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A Digital Workflow for the Design and Additive Manufacturing of Multi-thickness Dental Aligners

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Abstract. The demand for orthodontic and aesthetic treatments, aimed at having healthier teeth and more beautiful smiles, is increasingly growing. The devices on which these treatments are based must be rigorously bespoke for each patient. This is amplifying the need to develop digitized workflows, ranging from scanning to Additive Manufacturing (AM). The present work proposes an alternative workflow for designing and manufacturing orthodontic aligners, also known as clear aligners, starting from the intraoral scanning of the patient’s dentition. Orthodontic aligners are an alternative to metal brackets to correct dental malocclusions and they are often preferred by the patients because of their lower impact on facial aesthetics and for their higher comfort. The orthodontic treatments based on the aligners utilize a series of aligners, each one with a geometry slightly different from the previous one. The use of the single aligners is aimed to apply a force to the teeth and gradually aligning them until the end of the treatment. The workflow we propose in the present study is based on the following three main stages: intraoral scanning of the patient’s dentition, design of the aligners through a semi-automatic algorithm, and the direct additive manufacturing of the aligners through VAT photopolymerization technique. The possibility to directly additive manufacturing the aligners allows us to rethink the current orthodontic treatments. The aligners geometry can be re-designed, with the possibility of locally manipulating the thickness. This approach would allow the regulation of the amount of force applied locally to the tooth, thus optimizing the treatment and its duration. A feasibility study of the proposed workflow is reported in the present paper, with a focus on the semi-automatic design algorithm and on the additive manufacturing process of the aligners.

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1 INTRODUCTION

Dental aligners, also known as clear aligners, are removable and transparent devices used for orthodontic treatments aimed at correcting dental malocclusions. The aligner-based orthodontic treatments utilize a series of aligners, each one with a geometry slightly different from the previous one. The difference between the shape of the aligner and the geometry of the dentition generates forces distributed on all the contact surfaces of the tooth. In particular, each aligner must be worn sequentially during the treatment. They exert a slight force on the teeth to be aligned, until they are completely aligned. Compared to conventional fixed devices, the dental aligners are less invasive from an aesthetic point of view and more comfortable during their use. These characteristics have also led to an increase in the number of adults seeking orthodontic care, and a consequent increase of the total demand for dental aligners [4], [25].

The first step of the planning of a treatment with aligners is the 3D intraoral scanning for the acquisition of the patients' dentitions. After this initial stage, the individual aligners are modeled with CAD tools. In particular, each single aligner corresponds to a new desired tooth position and its use is aimed to perform only a step of the complete tooth alignment. Therefore, the full aligner-based orthodontic treatment consists of multiple aligners with a variable geometry that starts from the initial anatomy of the patients' dentition and reaches the final desired anatomy with the teeth fully aligned. To reach their final positions, some teeth must perform several movements, i.e., rotations, extrusions, intrusions, torque, mesial-distal and buccal-lingual movements. Each of these movements are planned on the basis of the affected tooth, by properly adjusting the magnitude of the force applied to it [26], [22]. The force, in turn, can be adjusted based on the misalignment between the geometry of the aligner and that of the dentition, the mechanical properties of the material used and the thickness of the aligner.

Currently, the software tools used to design the aligners are calibrated on their current manufacturing system, i.e., the thermoforming. In the thermoforming process, a sheet of a thermoplastic polymer (e.g., PETG and PU) is first heated. Once the sheet softens, it is typically forced against the surface of a mold through the application of a vacuum or pressure. In the case of aligners, the mold is represented by the dentition model. Consequently, the software generates the movements of the teeth by modeling the dentition and not by directly modeling the aligner [2], [18]. This manufacturing process, although well-established and used, does not allow the design of aligners with differentiated and above all controlled local thicknesses. However, the possibility to control locally the thickness of the aligner would allow us to set the magnitude of the forces and optimize the performances of the orthodontic treatments with aligners. The production technology that can offer this possibility is the Additive Manufacturing (AM) [3]. Several studies highlight the potentials associated with the use of this technology for the production of clear aligners [5], [13], [21]. However, these studies often focus either only on some specific properties of the materials, or on the geometric and dimensional accuracy of the printed parts, or only verify the feasibility of printing the aligners' geometries [11], [14]. In [12] compressive properties of the resin Dental LT, manufactured by AM and particularly by VAT photopolymerization, are investigated and compared with the same properties of PETG foils (Duran®, Scheu Dental) produced by thermoforming. Furthermore, the study also analyzes the geometric accuracy of the aligners manufactured with the two different materials and technologies. The results obtained show that the additively manufactured aligners have a higher geometric accuracy than the thermoformed ones and that the compression properties of Dental LT are comparable to those of PETG, if not superior. However, the study does not consider tensile and bending load conditions although they are of fundamental importance for the mechanical properties that an aligner must have [20]. Other studies [17], [14] also investigate the geometric accuracy of additively manufactured aligners. In particular, [14] evaluates and compares the dimensional accuracy of thermoformed and additively manufactured aligners produced by using the resin Tera Harz TC-85. Also in this case, the results demonstrated that AM aligners show a greater precision and accuracy than thermoformed aligners. Also [17] focuses on the dimensional accuracy of AM aligners, and in addition the authors analyze the effect of print orientation and of UV light post-curing duration on the dimensional accuracy. The results showed for both of them a small effect on the overall accuracy of the manufactured aligner. The effects of the post-curing UV treatments have also been studied in [11], where the authors evaluated the effects of the post-curing duration and temperature on the compressive properties of the Dental LT resin. The results showed that the post-curing conditions can significantly influence the compressive behavior, which can be tuned through a correct post-processing treatment setting. However, the study does not evaluate the effects that post-curing can have on the biological properties and biocompatibility of the resin used [6].

There is no evidence in the literature of studies proposing methods for modeling and manufacturing multi-thickness aligners where the thickness can be changed tooth by tooth. The purpose of this paper is to explore this possibility, with the aim of providing a scientific basis for more customized and advanced orthodontic treatments, and less-time-consuming. Starting from the mapping of the teeth and the movements that must be done for alignment, the development of such an approach can allow the diversification of the magnitude of the applied forces through an optimized use of material and geometry of the aligner. This latter aspect can also have a positive impact on environmental sustainability, promoting a cleaner production through the reduction of waste material compared to thermoforming. The following sections present the approach developed for the design of a clear aligner through a semi-automatic modeling algorithm, and the direct additive manufacturing of the aligner through the VAT photopolymerization technique.

2 MATERIALS AND METHODS

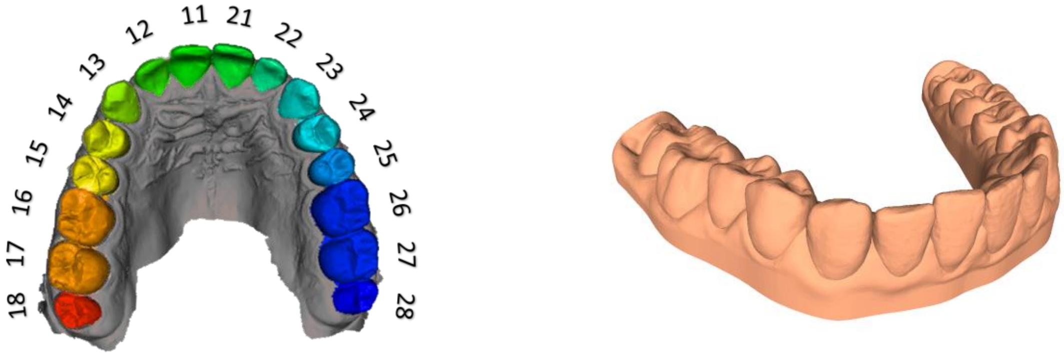
2.1 Aligner Modeling

The initial step of the aligners' modeling procedure is the acquisition of the surface of the patient's dentition using 3D intraoral scanners. The result consists of a unique mesh for the mandibular (lower) arch and one for the maxillary (upper) arch. This is the input data for the modeling algorithm. To reach the desired dentition with all the teeth aligned, the treatment requires the usage of a certain number of steps depending on the level of misalignment of the patient's dentition. Each step requires an aligner that moves one or more teeth towards an intermediate position till the final one.

Considering the aim of the aligners, it is necessary to segment the teeth from the gum and then classify every single tooth. The teeth need to be moved in the position required by each step to generate the single specific aligner. This step is usually performed with the support of a CAD tool. In the literature there are numerous research works aiming to solve this problem, mainly exploiting the capabilities of machine learning or geometrical features of the mesh [23], [8]. There are commercial software tools that assist the technicians to perform this step manually or in a semi-automatic way [24]. The output consists of a set of separate meshes, where the gum and the teeth are named according to the traditional two-digit nomenclature proposed by the standard ISO 3950:2016 [10]. Figure 1(a) reports an example of a segmented 3D scan based on the Python implementation of the neural network developed by Lian et al. [16].

The position and rotation of each element is stored in an ordered text file. After the segmentation, the mesh of teeth and gum are closed. Figure 1(b) shows the gum being cut with a horizontal plane. Then, the technician moves the teeth using a dedicated dental software tool to achieve the final alignment and generates the digital models of the intermediate steps from the initial teeth position to the final one.

The next step consists of generating the model of the aligner from each dental model. The idea is that the geometry of the aligner should cover the teeth surface and not the gum in order to be effective in force transmission and comfortable for patient. Once, the model is aligned along its principal axis, the algorithm combines four geometrical features to distinguish the gum from the teeth. For each of these features, the algorithm associates a value from 0 to 1 to each vertex. This value is related to the probability that the vertex belongs to a tooth (1) instead of gum (0). Initially, it computes the vertical and horizontal distribution of each vertex. Taking as reference Figure 2, the probability that a vertex belongs to one of the teeth instead of the gum is greater if both the vertical position and the horizontal distance from the center of the model are higher.



(a) (b)

Figure 1: The surface from the intraoral scan is segmented and the teeth and gum are classified according to the standard ISO 3950:2016 (a). After the roto-translation of the segmented parts, a virtual model representing the alignment step can be generated (b).

Considering the bounding box of the model as extreme values, Figure 2(a) shows the normalized vertical position of each vertex. Figure 2(b) shows the horizontal distance of each vertex from the center of the model. The third quantity evaluated is the geodesic distance of each vertex from the cusps of a tooth. Considering the shape of the teeth, the cusps are eminences that represent local maxima for the mesh. Furthermore, they usually have positive mean curvature values. Combining these two aspects and discarding the outliers and the points on border, the algorithm looks for the teeth cusps. Then, it computes the geodesic distance between each vertex and the selected cusps (Figure 2(c)). Lower is the value, higher is the probability that the vertices belong to a tooth. The last quantity is related to the principal directions of the curvature. They are computed using the pseudoinverse quadric fitting method. Given a fixed radius, for each point of the 3D mesh, the method chooses a set of the nearest vertices. Then, it computes the projection plane by averaging the normal vectors of the selected points. Finally, it fits a quadric surface using a singular value decomposition of these points with respect to the plane. The resulting mean curvature values are the ones of the fitted quadric [7]. Setting a threshold value on the curvature, it is possible to cut the model approximately along the teeth border (in which vertices mainly have negative curvature values) and performing a binary separation from the gum, even if numerous holes can be present (Figure 2(d)).

Normalizing these four qualities and combining them with multiplicative factors empirically determined, the algorithm splits the teeth from the gum using a threshold value (Figure 2(e)). To avoid jagged edges, a Laplacian smooth is applied to the border. Figure 2(f) shows an example of the resulting surface. Further details of the algorithm can be found in a previous work from the authors [1].

One of the greatest advantages of this algorithm is that combining the initial classification of the teeth and the surface of the aligner it is possible to select the desired teeth and apply a variable thickness to the surface to generate a custom aligner based on which tooth is active during each step of the orthodontic treatment. Figure 3(c) shows an example where the active teeth in the step are the ones till the second bicuspid (teeth 11:15, 21:25 according to the standard classification).

To obtain this output, the algorithm takes as input the coordinates of position and rotation of the active teeth from the text file generated in the classification step. Then, it reprojects the points on the aligner's surface and computes the geodesic distance between each vertex and the selected ones. Figure 3(a) shows an example of this selection. The vertices in red are the nearest, while the blue ones are the farthest. Setting a threshold on the color scale it is possible to select the active teeth highlighted in red (Figure 3(b)), and finally perform an automatic binary subdivision on the surface (Figure 3(c)).

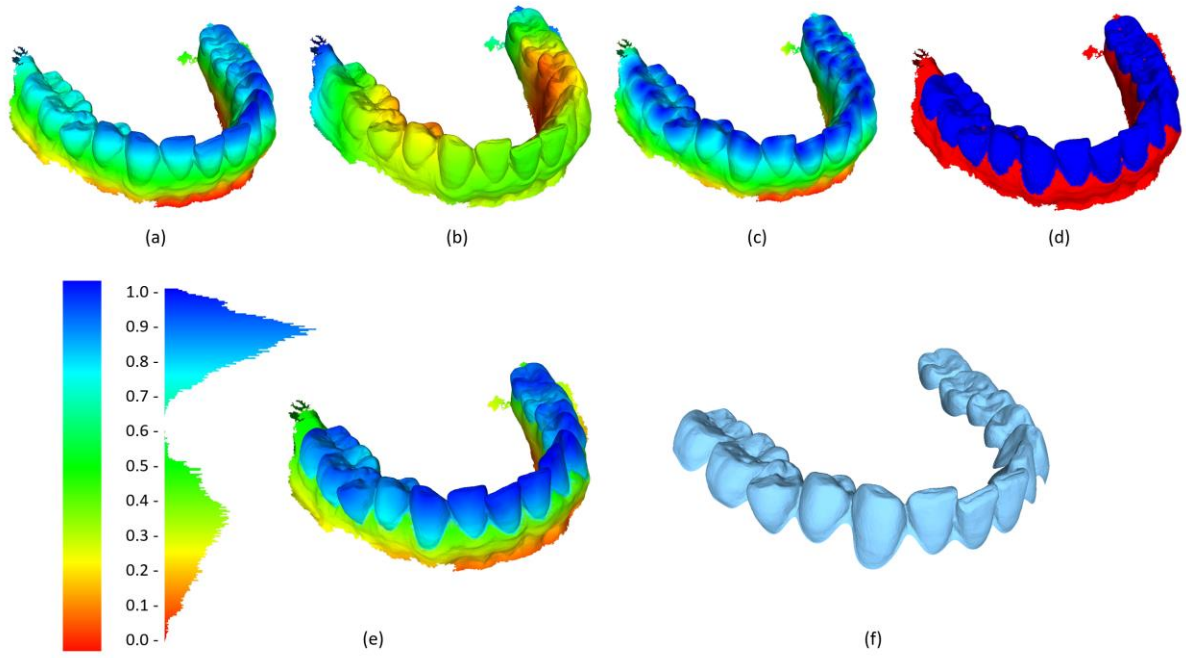
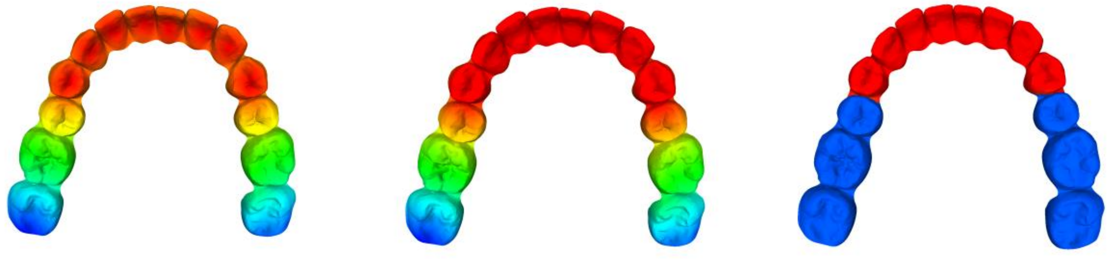


Figure 2: The algorithm computes four geometrical features to generate the aligner's internal surface. The vertical position (a), the horizontal distance of the vertices from the center (b), the geodesic distance from the teeth' cusps (c), and the binary separation using the mean curvature (d) values of vertices. Combining the four quantities for each vertex and defining a threshold on the distribution histogram (e) it is possible to obtain the aligner surface (f).



(a) (b) (c)

Figure 3: Process of selecting areas with a different thickness: from the computation of the geodesic distance from the desired teeth (a), to the selection of the teeth in red (b) and the final binarization (c).

Till now, the results consist of the internal surface of the aligner. The following step consists in generating a solid part that can be produced with additive manufacturing process. The binary subdivision allows us to generate an aligner with differential thicknesses. In the case study (Figure 4), the aligner presents a greater thickness (0.8mm) on the active teeth and a lower one (0.5mm) on the rest of the surface. The mesh is finally saved as STL file. This whole process can be repeated for all the steps of the orthodontic treatment to create all the STL files for the aligners.

(a) (b)

Figure 4: The 3D mesh of one aligner (a) with variable thickness (b).

2.2 Aligner Manufacturing and Verification

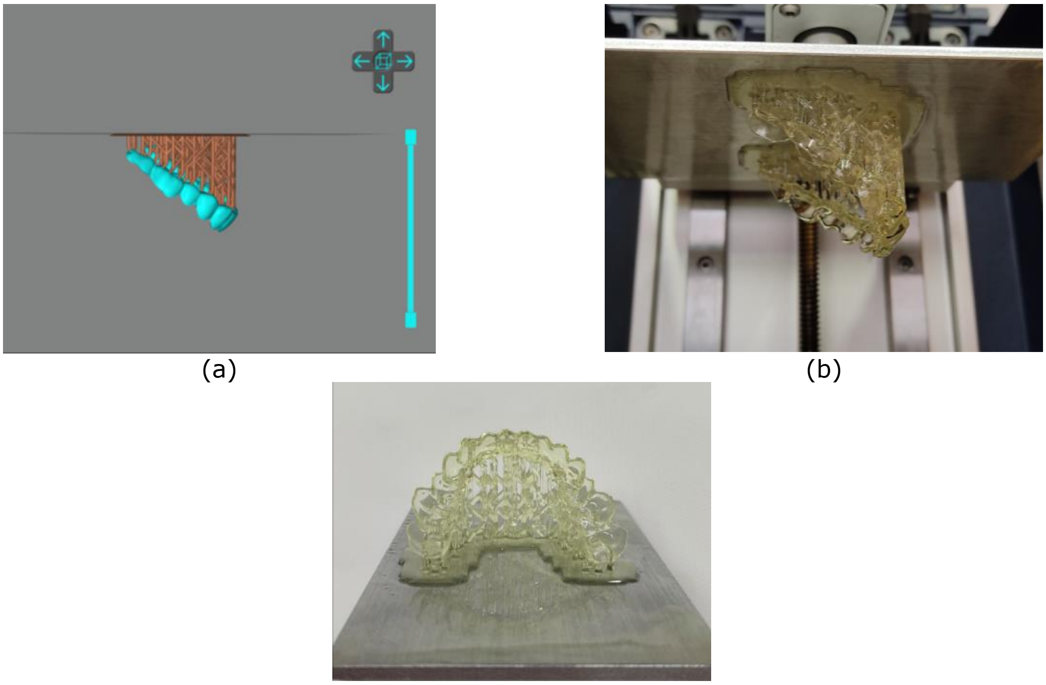
VAT technology has been chosen for manufacturing the aligners, and in particular the Digital Light Processing (DLP) technique. VAT photopolymerization is a process that creates a 3D geometry by selectively curing a liquid photopolymer, which is contained in a tank (vat), by light-activated polymerization. With DLP the light is generated by a projector or by a Liquid Crystal Display (LCD), and each single slice is cured all-at-once by projecting a single digital image. DLP technique is generally characterized by a high level of dimensional accuracy and by a good surface finishing [9], [19]. In our study the Anycubic Photon Mono SE machine, equipped with a 6-inch monochrome LCD display, has been used. The printing parameters have been set with the software Photon Workshop. The main parameters set are reported in Table 1.

Layer thickness (mm)	0.05
Exposure time (s)	3.5
Z lift distance (mm)	8
Z lift speed (mm/s)	1
Z retract speed (mm/s)	2.5

Table 1: Main printing parameters used.

In addition, a 30 degrees tilt angle of the aligner relative to the build platform has been used and supports have been added. The resin used to print the aligners is the Tera Harz TC-85. It is a bio-compatible photopolymer developed and commercialized for the direct 3D printing of clear aligners. This resin is also very interesting for its thermo-mechanical properties and for its ability to have shape memory properties. This characteristic can allow us to constantly apply a light force to the teeth and may provide advantages for the clinical applications, if compared to the thermoformed materials currently used [15]. Tera Harz TC-85, like the other photoresins used with VAT photopolymerization technologies, involves the use of UV post-curing treatments. The application of these treatments gives the printed material the final mechanical properties.

The aligner manufacturing process, from the preparation of the printing file to the final production of the aligner, is shown in Figure 5. At the end of the process, the generated supports are mechanically removed using a simple plier. The accuracy of the geometry of the printed aligners has been verified, using a 3Shape E2 optical scanner, equipped with a two-axis rotary table and a proprietary software for processing the acquired data and generate an STL file. Typically, optical scanning methods meet difficulties in acquiring transparent parts. To overcome this issue, the clear aligner was sprayed with a green colored powder scan spray. The scanned geometry of the additively manufactured aligner was then compared with the 3D modeled aligner used for printing. The deviations of the global geometry and the deviations referred to the thickness of the aligner were verified by using a freeware measurement software.

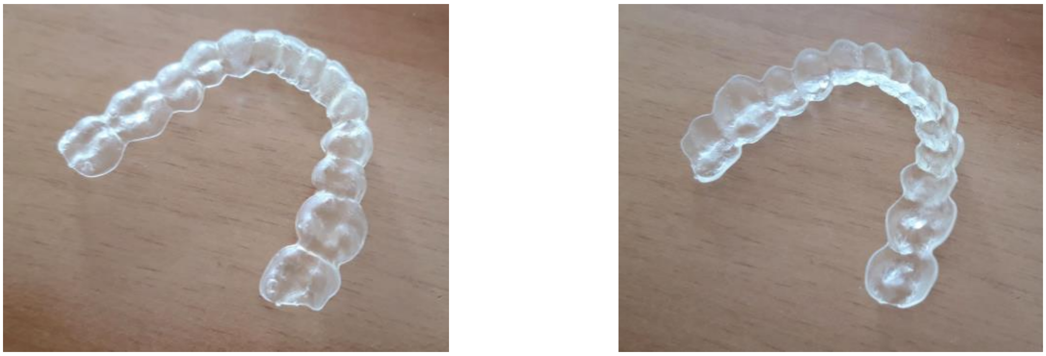


(a) (b) (c)

Figure 5: The virtual model of the aligner is oriented and the supports are generated (a), the final manufactured aligner, still attached to the build platform, is visible from different angles (b, c).

3 RESULTS

This section reports the results obtained from the manufacturing of the aligners. From Figure 6 it is possible to see an example of a printed aligner, and specifically its external surface (Figure 6 (a)) and the internal one (Figure 6 (b)). From the images it can be seen that the aligner has a good general quality, an excellent definition of the geometry and a good transparency. Furthermore, the typical stratification of the additive manufacturing processes is minimal and some residue of the mechanically removed supports is only partially visible. It is interesting to observe how the resin, after printing and its post-processing, greatly improves its degree of transparency and the yellowish aspect is no longer present.



(a) (b)

Figure 6: Internal (a) and external (b) surfaces of the aligners after printing, supports' removal and post-curing treatment.

Figure 7 reports the analysis of the deviations of the global geometry of the aligner. The gray areas represent the areas where the mesh obtained with the scan is not perfectly closed and there are voids. In these areas there are essentially no points to assess deviations. In addition, it is necessary to specify that the lower left part of the geometry (gray and red colored), corresponding to the last tooth (third molar), was used to grasp the aligner during the scan. For this reason, that part cannot be used for the comparison between the printed geometry and the corresponding virtual model. Nevertheless, the scan is of good quality and much of the geometry of the printed aligner can be compared with the virtual model used for printing. From the figure it can be seen that in most cases the dimensional deviations are positive (green and yellow areas), i.e. the manufactured geometry is oversized compared to its virtual model, and for small portions of the geometry (cyan areas) they are negative. The average deviation of the 3D printed aligner is 0.14 mm and the standard deviation is 0.23 mm.

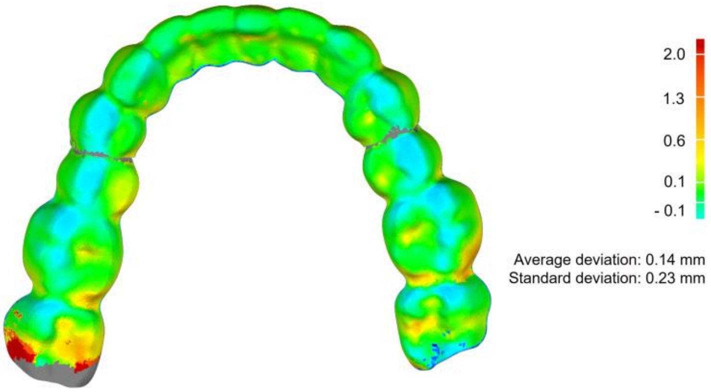


Figure 7: Analysis of the dimensional accuracy of the global geometry of the aligner.

Figure 8 reports the analysis of the aligner thickness accuracy. From the observation of the color map, the distinction between the two thicknesses used for the virtual model (i.e., 0.5 mm and 0.8 mm) is evident. The deviations with respect to the modeled thicknesses are minimal and generally not exceeding 10%, as also visible from the sampling reported in the figure. It should also be noted that, although the spray used for the preparation of the aligner to be scanned is specific for use in the dental field, its manual application can produce slight inhomogeneities and the thickness of the applied film may not be perfectly uniform. This unevenness is reflected in the final geometry of the scanned aligner. Finally, it should be also observed that the occurrence of some red areas is linked to the presence of small residues due to the mechanical removal of the supports, which could be eliminated with a simple local polishing.

4 DISCUSSION

The use of additive manufacturing in the dental sector is becoming more and more widespread. For some applications, the dental device is manufactured directly and for others, such as clear aligners, a template is produced and then used for the thermoforming of the final device. The direct or indirect additive manufacturing of the dental device leads not only to a change in the design process, but also opens up new and unexplored design possibilities. To do this, new tools and modeling strategies for obtaining the final product are necessary. Furthermore, these tools must provide possibilities that are compatible with features and restrictions of the additive manufacturing technologies used. For these reasons, a feasibility study and quality control of the geometries produced is always necessary. In this study the new possibility explored is the development of a new method for the modeling and manufacturing of a multi-thickness aligner. The results showed that the reported approach allows us to customize the thicknesses locally and that the geometries modeled after their manufacturing have a good geometrical and dimensional accuracy.

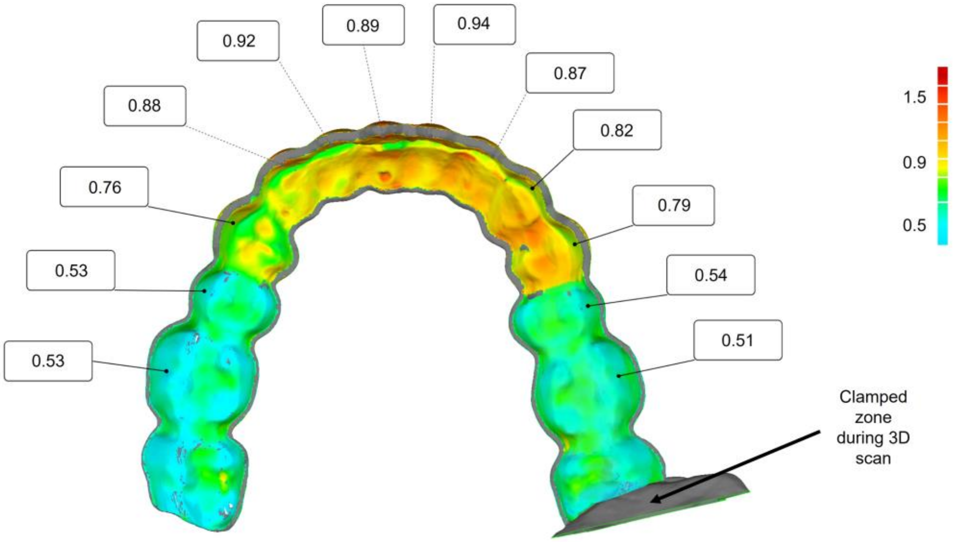


Figure 8: Analysis of the aligner thickness accuracy.

The two different thicknesses and the teeth to apply them were chosen arbitrarily. However, this possibility can represent a powerful tool, for more customized and advanced orthodontic treatments, in the hands of clinicians who deal with orthodontic treatments based on clear aligners. Starting from the mapping of the teeth and the movements that they must carry out for alignment, a multi-thickness aligner can allow the diversification of the entity and direction of the applied forces, optimizing the entire treatment and its duration. Moreover, the creation of multi-thickness aligners can provide the possibility of minimizing thicknesses in areas where there is no need to exert forces. This can have a positive impact on the comfort of the aligner, reducing its size and the feeling of discomfort. Furthermore, the dimensional discrepancies measured in this study for the overall geometry (average deviation 0.14 mm) and its thicknesses (maximum 10%), are smaller than those of the thermoformed aligners, and in line or even better than those of the aligners obtained from direct 3D printing reported in other studies [17], [14]. These results are positive, considering also the application of non-uniform thicknesses and the use of a low-cost 3D printer for the production of the aligners. Finally, direct aligner manufacturing would reduce the amount of waste material produced during the fabrication with respect to the current aligner production process, which consists of a larger number of steps. In fact, differently from the traditional thermoforming technique, there is no need to manufacture a mold for each aligner. This aspect can result into a final benefit in terms of environmental sustainability.

5 CONCLUSIONS

In the present study a new method for the design and the additive manufacturing of multi-thickness dental aligners have been presented. A feasibility study was carried out, from modeling to final production. The proposed modeling algorithm has shown the possibility of creating aligners with a different tooth by tooth thickness. The choice of VAT photopolymerization as additive manufacturing technology and the use of material and printing parameters used proved to be adequate for a reliable production process.

This is also demonstrated by the results of the verification of the dimensional accuracy of the produced aligner. The average dimensional deviation of the 3D printed aligner with respect to its virtual 3D model is 0.14 mm. The maximum thickness discrepancies with respect to the modeled thicknesses are minimal and generally not higher than 10%.

Future developments of this study include the development of a method which can automatically apply the local thickness of the aligner, based on the movements that the tooth has to make for its alignment. Furthermore, the proposed approach could be validated through the use of multi-thickness aligners for clinical studies on patients.

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