RESEARCH

3D printing of molds for the creation of facsimiles and volumetric reintegrations in wax anatomical sculptures

Emanuel Sterp Moga [1*], Alicia Sánchez-Ortiz[1] and Óscar Hernández-Muñoz[2]

Abstract

In recent years, 3D printing technologies have had a considerable impact on the field of conservation and restoration of cultural heritage. Professionals in this sector have been provided with exploratory tools for documenting, analyzing, intervening, and preserving objects and works of art that make up our history. This research focuses on finding the most suitable material along with the ideal printing position that could provide molds for the production of anatomical wax facsimiles that guarantee maximum quality and fidelity when compared to its original. These replicas and fragments allow conservator-restorers to volumetrically reintegrate while testing different options before applying direct treatment to the works. The results obtained from testing on different types of printing materials as well as the positives achieved from them are presented.

Keywords: Digital modeling, 3D printing, Molds, Facsimile, Wax artifacts, Conservation

Introduction

Recently, 3D printing has played an increasingly important role in the field of conservation and restoration of cultural heritage. Practitioners have had access to new methodological avenues to solve specific case studies when the usage of other systems could add additional risks during treatment. 3D printings have been applied in various specific ways [1–8]. The results achieved by multiple teams have demonstrated the effectiveness of this technology in the service of cultural heritage conservation and restoration.

The 3D printing of molds, which is the main focus of this paper, continues to be a useful method because it minimizes handling and avoids direct contact with the original objects and works of art [9–11]. When it comes to wax artifacts and sculptures, applying traditional molding techniques would be unthinkable because the materials are very delicate. The complex volumes and fine details could be irreversibly damaged during the removal of the silicone. Also, additional risks arise due to the constant movements and forces involved in this process. Moreover, the material often used to facilitate the removal of the mold would alter the pH of the surface of the sculpture leading to various long-term alterations. This is why printed molds can be a great alternative for creating facsimiles to test various conservation and restoration treatments [12].

In a previous study, different techniques for the elaboration of printed molds for the production of wax pieces focused on the reconstruction of volumetric losses in anatomical models were analyzed [13]. Other researchers have provided relevant information regarding printing direction as a determining factor affecting prototype quality [14–16]. Some mathematical algorithms have been investigated to modify and refine certain types of printing for the analysis of prototype quality [17]. The choice of the correct orientation in the construction of the volume, as well as the thickness of each layer, among

*Correspondence: emasterp@ucm.es

[1] Department of Painting and Conservation-Restoration, Faculty of Fine Arts, Complutense University of Madrid, Ciudad Universitaria S/N, 28040 Madrid, Spain

Full list of author information is available at the end of the article

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other factors, are very important in providing certain mechanical properties and surface details. Each part requires a need, and a configuration and this will impact the working time [18]. Several studies have focused on the analysis of orientation and the influence of printing time [19]. During printing, not only the build orientation and layer thickness have noticeable effects on the part, but also the extrusion width, infill percentage and raster angle [20]. In this research, our objective was to find the most suitable material and orientation during the printing of the molds to achieve the highest quality and fidelity in the volumetric reintegrations. The ultimate goal of this analysis was to determine which parameters allow to obtain the highest quality of facsimiles in the field of conservation-restoration.

Materials and methods
3D Modeling
The wax models were digitized using two structured light scanners, Artec Space Spider 3D and Artec Eva, both manufactured by Artec 3D (Luxembourg City, Luxembourg). The 3D modeling of the molds was carried out in silico using software Blender (Blender Foundation, Amsterdam, The Netherlands). To do this, different geometric elements such as cubes and spheres were used as a starting point. By moving the vertices on the X, Y and Z axes, each piece was shaped and adapted to the corresponding fragment, moving the vertices and extruding the polygons when necessary. The modeling was facilitated by using and combining different tools within the modeling software including *Bevel, Loop cut*, and *Knife*. The desired finishes could be obtained with any of these combinations. To achieve the maximum level of precision, the use of a vertex-oriented *Snap* became essential. This option allowed a perfect joined union between the two surfaces of each mold fragment. A detailed preliminary analysis of the construction and shape of the particular mold was required in order to dismantle it in the simplest way and to ensure that the removal of the replica was smooth. The most important tool for obtaining the negative part of the mold was *Boolean*. Using this tool, the digitized part was subtracted from each mold portion with the *Subtract* option. The *Boolean* tool was also used to create the different necessary keys to ensure the perfect coupling of each part of the mold.

3D Printing
The 3D printing of the designed molds was carried out using the Ultimaker S5 printer, Ultimaker (Utrecht, The Netherlands). This machine was chosen because of its very fine layer resolution, which can reach up to 20 microns (0.02 mm) in the Z-axis, and a resolution in the X–Y plane of 6.9 microns (0.0069), a maximum printing volume of $330 \times 240 \times 300$ mm, and the presence of a dual extruder. The dual-head arrangement facilitates printing because the Ultimate S5 printer is able to simultaneously print with two materials; one tough for the object construction and another more fragile for the auxiliary supports. In the case of the latter, a PVA (polyvinyl alcohol) was used and can be later removed with water. Also, the Ultimaker S5 printer features a print speed < 24 mm^3/s, a filament diameter of 2.85 mm and a nozzle diameter of 0.4 mm, with a temperature of 180–280 ℃. In addition, it has a heated printing plate with a temperature of 20–140 ℃. This provides a wide range of applications as required for each specific case. The models to be printed were exported in STL format from the 3D modeling program Blender, The Blender Foundation (Amsterdam, The Netherlands) to be later edited using the Ultimaker Cura 4.10 program, Ultimaker (Utrecht, The Netherlands). Finally, the quality of the FDM (Fused Deposition Modeling) printing is conditioned by three main factors: the print resolution, the orientation, and the type of material [21, 22]. Regarding the resolution, the lower the resolution the higher the quality. In terms of the orientation, depending on the angle or position, one quality or another will be obtained. Finally, when considering the type of material, it is key to remember that not all of them offer the same precision and finish.

Fourteen materials were selected for the production of the molds in order to test the behavior and qualities of each one of them. Among the best-known are the following: PLA (polylactic acid), ABS (acrylonitrile butadiene styrene) or PETG (polyethene terephthalate). Other materials that were also considered to be of interest were: ASA (acrylonitrile Styrene Acrylate), NYLSTRONG (nylon [PA6] polyamide with glass fibre), HIPS (polystyrene and polybutadiene rubber), the INNOVATEFIL POLYCARBONATE (polycarbonate), PP (polypropylene), PLA 3D870 (polylactic acid), INNOVATEFIL PA HT (polyamide), PLA Tough (polylactic acid), TPU 95 A (thermoplastic polyurethane), FLEX (polyurethane) and PVA (polyvinyl alcohol). The materials were supplied by Smart Materials 3D (Alcalá la Real, Spain), with the exception of PLA Tough, TPU 95 A or PVA which were supplied by Ultimaker. The printing parameters for each material are listed in Table 1.

The tests of the different selected materials were carried out in two phases. The first consisted of finding the best position and orientation to adopt. To do this, six identical molds were printed in the PLA material, three in a horizontal position, at 0º, 45º and 90º, and three in a vertical position at the same angles. Once the analysis of the most suitable arrangement had been completed, the other thirteen materials were tested in the position that had provided the best results. Once the prints were

Table 1 3D printing materials and printing characteristics

Printing material	Material density g/cm³	Layer height	Wall thickness	Filling pattern	Print speed mm/s	Plate adhesion pattern	Printing temperature (ºC)	Temperature in the warm bed (ºC)
ABS	1.04	0.06	1.5	Grid	50	Raft	240	85 ºC
PLA Tough	1.22	0.06	1.5	Grid	50	Raft	210	60 ºC
PLA	1.24	0.06	1.5	Grid	50	Raft	215	60 ºC
INNOVATEFIL PA HT	1.20	0.06	1.5	Grid	50	Raft	270	90 ºC
HIPS	1.05	0.06	1.5	Grid	50	Raft	240	90 ºC
PP	0.90	0.1	1.5	Grid	25	Raft	225	80 ºC
TPU 95	1.22	0.1	1.5	Grid	25	Raft	225	60 ºC
FLEX	1.21	0.1	1.5	Grid	25	Raft	230	60 ºC
PETG	1.27	0.06	1.5	Grid	50	Raft	240	80 ºC
PLA 3D870	1.22	0.06	1.5	Grid	50	Raft	220	60 ºC
ASA	1.07	0.06	1.5	Grid	50	Raft	250	100 ºC
INNOVATEFIL POLYCARBONATE	1.20	0.06	1.5	Grid	50	Raft	260ºC	100 ºC
PVA	1.23	0.06	1.5	Grid	50	Raft	215ºC	60 ºC
NYLSTRONG	1.58	0.06	1.5	Grid	50	Raft	260ºC	100 ºC

completed, its quality was analyzed in depth. Firstly, a Dino-Lite AM4113 T-FVW digital microscope by Dino-Lite (Taipei, Taiwan) was used to explore the details of the print to analyze errors, impurities, the lines of the deposited filament, and other issues. Secondly, in order to check its effectiveness and study the quality and fidelity of the piece to be obtained, the wax positive of each of the molds was made by pouring the wax. Before applying this material, a layer of petroleum jelly was brushed on as a release agent. The waxy paste chosen was composed of 6 parts beeswax, 1 part lard and 3 parts Venetian turpentine. This recipe was provided by Jaime Bonell and Ignacio Lacaba in their description of the functioning of the anatomical cabinet of the Colegio de San Carlos (Bonell and Lacaba 1800, p.500). The positives obtained were also examined in detail with a digital microscope.

Creation of positives
In order to facilitate the removal of the positives without damaging the wax volume during extraction, a layer of petroleum jelly was applied to each of the fragments that made up the mold prior to the printing process. The application was carried out with a soft synthetic brush. The brush has only been brushed with petroleum jelly so no excessive load has been applied. All the molds were then closed with elastic bands. At the joints between each part of the mold, a little plasticine was applied on the outside to avoid wax leaks. The waxy paste was poured in layers on the molds at a temperature of 75 ºC. For those that were made up of two or more fragments, several layers of wax were applied on each portion during the first

phase. Subsequently, fragments were joined to each other by pouring the wax inside them until the mold was filled. This last operation allowed the joining of the fragments into one piece.

Results and discussion
3D Modeling
The virtual design of the molds was a critical step that was only possible with this technological methodology. This process made it possible to analyze the level, position, and depth of each of the fragments that make up the mold. This ensured a correct and precise construction of the digitized object. This was taken into account during the design at all times to ensure an easy and safe disassembly of the positive to be obtained with the waxy material. The *Boolean* tool greatly facilitated the 3D modeling making it possible to obtain a reliable copy of the fragments to be reproduced. The modeling proved to be very fluid while the whole process went quite fast once the necessary design for each piece had been established (Fig. 1). Finally, because the scanned model offers a 1:1 scale of work that is also applied to the molds, great volumetric precision was achieved.

3D Printing
The 3D printing tests of molds to determine the best position and orientation of the parts have given the best results when carried out with PLA filament. Firstly, the horizontal arrangement of the mold along its main axis, and with its base forming a 0º angle with the printing platform provided poor quality in the details of certain
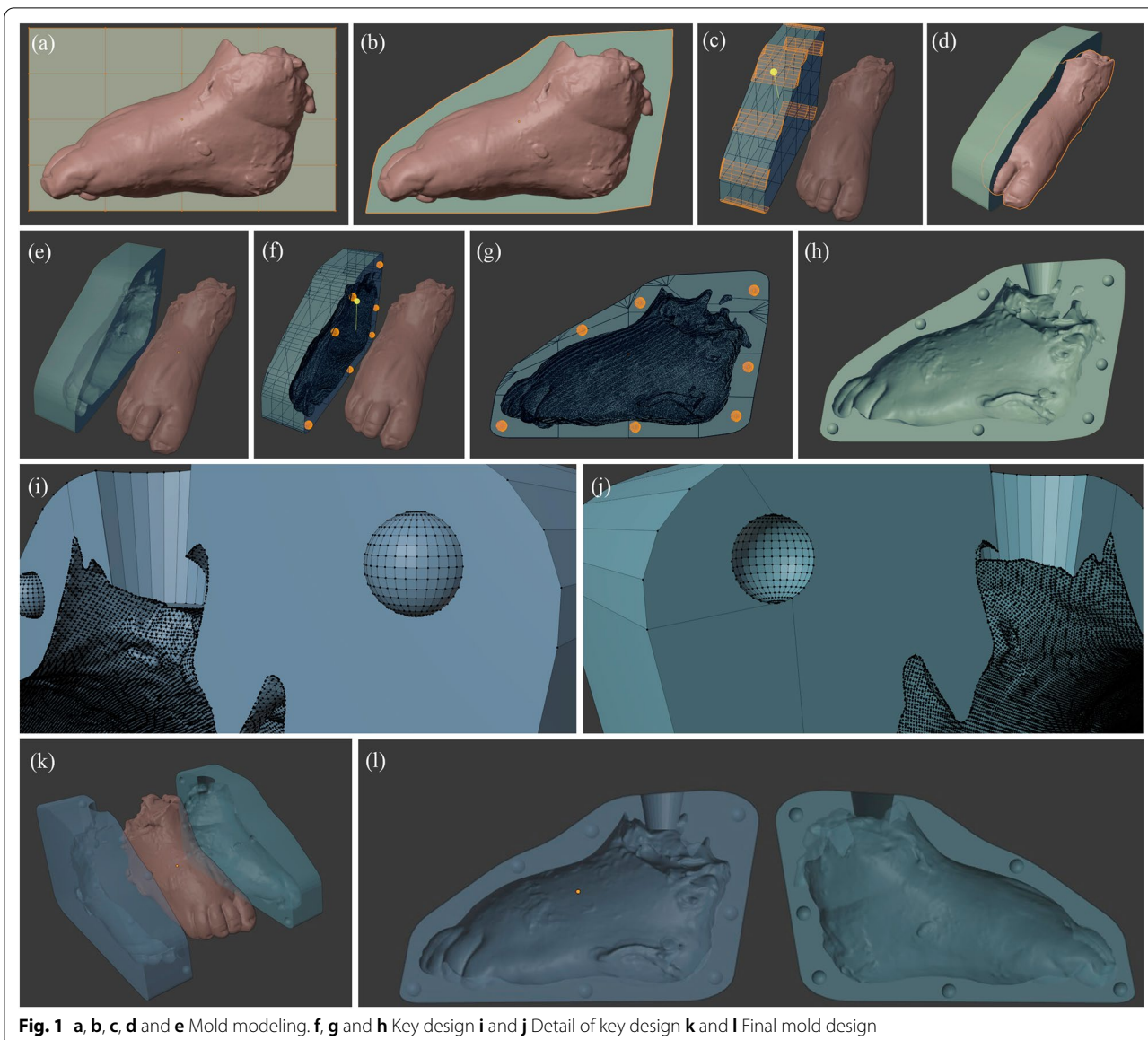
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Fig. 1 **a**, **b**, **c**, **d** and **e** Mold modeling. **f**, **g** and **h** Key design **i** and **j** Detail of key design **k** and **l** Final mold design

areas of the mold. This occurred because during the printing process some parts require support structures to hold areas that are not in contact with the plate and these supports are difficult to remove without leaving marks. Once the copy is finished, these supports are sometimes difficult to remove without leaving marks and for this reason it is preferable to look for positions in which the least amount of them is created. In this case, several threads in complex areas were not correctly deposited and fused despite the fact that the layers, in general, have been faithfully placed without highlighting the lines of each one of them (Fig. 2a). The horizontal position with the base at 45° to the printing platform gave very good results. Printed at this angle, the previously altered areas

were not affected, as the deposition of the filament was carried out with great precision, without the need for structures. Regarding the printing lines of each layer, these are practically unnoticeable (Fig. 2b). The horizontal position of the printing platform with the base at 90° made it possible to obtain adequate results in terms of detailing complex areas. However, by depositing the filament perpendicularly on most of the mold, the lines were very conspicuous, greatly reducing surface detail (Fig. 2c).

Regarding the vertical position with the various angles of 0°, 45° and 90° concerning the printing base, the results were very similar to those obtained in the horizontal position. The angle at 0° generated some more visible
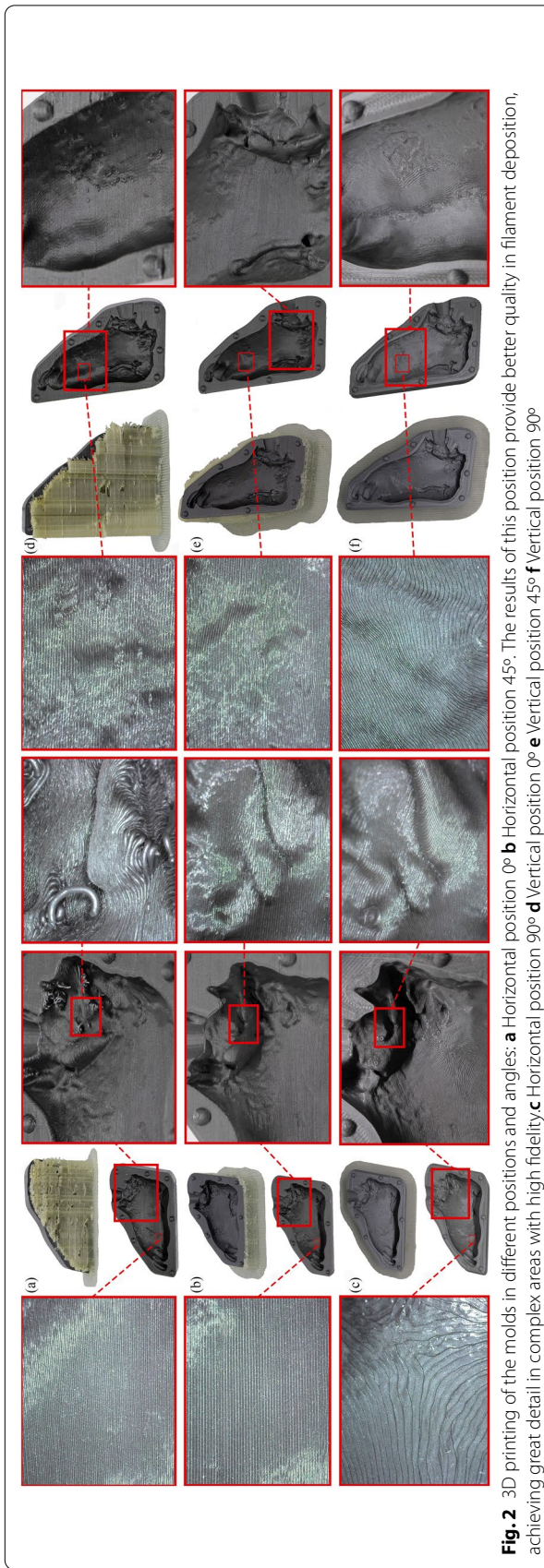
Fig. 2 3D printing of the molds in different positions and angles: **a** Horizontal position 0° **b** Horizontal position 45°. The results of this position provide better quality in filament deposition, achieving great detail in complex areas with high fidelity.**c** Horizontal position 90° **d** Vertical position 0° **e** Vertical position 45° **f** Vertical position 90°

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imperfections compared to the horizontal position, negatively affecting the quality of the mold (Fig. 2d). As for the 45º angle, good results were achieved in general, although it should be noted that the filament in this position was more evident than in the horizontal position, producing irregularities (Fig. 2e). Finally, using an angle of 90º, the filament was very marked, practically the same as in the horizontal position (Fig. 2f). The printing times for the different angles were almost identical in the two positions. The 90° angle was the fastest by taking 651 min to print. The 0º angle took 888 min to print, and the 45º angle was the longest, taking 1051 min.

Once the first phase was completed, the casting positives obtained from the molds were analyzed. The horizontal positive at 0º recorded several lines of the mold impression, not achieving adequate results for the purpose of this study (Fig. 3a and d). However, with the horizontal position at 45º, a uniform surface finish was achieved, with hardly any imperfections in the mold (Fig. 3b and e). On the other hand, the 90° positive
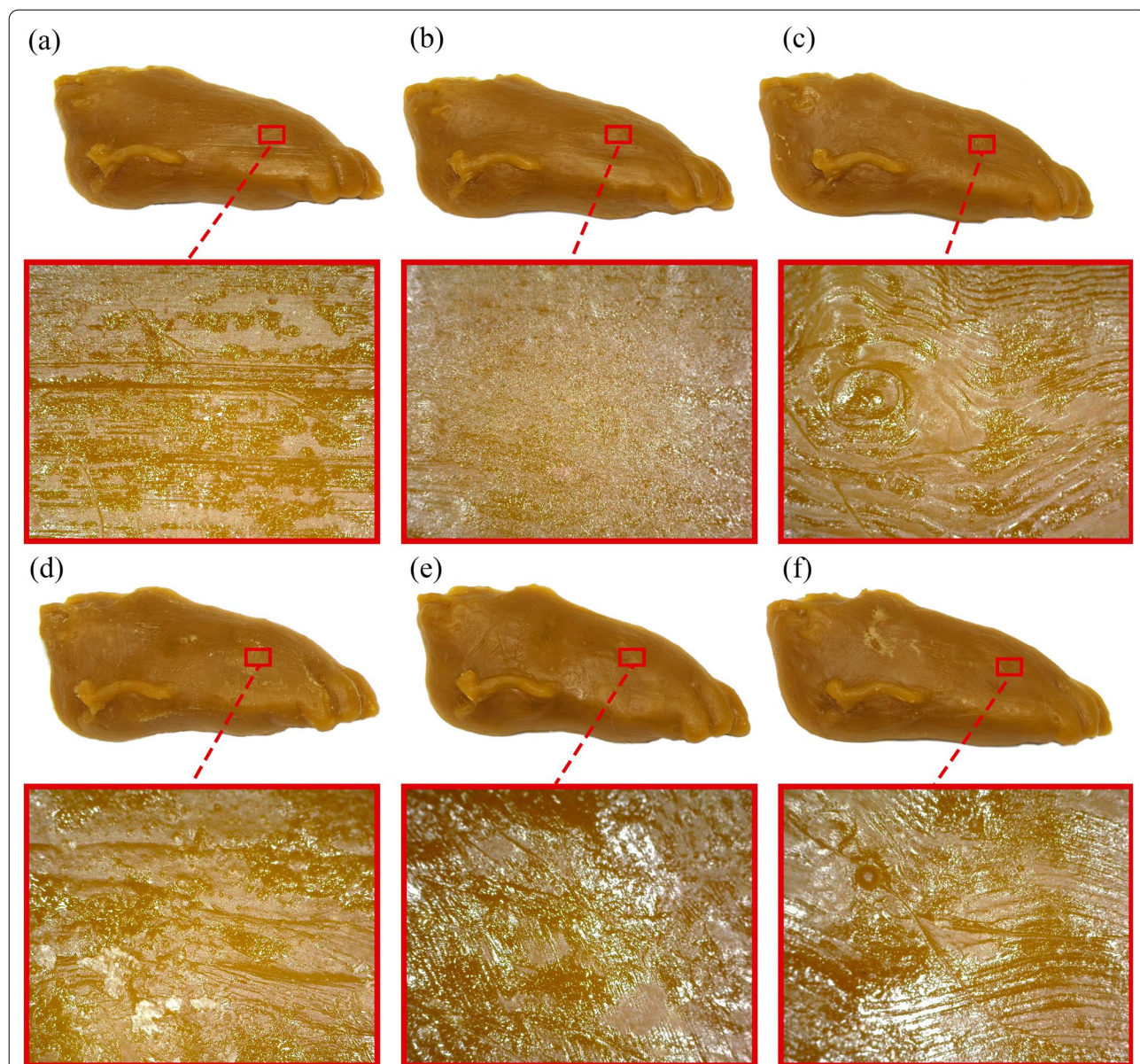

Fig. 3 Wax positive of the 3D printed models with different positions and angles: **a** Horizontal position 0º **b** Horizontal position 45º. The results of this position provide the best quality in terms of surface finishes, as observed in the respective mold analysis **c** Horizontal position 90º **d** Vertical position 0º **e** Vertical position 45º **f** Vertical position 90º

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recorded the obvious lines of the impression (Fig. 3c and f), considerably reducing the surface details of the model. Drawing from these characteristics, its use was discarded. As for the vertical positions, all three recorded the imperfections of the molds. The 0° and 90° positions show the most irregularities and impression lines. Of the three vertical positions, the one with the best results was the 45° position. However, some small flaws in the details became visible. Drawing from these data, the use of the vertical position with its respective angles was discarded because the expected results were not obtained. In all six cases, the use of petroleum jelly made possible the removal of the positive from the mold very easily while avoiding the use of force or any other operation during the handling of the parts to remove the casting positive that could cause minor damage or breakage.

Drawing from obtained data that includes both the analysis of the molds and the wax positives, it was confirmed that the molds printed in the horizontal and vertical position of 45° met the appropriate characteristics to solve the case study proposed in this paper. They both achieved optimum results in terms of the quality of the deposition of the filament per layer and the reproduction of the details. Of the two positions, the horizontal position provided the best performance. At a 45° angle, there is very little surface area on the inner side of the mold perpendicular to the printing base, which means that the layer lines are not noticeably marked. This is how a high level of detail was achieved over most of the mold. For these reasons, it was considered appropriate to use the horizontal 45° position for testing the different materials (Table 1).

In general, the ABS material achieved good results. The deposition of the filament is slightly marked and, as a result, certain fine details were not sufficiently well rendered (Fig. 4a). However, the PLA material, in contrast to ABS, was able to reproduce them. The deposition of the filament was practically unnoticeable, offering a slight improvement in the surface finish and, therefore, in the rendering of details (Fig. 4b). In turn, PLA Tough achieved slightly better results than PLA in terms of surface relief definition (Fig. 4c). In the case of PLA 3D870, as with the two previous materials, good surface finishes have been achieved, with the exception of some small imperfections (Fig. 4j).

The INNOVATEFIL PA HT material, in general, has captured the details with good quality, however, it has generated certain imperfections during the deposition of the filament in complex areas, not being able to obtain the existing details (Fig. 4d). On the other hand, the HIPS material in general has achieved a good finish, but as in the previous material, the details have been somewhat

reduced due to the deposition of the filament leaving slight marks between layers (Fig. 4e).

For the PETG material, it has generally achieved good finishes, however, the deposition of the yarns again in each layer has been marked, resulting in the loss of subtle details (Fig. 4i). Another of the materials tested, ASA, has achieved very similar results to PETG. Despite achieving good overall quality, some of the details have been lost, as the deposition of the filament is very evident (Fig. 4k).

In one of the semi-rigid materials, specifically, PP, when depositing the filament, these lines did not achieve a uniform finish, causing some loss of detail (Fig. 4f). Some stringing has also occurred in certain areas despite setting the temperature and shrinkage rate recommended by the manufacturer. This phenomenon occurs because during printing movements the extruder tip drips a small amount of material and this causes the generation of fine threads that are distributed over the entire printing area. Flexible materials, such as TPU95 A and FLEX, generated constant stringing during printing (Fig. 4g and h). Despite setting the temperature and the shrinkage speed recommended by the manufacturer, this problem has remained constant during the printing process. As a result, a significant loss of detail has occurred. As for the INNOVATEFIL POLYCARBONATE material, it has not provided valid results, as the deposition of the filament is again very marked (Fig. 4l).

NYLSTRONG is one of the materials that achieved really good finishes (Fig. 4m). The big drawback of this product is the constant generation of cracking, or delaminations, between the layers. The printing parameters recommended by the manufacturer made possible a perfect fusion. However, it has been observed that temperature is a factor to be taken into account, as fluctuations in this value favor the delamination process and increase the tendency of the mold to crack. Despite the good results in the reproduction of details, the difficulty of printing was very high. Regarding the PVA material, it provided finishes that were below expectations because it requires very specific storage conditions. It was observed that any small variation in temperature or humidity slightly modifies the surface finishes (Fig. 4n). Finally, the printing time for each of the molds in the horizontal position with the base at 45° to the printing platform ranged between 747 and 1169 min. Although the position selected at a 45° angle took the longest to print compared to the other angles that were tested, it is undoubtedly the one with the best quality on the final finishes.

During the processing of the wax positive, it was possible to corroborate the data obtained previously (Fig. 5). In the case of PLA (Fig. 5b), PLA Tough (Fig. 5c), and PLA 3D870 (Fig. 5j), the results were very similar. Of the three, the PLA Tough performed
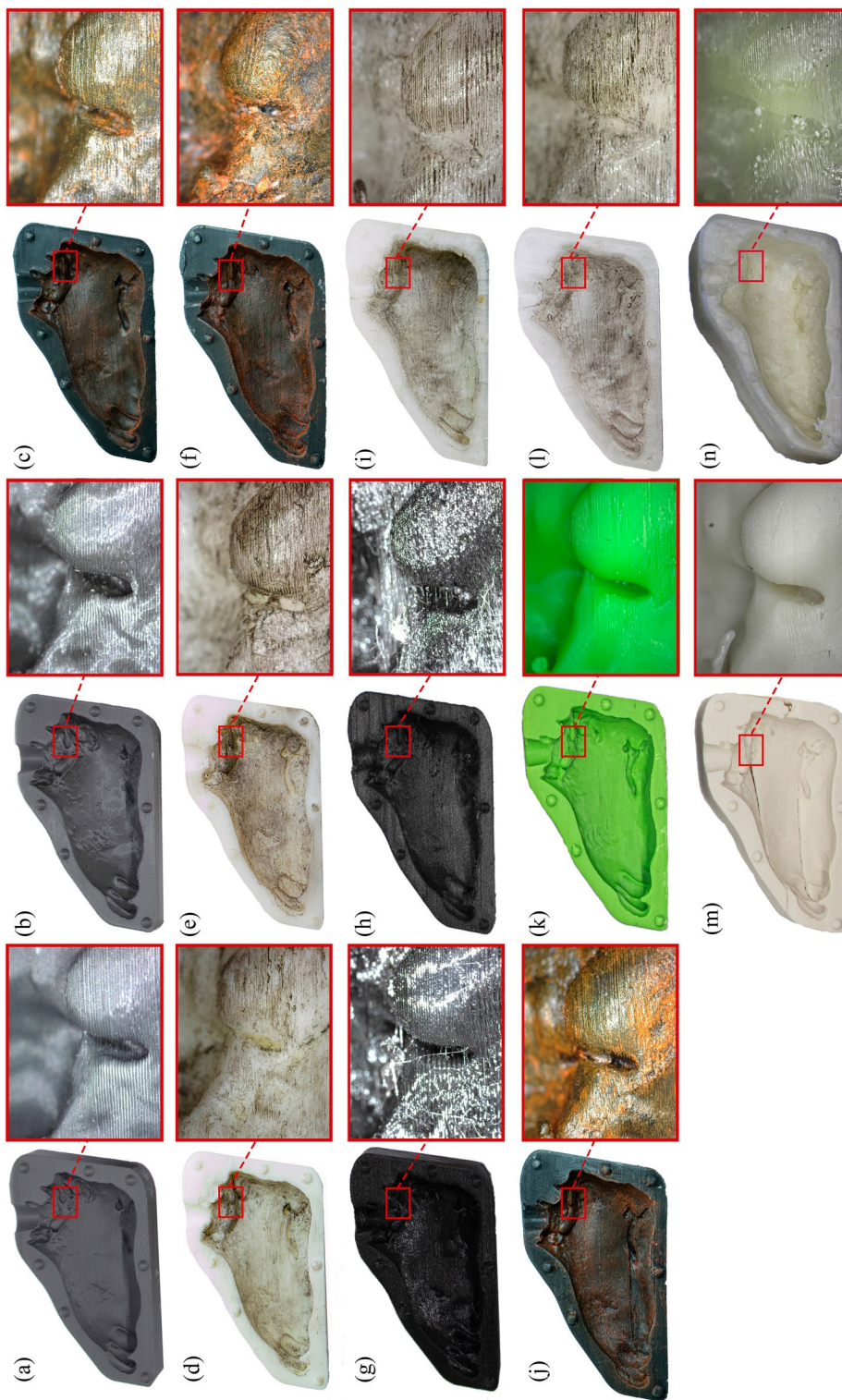
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Fig. 4 3D printing of the molds with various materials: **a** ABS **b** PLA **c** PLA Tough (a colored glaze has been applied to better appreciate the irregularities and the line of each layer). The results of the surface details analyzed in the different materials have shown that this material is the one that provides the best quality **d** INNOVATEFIL PA HT (a colored glaze has been applied to better appreciate the irregularities and the line of each layer) **e** HIPS (a colored glaze has been applied to better appreciate the irregularities and the line of each layer) **f** PP (a colored glaze has been applied to better appreciate the irregularities and the line of each layer) **g** TPU 95 **h** FLEX **i** PETG (a colored glaze has been applied to better appreciate the irregularities and the line of each layer) **j** PLA 3D870 (a colored glaze has been applied to better appreciate the irregularities and the line of each layer) **k** ASA **l** INNOVATEFIL POLYCARBONATE (a colored glaze has been applied to better appreciate the irregularities and the line of each layer) **m** NYLSTRONG **n** PVA

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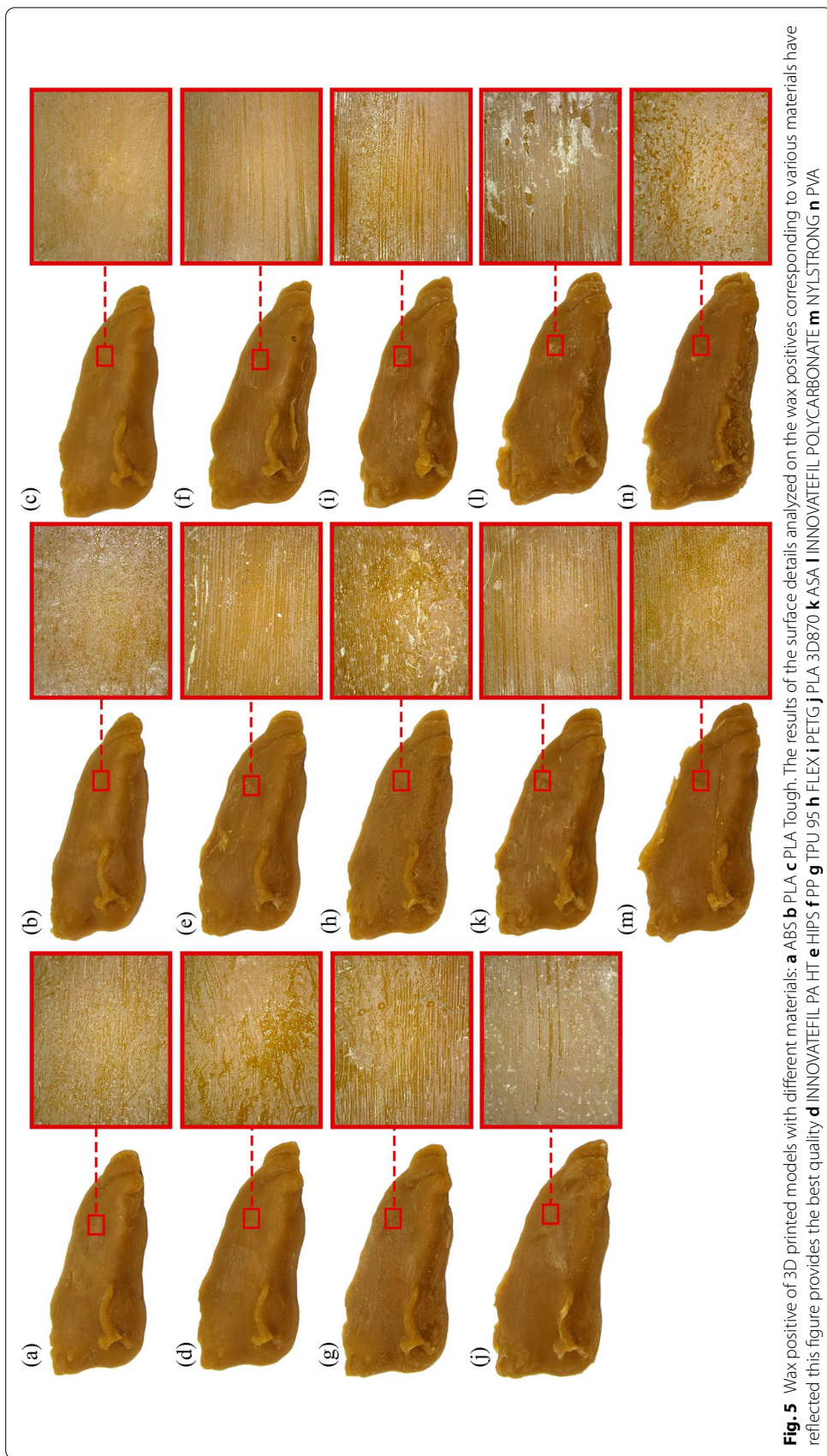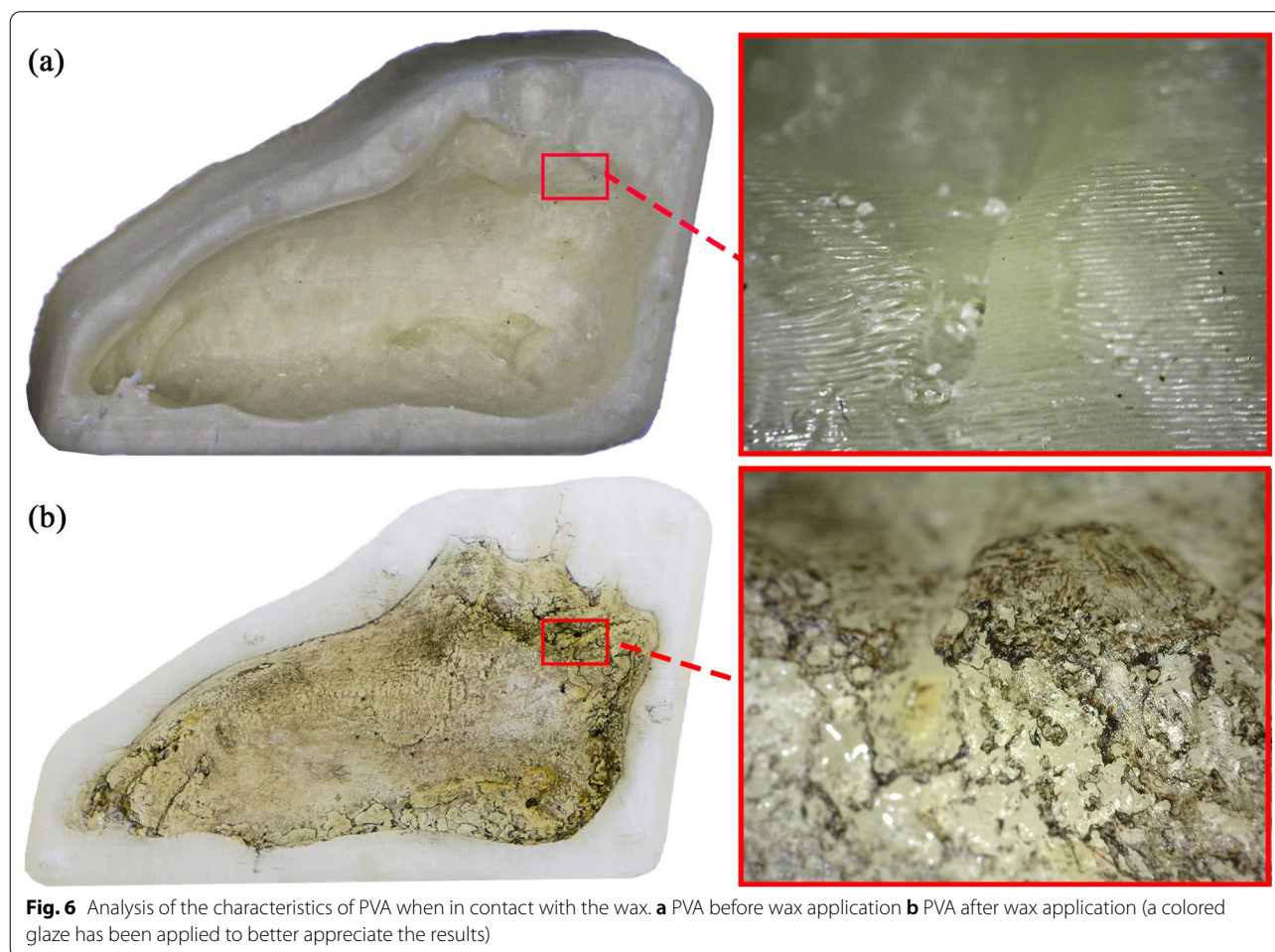
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Fig. 5 Wax positive of 3D printed models with different materials: **a** ABS **b** PLA **c** PLA Tough. The results of the surface details analyzed on the wax positives corresponding to various materials have reflected this figure provides the best quality **d** INNOVATEFIL PA HT **e** HIPS **f** PP **g** TPU 95 **h** FLEX **i** PETG **j** PLA 3D870 **k** ASA **l** INNOVATEFIL POLYCARBONATE **m** NYLSTRONG **n** PVA

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the best because it shows a slightly better finish than the other two. Consequently, materials such as ABS (Fig. 5a), HIPS (Fig. 5e), PETG (Fig. 5i), ASA (Fig. 5k), and INNOVATEFIL POLYCARBONATE (Fig. 5l), tend to record filament at greater or lesser extent causing the loss of small details. Other materials such as INNO-VATEFIL PA HT (Fig. 5d) have shown good detail in almost all areas of the mold, with the exception of a few finer and more complex parts. Regarding flexible materials, in the TPU 95 A (Fig. 5g) and in FLEX (Fig. 5h), the generation of a stringing caused a significant loss of definition, the reason why these products were discarded. In the case of NYLSTRONG, the details obtained were very good, but the constant generation of cracking is a clear reason why its use was discarded (Fig. 5m). Finally, water-soluble PVA filament was tested to see if it could be used to make reproductions using the lost mold technique, that is, by dissolving the cast to extract the copy. After several tests, the mold was worn and the surface was altered due to the temperature of the wax during pouring. This resulted in a considerable loss of detail, which led to discarding it as a possible option (Figs. 5n and 6).

Drawing from the obtained results, it was concluded that the thermoplastic materials (PLA, PLA Thought and PLA 3D870) offered the best finishes. Among them, PLA Thought has shown the best performance both during mold printing and through the process of obtaining the wax positive. The complete reproduction of details and the ease with which the positive can be extracted from the mold make it a very suitable material for 3D printing molds, ensuring high quality and fidelity in the production of the wax facsimile.

One factor that was taken into account during this study was the possible alteration of the properties of the materials used to create the molds due to thermal degradation. This factor is determinant when 3D printed objects have a support or mechanical function where its use is acting under different pressure forces. Large forces are required depending on the printed volume to alter the mechanical properties by thermal degradation until breakage. This is analyzed by mechanical tests, either
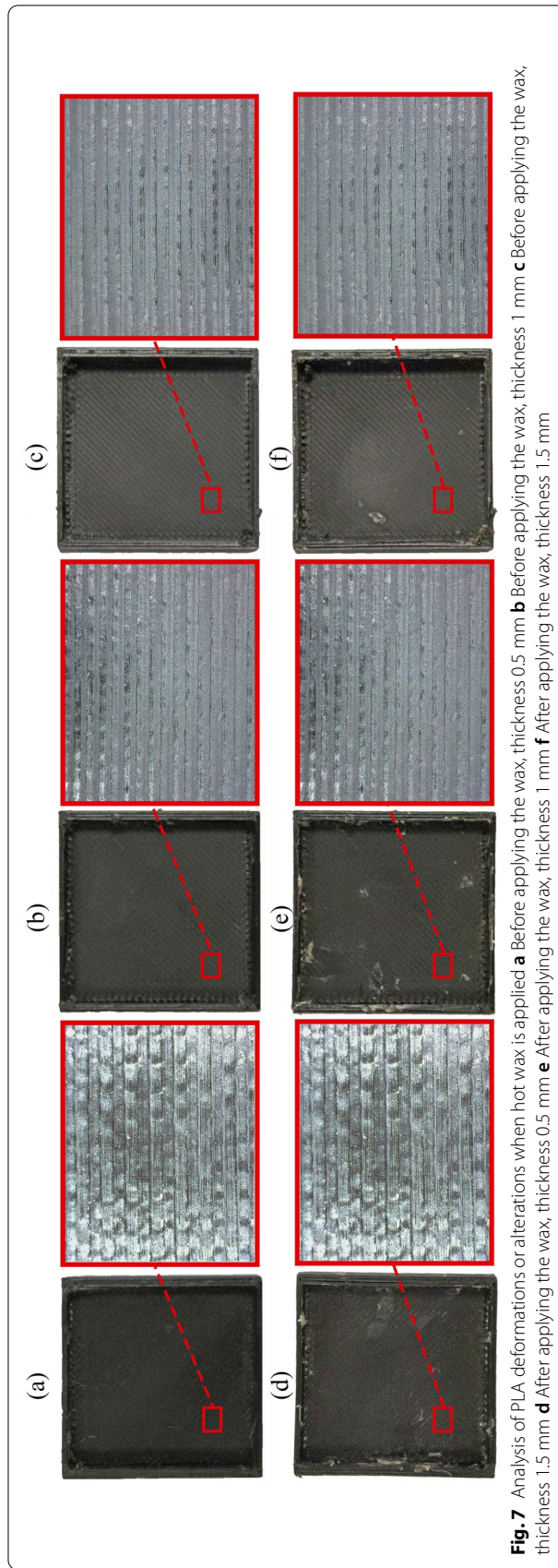

Fig. 6 Analysis of the characteristics of PVA when in contact with the wax. **a** PVA before wax application **b** PVA after wax application (a colored glaze has been applied to better appreciate the results)

Fig. 7 Analysis of PLA deformations or alterations when hot wax is applied **a** Before applying the wax, thickness 1.5 mm **b** Before applying the wax, thickness 1 mm **c** Before applying the wax, thickness 0.5 mm **d** After applying the wax, thickness 1.5 mm **e** After applying the wax, thickness 1 mm **f** After applying the wax, thickness 0.5 mm
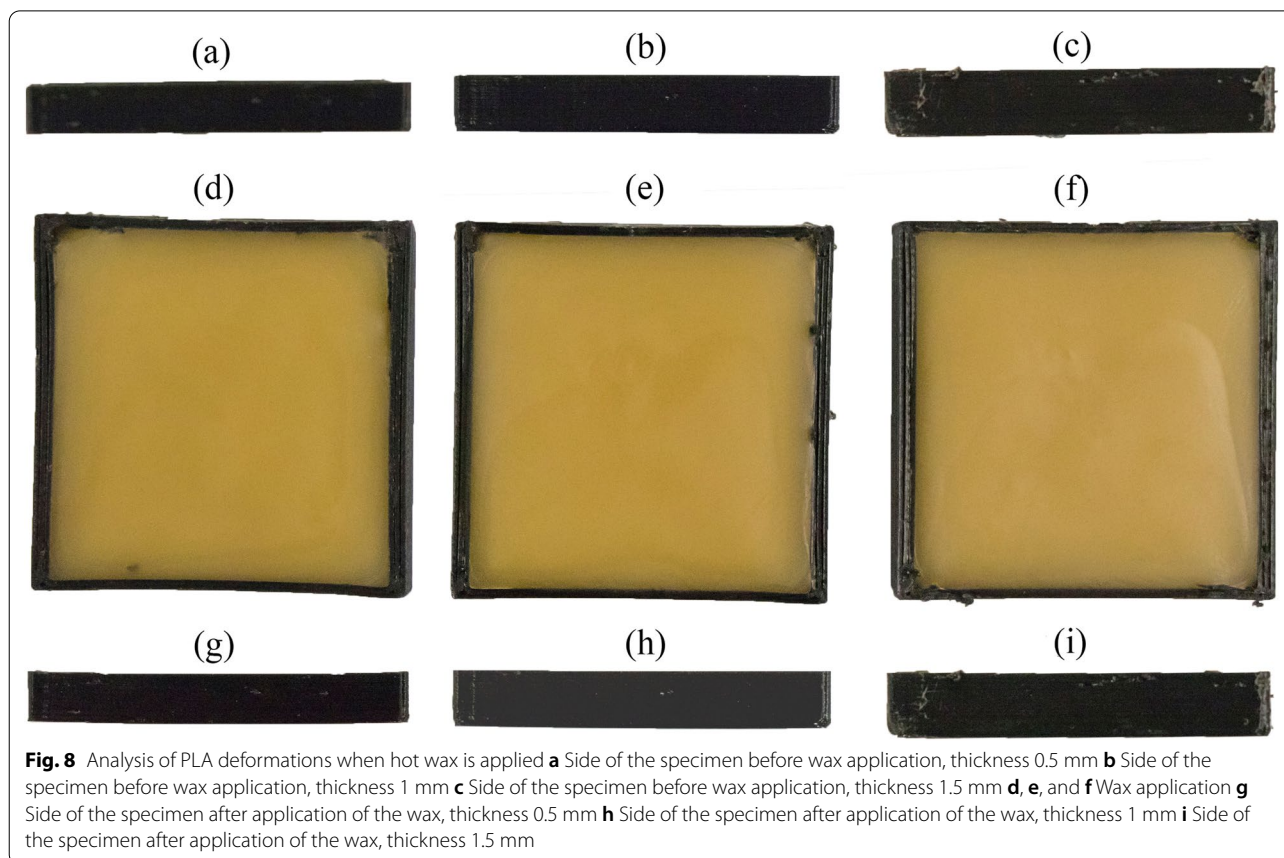
Fig. 8 Analysis of PLA deformations when hot wax is applied **a** Side of the specimen before wax application, thickness 0.5 mm **b** Side of the specimen before wax application, thickness 1 mm **c** Side of the specimen before wax application, thickness 1.5 mm **d**, **e**, and **f** Wax application **g** Side of the specimen after application of the wax, thickness 0.5 mm **h** Side of the specimen after application of the wax, thickness 1 mm **i** Side of the specimen after application of the wax, thickness 1.5 mm

tensile or flexural. When a certain force is applied at a given point the material undergoes a deformation and therefore a temperature increase that eventually produces a permanent deformation in the material [23, 24]. However, in our study, the molds were not subjected to bending or tensile forces at any time, so deformation was not expected. However, since the reproduction material we were going to use in the molds was molten wax, we performed a temperature test using specimens of different wall thickness to analyze the deformation of the different materials that had given the best results in terms of reproduction accuracy. The wax was poured at 75ºC on 0.5, 1 and 1.5 mm specimens (This last mentioned thickness is the one that was established to the wall of the molds), and no degradation or deformation of the material was observed (Figs. 7 and 8) considering that PLA melts at 180ºC approximately.

Creation of the facsimile

The elaboration of the facsimile of the anatomical artifact consists of six fragments. These are: (1) little finger, (2) ring finger, (3) middle finger, (4) right foot of the fetus, (5) left hand, and (6) the protruding part of the fetus, vagina,

uterus and placenta (Fig. 6a1). Because not all fragments present the same difficulty in reproducing their volume, the less complex and smaller fragments have been developed in two pieces (Fig. 9b1, b2, c1, c2, d1, d2, e1 and e2), with the more complicated parts consisting of 9 (Fig. 9f1 and f2) and 14 (Fig. 9g1 and g2) pieces.

The use of elastic tapes and plasticine on the outer joints of each piece that made up the mold (Fig. 10a and b) has provided great resistance to the whole assembly. This prevented certain movements during handling that could cause the pieces to dislodge minimally. With regard to the wax casting in layers in the corresponding fragments of each mold, the wax was correctly distributed over the entire surface until the solid piece was achieved (Fig. 10a–c).

The result obtained has greatly exceeded the initial expectations, as all the details, even the most minute ones, have been recorded with high quality. Once all the molds had been removed (Fig. 10d), some small cracks in the joining areas were reworked with different instruments (Fig. 10e). The results obtained in the facsimile show a very high level of similarity with the original work (Fig. 10f and g), reproducing all the surface Details.
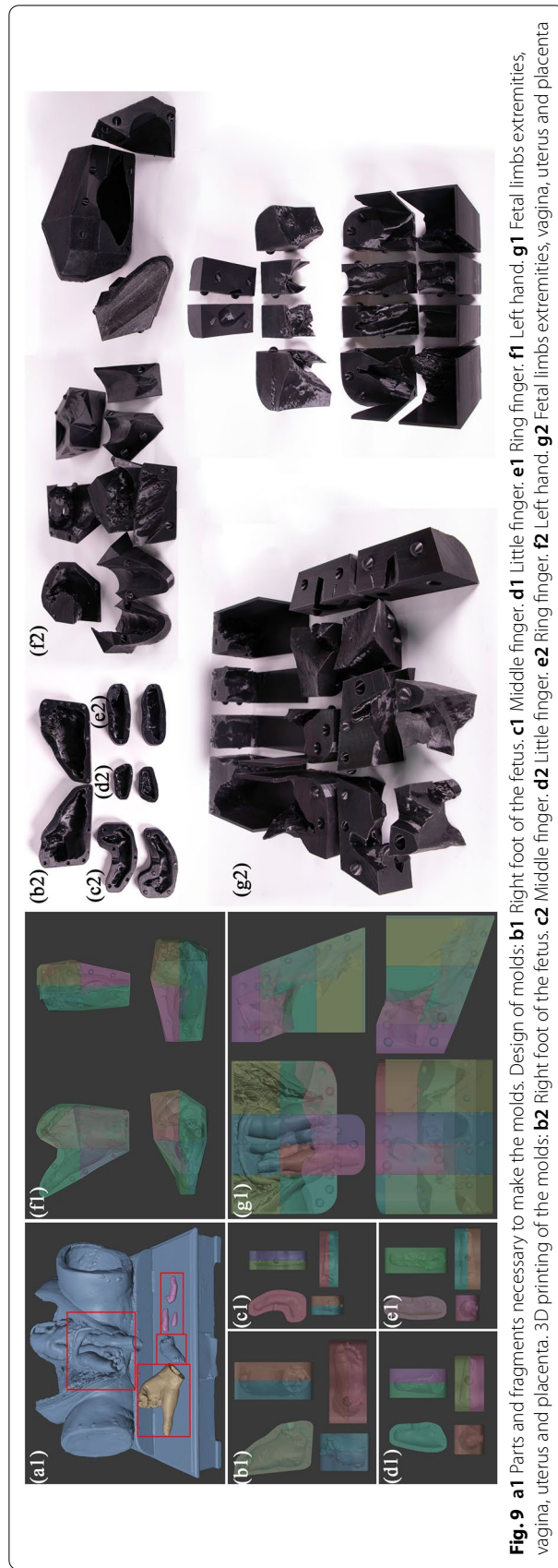
Fig. 9 **a1** Parts and fragments necessary to make the molds. Design of molds: **b1** Right foot of the fetus. **c1** Middle finger. **d1** Little finger. **e1** Ring finger. **f1** Left hand. **g1** Fetal limbs extremities, vagina, uterus and placenta. 3D printing of the molds: **b2** Right foot of the fetus. **c2** Middle finger. **d2** Little finger. **e2** Ring finger. **f2** Left hand. **g2** Fetal limbs extremities, vagina, uterus and placenta

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Fig. 10 **a** and **b** Process of pouring the wax into the mold. **c** Completion of pouring the wax into the molds. **d** Demolding process of the facsímile. **e** Polishing of the details. **f** Original work Internal versión. **g** Finished facsimile of the work

Obtaining the facsimile has allowed a deeper understanding of the problems of intervention, the methods of approach, and needs and difficulties when dealing with each treatment.

This made it easier to make decisions regarding the treatment of the real work. The tools used in this research can help professionals in the field of conservation and restoration of cultural heritage to reduce manipulations during interventions, to better understand the constructive technique of the models, and to test and plan conservation strategies with determination.

Conclusion

The use of 3D technologies based on digitization by structured light scanning, modeling the forms in silico, and 3D printing of the molds is an effective tool when the conservator-restorer requires a facsimile on which to test different solutions before applying the selected treatment

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directly to the work. The tests conducted in relation to the position and printing angles of the molds allowed us to analyze differences obtained in each case when depositing the 3D printing filament on the reproduced components. This permitted us to select the most suitable ones to achieve maximum quality and fidelity in the reproduction of the volumes. As for the chosen materials, it should be noted that all of them have perfectly registered the volumes despite showing some differences in the finish of the surface details. We conducted a substantial analysis to determine the product that has least marked the linear pattern on the surface of both the mold and the wax positive, while also providing the greatest definition and fidelity.

The virtual design of the rigid molds gave us the opportunity to study their design in detail in order to achieve a perfect fit between the fragments that make up the mold during 3D printing. The incorporation of various registration keys strategically located in each fragment has ensured the exact position of the different pieces that make up the mold. Likewise, the fixing system used by means of elastic bands and the sealing of some joints with plasticine provided the whole mold with sufficient stability and water tightness to ensure the absence of leaks during the wax casting. The demolding process was sped up by the application of petroleum jelly, as no resistance was encountered during the removal of the casting positive. The tools used in this research can help professionals in the field of conservation and restoration of cultural heritage to reduce manipulations during interventions, to carry out accurate volumetric reintegrations, and to test and plan conservation strategies with determination.

Abbreviations
FDM: Fused Deposition Modeling; ABS: Acrylonitrile Butadiene Styrene; PETG: Polyethylene Terephthalate; ASA: Acrylonitrile Styrene Acrylate; NYLSTRONG: Nylon [PA6] Polyamide With Glass Fiber; HIPS: Polystyrene and Polybutadiene Rubber; INNOVATEFIL POLYCARBONATE: Polycarbonate; PP: Polypropylene; PLA: Polylactic acid; PLA Tough: Polylactic acid; PLA 3D870: Polylactic acid; INNOVATEFIL PA HT: Polyamide; PVA: Polyvinyl alcohol; TPU 95A: Polyurethane; FLEX: Polyurethane; STL: Standard template library.

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The authors declare that they have no competing interests.

Author details
[1]Department of Painting and Conservation-Restoration, Faculty of Fine Arts, Complutense University of Madrid, Ciudad Universitaria S/N, 28040 Madrid, Spain. [2]Department of Design and Image, Faculty of Fine Arts, Complutense University of Madrid, Ciudad Universitaria S/N, 28040 Madrid, Spain.

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