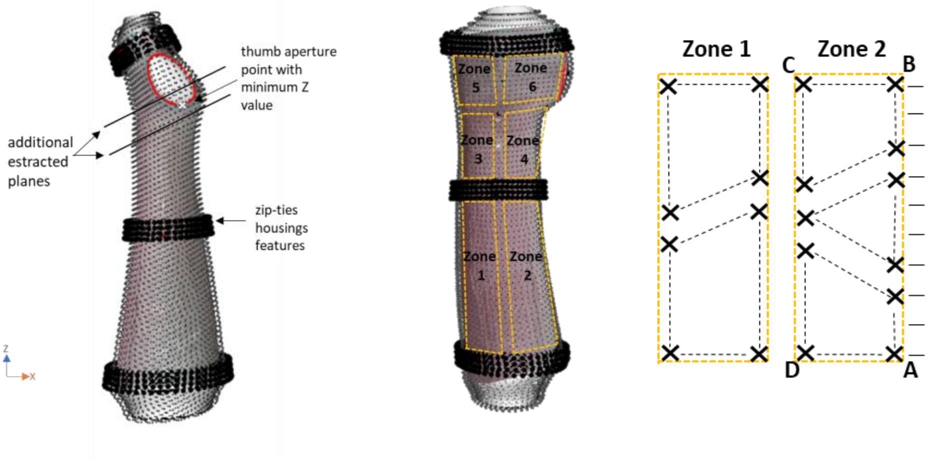


Figure 9: a) Extraction of the two planes defining the wrist area; b) the six zones of the dorsal pattern; c) template of the holes to be adapted for zone 1 and 2.

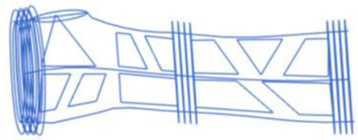
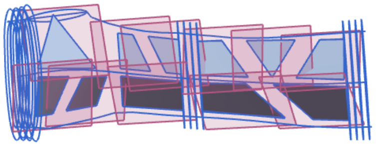
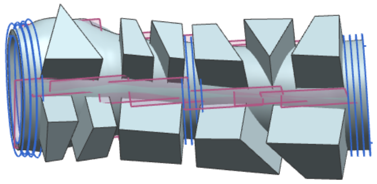
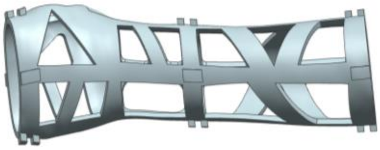
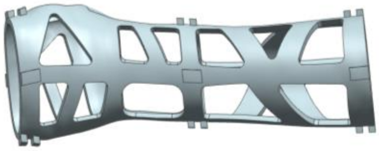
	The splines for the holes are created from the points saved in the text files. The splines are created of grade 1 to ensure that the shape is consistent with the template.
	The splines are projected onto the best-fit plane created on the curve itself.
	The projected curves are extruded towards the shell to create solids.
	The shell is perforated by subtracting the created solids.
	Fillets are generated on each internal edge with a radius of 5 mm to ensure easy construction of the device and patient comfort.

Table 2: Phases of the CAD holes adaptation.

Figure 10 shows the result, on both sides, of the entire adaptation of the pattern and generation of holes. It is worth noting that on the dorsal side a larger opening is left in correspondence of the ulnar styloid process to prevent cutaneous lesions and to avoid discomfort.

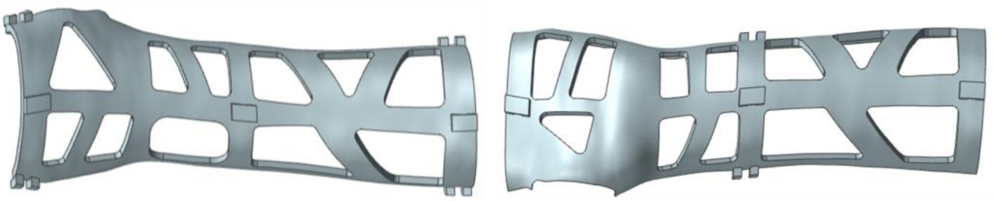


Figure 10: Final result of the CAD modelling and hole-generation procedure.

4 VALIDATION

The devised methodology was applied to five orthoses that are significantly different in size and local geometry from each other. The resulting pattern was approved from a medical perspective in all cases since all the medical requirements were satisfied. Mechanical performance of the orthoses was tested by means of FEA, performed following the indications of Figure 2. The most severe configuration was, as expected, due to the flexion load, which, in the worst case, caused a von Mises maximum stress equal to 24.8 MPa. The results for the five orthoses, in terms of maximum von Mises stress using the flexion load configuration, are reported in Table 3. The worst condition was registered for the orthosis #1 and the resulting stress map is depicted in Figure 11. It is important to note that, according to the stress distribution map of Figure 11, most areas of the orthosis are subjected to stress values in the 6-12 MPa range. Higher stress values, probably caused by stress concentrations factors and FE artefacts, are limited to small regions of the cast and therefore will not have any major impact on the strength of the whole device.

Orthosis	*Arm Length [mm]*	*Maximum Stress Value (Flexion Load Configuration) [MPa]*
#1	~230	24.8
#2	~235	24.6
#3	~190	13.9
#4	~234	11.7
#5	~390	12.0

Table 3: Results of the FE analyses performed to validate the adaptation procedure.

Figure 11: von Mises stress map on orthosis#1 under Flexion Load configuration.

5 CONCLUSIONS

The present paper proposed a semi-automatic CAD-based method for the generation of ventilation holes on ABS AM-manufactured arm orthoses. The process makes use of a template pattern that is adapted to each patient-specific device in order to generate a valid set of holes. The template pattern was defined according to i) medical guidelines, ii) structural needs. The reference pattern was validated with FE analyses: two orthoses, whose dimensions are representative of the entire size spectrum of the considered pediatric application, were used to this purpose.

The pattern was subsequently simplified in order to obtain a set of regular shapes, defining the holes, that could be easily mapped and replicated onto different orthoses. The orthosis surface is subdivided into 12 holes zones; in each zone, an automatic mapping algorithm, specifically devised for this application, has been applied to obtain information on the geometry and proportions of the holes to replicate. Through a set of regular grids, built using notable key-points as reference, the algorithm is capable of replicate the geometry of the holes on new similar orthoses surfaces. The geometry information provided by the algorithm is then used in a set of macro functions, programmed within Siemens NX, to generate the final hollowed orthosis.

The whole strategy has been validated by applying the adaptation algorithm to a set of 5 orthoses and evaluating the performances of obtained devices both from a structural and a medical point of view. The devised strategy offers significant advantages w.r.t. direct modeling of a pattern of holes on each specific orthosis since it does not require to perform FE analysis and/or Topology Optimization each time. This means a significant boost in terms of time saving to model a pattern. Specifically, the entire procedure requires ~1 minute for the automatic elaboration, while a manual approach requires ~1 hour to an expert CAD modeler to be performed.

Future works will be addressed to the study of more refined pattern configuration that could be replicated using the proposed approach. An interesting area to explore would be, with this respect, the definition of a pattern defined following a distribution capable of maximizing the thermal comfort of the patient.

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