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3D SCANNING FOR COMPARATIVE ANALYSIS OF MANUFACTURE AND DETERIORATION TRACKING: A CASE STUDY OF THE 18TH CENTURY WAX VENUS DE' MEDICI

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Abstract

In recent years, 3D digital technologies have proven to be essential tools for professionals in the field of conservation and restoration of cultural heritage. This research presents the potential offered by structured light 3D scanners and the geometry analysis strategies carried out for the comparative study between the plaster Venus de' Medici of the Royal Academy of Fine Arts of San Fernando (Madrid) and the Anatomical Venus in wax of the Royal College of Surgery of San Carlos (Madrid), as well as the monitoring of the state of conservation. Using high-precision, high-resolution 3D morphology, the results obtained have been highly satisfactory, as it has made it possible to find the dimensional differences to the millimetre, offering a better understanding of the construction technique and the state of conservation in order to detect the evolution of the damage and to be able to act quickly.

Keywords

3D digitisation, 3D scanning, comparative analysis, deterioration monitoring, conservation-restoration, anatomical wax sculpting, Venus de' Medici.

1. *Introduction*

During the second half of the 18th century, the teaching of anatomy was boosted by the new ideals of the Enlightenment. The result of this was the opening of establishments such as the Royal Colleges of Surgery, which contributed significantly to the implementation of new learning methods. With the aim of offering their students a practical approach to the knowledge of the human body in order to improve the training of future surgeons, these centres collected anatomical preparations and had cabinets in which wax casts of body sections, internal organs and complete bodies were made.

After completing a period of two years as a pensioner in Paris to perfect his anatomical training, Ignacio Lacaba (1745-1814) - royal surgeon of the Chamber - returned to Madrid and took up his post as master dissector at the Royal College of Surgery of San Carlos, with the aspiration of promoting anatomical wax sculptures as didactic material, in imitation of the collections that already existed in other European centres of reference (Chinchilla, 1841-1846). His figure combined scientific medical learning with knowledge of the technique of anatomical wax sculpting, whose workshop secrets he described in detail in the book he published in collaboration with the Catalan doctor Jaime Bonells under the title Curso completo de anatomía del cuerpo humano (Bonells, & Lacaba, 1800). In 1786 he undertook a major professional challenge by devoting his efforts to the construction of a life-size female figure that he "worked on and anatomised in wax", finished in December of that year and referred to in the Memorial of January 1787 as the anatomical Venus, of which he provided a detailed description (Memorial Literario, Instructivo y Curioso de la Corte de Madrid, enero de 1787). In his medical Venus, which was polychromed to make it more plausible, he succeeded in combining classical beauty with the usefulness of the wax artefact as a substitute for dissected corpses. His source of inspiration was the sculpture of the Medici Venus, a 1st century BC marble copy of a 3rd century BC Greek bronze original, documented in 1638 in the Villa Medici in Rome and later transferred to the Uffizi Gallery in Florence (Fig.1a) (Sánchez Ortiz, Del Moral, & Ballestriero, 2013). This work gained great recognition and achieved worldwide fame through the Grand Tour of travellers, connoisseurs and artists who visited and admired it until it became one of the most reproduced statues of all time (Haskell, & Penny, 1990). Among the artists was Antonio Raphael Mengs - Charles III's first court painter - who, in 1780, obtained permission from the director of the Uffizi Gallery to extract the plaster cast directly from the marble Venus with the help of Vincenzo Ciampi, after being refused permission to use the institution's existing moulds (Mengs, 1780). The plaster copy obtained was a part of his collections in the Madrid workshop and it was later transferred to the Royal Academy of Fine Arts of San Fernando in Madrid (RABASF). It seems plausible to think that the anatomical dissector may have had the existing moulds at his disposal in that institution so as to obtain the body parts that would make up the wax figure of the woman. In order to adapt the model to the requirements of anatomy teaching at the Royal College, he made the anatomical structures that make up the pectoral area and the abdominal region from dissections made on cadavers from the General Hospital.

1.1 Description of the two Venuses

The plaster sculpture of the Venus de' Medici, conserved in the RABASF (inv. no.: V-076), is dated 1770, measures 1.62 x 0.53 x 0.49 m, and was part of the collection of sculpture casts that Mengs had formed over the years during his travels in Rome and Florence, and which he donated to the king so that the institution could provide plaster models that would serve as a guideline and source of inspiration for Spanish artists (Fig.1b). On 23 June 1770, the sculptor Vincenzo Ciampi signed a document in which he assured that he had received the sculpture of the Medici Venus without any breakages or faults "tante nelle parti antiche che in quelle restaurate" (Becattini, 1991), undertaking to return it in the same state as it had been consigned to him once he had obtained the copy requested (Negrete Plano, 2005 & 2012).

The medical Venus in wax, conserved in the "Javier Puerta" Anatomy Museum located in the Faculty of Medicine belonging to the Complutense University of Madrid (inv 000034), is dated 1787, measures 1.59 x 0.53 x 0.49 m, and was made by the anatomical dissector, Ignacio Lacaba, for the cabinet of the Royal College of Surgery of San Carlos (Fig. 1c). For the construction of the figure he received, on 10 January of that year, a payment of two thousand four hundred and ninety-nine and twenty-four billon maravedís (Libro de Acuerdos para el Real Colegio de Cirugía de San Carlos establecido en Madrid, 1787). The figure was fitted with two covers - one on the pectoral area and the other on the abdominal part -, which, when lifted, reveal the anatomical structures. In the pectoral region, more superficial layers corresponding to the mammary glands, the pectoral muscles, and the entire vascular network that irrigates the area are shown. In the abdominal region, however, both the skin layers and the abdominal hollow viscera have been removed in order to allow detailed observation of the entire vascular network of the great vessels and their branches. The kidneys, the posterior muscular region, the urinary and reproductive apparatus with the uterus, fallopian tubes and ovaries and their vascularisation are depicted. Finally, the womb has a cover which, when removed, reveals its inner anatomy (Memorial Literario, Instructivo y Curioso de la Corte de Madrid, enero de 1787).

Fig. 1: a) Venus de' Medici, marble copy, 1st century BC**,** the Uffizi Gallery, Florence; b) Venus de' Medici, plaster copy, 18th century, RABASF; c) Venus de' Medici, polychrome wax copy, 18th century**,** "Javier Puerta" Anatomy Museum, Faculty of Medicine (UCM).

The current state of conservation of the sculpture makes it impossible to view the figure as intended by its creator. The serious alterations affecting the anatomical model have required an exhaustive analysis to determine the agents of degradation that have caused its current state, and there is a high risk of collapse of the whole if urgent measures are not taken to halt the deterioration. For this reason, it has been essential to choose digital tools that allow a rigorous diagnosis of the serious structural damage (Donadino, Sambuelli, Spanò, & Picchi, 2018; Jo, Hong, Jo, & Kwon, 2020; Valzano, & Mannino, 2020). Some recent research has demonstrated the usefulness of comparative analysis between sculptures with the help of virtual models (Girelli, Tini, D'Apuzzo, & Bitelli, 2020) and also of monitoring the state of conservation through periodic digitisations of a sculpture (Payne, 2019). Furthermore, in 2017, a comparison of the wax Venus de' Medici with the Venus de' Medici in The Royal Cast Collection, Copenhagen was carried out in order to understand the process of creation (Sterp, 2017). The insufficient quality of the photogrammetric models used at the time did not allow for a detailed analysis or to specify possible hypotheses of the creation process. In the present study, structured light scanners were used. These devices base their operation on the projection of a light pattern on the object, which is subsequently captured by the device's sensors to determine the position of each point on its surface, analysing the deformation of this pattern from different points of view by means of a triangulation system (Bell, Li, & Zhang, 2016).

Compared to photogrammetry, structured light 3D scanners have different advantages, such as better volumetric accuracy (Marić, Šiljeg, Cukrov, Roland, & Domazetović, 2020), better results in the digitisation of small or medium-sized parts (Graciano, Alvarado, Sánchez, & Higueruela, 2017), much higher data processing speed, a preview of results during the scanning process, lighter and more portable equipment (Adams, Olah, McCurry, Potze, & Wilson, 2015), no special requirements for the working area (Montusiewicz, Miłosz, Kęsik, & Żyła, 2021), as well as a better response to figures with shiny surfaces, such as varnished wax.

In order to compare the two sculptures volumetrically and to determine whether the moulds of the RABASF Venus de' Medici could be used for the wax Venus of the "Javier Puerta" Anatomy Museum, both figures were digitised using two types of structured light scanners. The 3D models obtained by this procedure were also used to thoroughly analyse the state of conservation of the anatomical wax model, with special attention paid to its degree of inclination, as well as to plan a constant monitoring of the alterations detected through serial measurements with the help of digital models.

2. *Methodology*

2.1 Study and diagnosis of the state of conservation of the anatomical model

As part of the documentation and diagnostic processes, the surface of both sculptures was examined using magnifying glasses and a Dino-lite digital microscope in order to identify possible traces left by the tools used by the sculptors, as well as marks that may have been caused by previous manipulation processes or interventions. The aim was to locate the imprint left in the joint areas of the different moulds or, failing that, any signs of past erasure with files, spatulas or other tools. The importance of these traces lay in the fact that they could confirm the use of the same moulds if they coincided in both shape and location.

The surface of the wax Venus was also specifically searched for traces or marks corresponding to the anchoring points of the support that the RABASF plaster Venus had, as these traces could confirm that the anatomical model had been made by moulding from this sculpture.

Finally, attention was paid to those alterations related to the lack of stability of the wax figure, such as fissures, cracks, fractures and deformations, recording both their location and their extent.

2.2 Digitisation

The two sculptures compared in this study, the wax Venus de' Medici from the Faculty of Medicine and the Venus de' Medici from the RABASF, were digitised by combining two structured light scanners, Eva and Space Spider from the Artec company.

The use of two scanners from the same company is based on their absolute compatibility for a combined use on a model in the same work session, allowing high accuracy in the combination of meshes to be obtained. The Eva scanner has been used to record the general volume, while the fractures, cracks and fissures have been digitised with the Space Spider, in order to obtain greater detail.

Both models have a high volumetric accuracy, 0.05 mm for Space Spider and 0.1 mm in the case of the Eva scanner, which ensures a high reliability of the data obtained. The main differences between these two devices are related to the resolution and scanning area. Thus, the resolution of the Space Spider can reach 0.1 mm, being able to capture the finest details of the surface of the figure. Its scanning area is 90 x 70 mm when the device is placed at the closest distance range to the surface of the object and 180 x 140 mm at the furthest range. All these features make it ideal for scanning small shapes, even as small as 5 mm, where a high degree of surface detail is required. This is the reason why this scanner has been used to digitise those areas of the figures where there were alterations, such as cracks or fractures, which needed to be recorded with the highest possible definition. However, its small scanning area and working distance range, which is excessively close to the figure, make it very difficult to record large surfaces with such a device, so the decision was made to use a different model to capture the general volumes of the sculptures, an Artec Eva scanner being chosen, as mentioned above, due to its compatibility with Space Spider and the fact that both share the same processing software, Artec Studio 15 Professional.

The Artec Eva scanner has a fairly wide scanning area of 214 x 148 mm at its closest range and 536 x 371 mm at its furthest range, allowing it to capture quite large regions. However, the resolution is slightly lower than that mentioned for Space Spider, reaching a maximum of 0.2 mm, which means that its definition of small superficial inflections is likewise somewhat lower. It is therefore a device designed for the digitisation of medium and large objects, where it is not essential to capture the finest surface details. However, as explained, in this study the records from both scanners were combined to take advantage of the features of each of them, accurately superimposing the partial high definition scans obtained with Artec Space Spider from the areas with cracks or breaks on the lower resolution model scanned with Artec Eva.

The strategy of three-dimensional registration of the sculptures consisted in surrounding the piece from different points of view at a distance of approximately 20-30 cm in the case of Artec Space Spider and 40-90 cm in the case of Artec Eva.

The data processing obtained from the models has been carried out using the Studio Professional 15.1 software, from the same company as the Artec scanner. Post-processing has consisted in various phases. The first of them has focused on cleaning impurities, eliminating all elements foreign to the model with the manual lasso tool to avoid possible errors or non-existent volumetric artefacts. In the second phase, the alignment was carried out using the rigid option in manual mode. For this, three or more points in common have been established in each scanned fragment. The rigid option only applies the revolution and rotation algorithms, ensuring maximum volume fidelity. The next phase focused on eliminating all those frames with errors or anomalies from the same scan and with duplicated areas. During the registration process in certain complex areas with very thin matter thicknesses, the scanner begins to duplicate the model, merging two models with a slight deviation. For this reason, each frame has been analysed in detail, suppressing all those that did not correspond to a real volume, in order to obtain maximum volumetric fidelity. The fourth phase has been one of the most relevant for achieving maximum precision in the different fragments aligned. The global registration tool uses an algorithm that converts all surfaces to a single coordinate system. This corrected the small imperfections during the union of the different fragments aligned. Once the maximum volumetric fidelity in the maximum error scale provided by the programme had been obtained, all those outliers were eliminated. In the case of the Artec Space Spider, the range with excellent results oscillates between 0 and 0.1 while middling results are obtained with >0.4 values. In the case of Artec Eva, the results are good within a range of 0-0.3, middling results being achieved within the range >1.0. Therefore, all those values above 0.2 were eliminated. To conclude the model, the last two phases consisted in generating the polygonal mesh by means of a hard fusion applying a 0.2 resolution, and the colour texture was obtained with a 16384x1638 resolution.

2.3 Volumetric analysis

In order to make a morphological comparison between both figures and to be able to determine if the two coincide in shape and size, the computer programme *Artec Studio 15 Professional* was also used to analyse the previously scanned models of each sculpture, since it has various functions oriented towards the alignment of the 3D meshes. First, a different colour was given to each sculpture to clearly differentiate them once superimposed. Next, an attempt was made to align them automatically, but it was not successful as there were excessive discrepancies between the two works, which is why the decision was made to determine fifteen pairs of analogous points in each model to help achieve a better correspondence. This did not result in a satisfactory alignment either, so it was decided to carry out the operation manually, making the feet of both figures coincide at first, since that would theoretically be the least deformed area of the figure as it is less subject to possible inclinations or changes in position. Once both figures were placed with this new reference, it was possible to appreciate that there was an extraordinary coincidence in the anatomy of the lower limbs but also a notable deviation of the upper portions of the wax sculpture with respect to the plaster sculpture, so it was decided to compare the different regions separately. In this way, following the lower extremities, the thoracic regions and the heads of both Venuses were successively aligned. To facilitate the morphological comparison of both works, the visualisation mode known as *X-Ray* was used, since it makes it possible, by means of transparency, to view areas hidden by structures located closer to the observer.

In addition to superimposing the 3D meshes, multiple equivalent distance measurements were made on one figure and the other to see if they matched. For this purpose, use was made of the Linear measure function, which determines the distance in a straight line between two points selected by the researcher. Global measurements were taken of, for instance, the height and width of the sculptures, and also of specific anatomical regions, taking similar reference points.

In order to determine if there was any difference in inclination with respect to the vertical axis, the angle between the lines joining the sternal manubrium and the centre of the heel of the main supporting leg- in this case, the left one- was determined.

Finally, the volumetric examination of the two Venuses using *Artec Studio 15 Professional* concluded with the creation of *surface distance maps*, including a general one for the whole figure, as well as three specific ones for each of the aforementioned regions: lower limbs, trunk and head. The aim of this approach was to confirm whether both sculptures had been made with the same moulds and, if so, to determine both the possible global deviations of the wax sculpture and the partial inclinations or deformations of each anatomical area.

2.4 Monitoring and control of alterations due to lack of stability of the wax figure

To monitor the state of conservation, the two models were again superimposed, making the part of the feet coincide in order to make it possible for one to see the deviations that the wax Venus has undergone with respect to the plaster Venus. The study was complemented with the help of surface distance maps so as to find the maximum precision in millimetres of the deviations suffered by the wax model. In order to progressively analyse the results based on the distance in millimetres, the scanning error parameter was manipulated. By default, at the end of the calculation, this parameter appears to the maximum extent, showing the best result. It was gradually manipulated down to 0.001 mm to observe the different error heights during the calculation and comparison process. At this point, the colour scale was fundamental to obtain clear conclusions. The colours of the map range from red, which represents a positive distance, to blue, which corresponds to a negative distance. The green colour represents the distance between the surface close to zero, and the orange colour represents the distance above or below the limits of the scale.

On the other hand, all those alterations such as fractures and cracks that seriously damage the state of conservation of the anatomical wax model were measured. To do this, we first used Geodesic measures, which consist in calculating the shortest distance between two or more points on the surface of the scanned model, adapting perfectly to the planimetry of the model. In this way, it has been possible to accurately measure the extent of each fracture or crack. Secondly, the measurements were used through Linear measure at different points to find the separation of the fractures or cracks.

3. Results and discussion

3.1 Pathologies and causes of alteration

The sculpture of the wax Venus has numerous damages that affect both an aesthetic-formal assessment and its structural stability. The surface is covered with a thick layer of dust particles that have become embedded in the waxy paste due to its high retention at room temperature. Close inspection of the work reveals previous undocumented restoration work, which was probably carried out to re-attach fragments damaged during the handling and moving of the figure. In the areas coinciding with the joining edges, there were traces of adhesive and wax pastes, which had been added at high temperature, covering not only the damaged areas but also the surrounding original parts (Fig. 2).

Over time and in response to the fluctuations in the relative humidity (RH) and temperature of the room where the statue is displayed, numerous fractures, cracks and detachments have formed, this damage being mainly located in the joint areas, which suggests that the object has been subjected to movements by unqualified personnel who did not take into account the weight and fragility of the statue. The decrease in fatty acids and free alcohols leads to an increase in acidity, polarity and rigidity (Fig. 2).

The Venus de' Medici in Wax is in a fragile state and shows significant structural damage as a result of the constant manipulation it has undergone over the course of its lifetime due to changes of location, removals and relocations. To this anthropic alteration factor, we must add the environmental conditions with strong fluctuations in the RH and temperature parameters. As a result of their action, mechanical stresses have taken place in the waxy pastes which, after constant

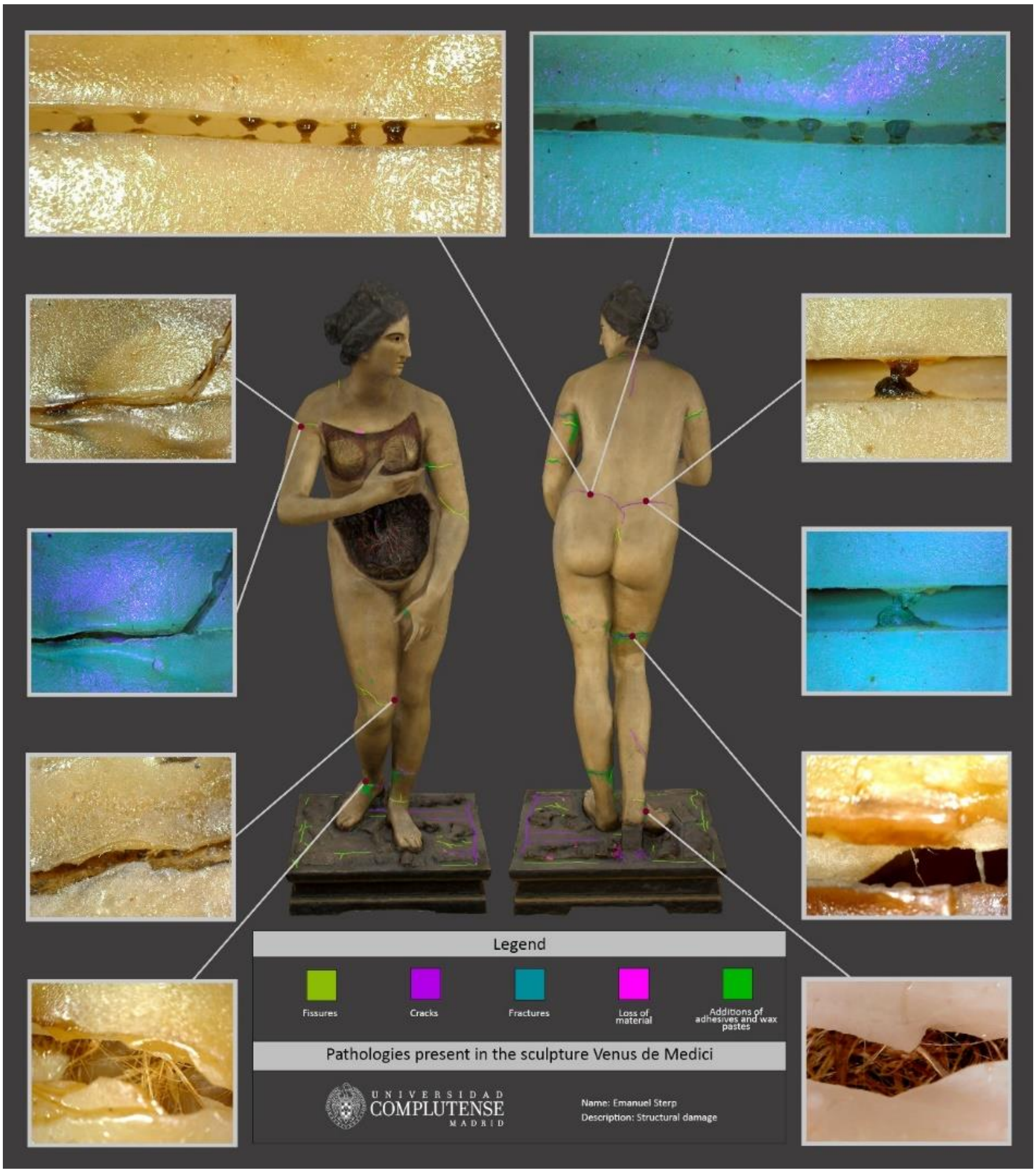

Fig. 2: 3D pathology mapping: Structural damage.

dimensional changes, have cracked and fractured in the weakest areas of the model, with the high risk of collapse this entails. The fractures most detrimental to the stability of the work are located above all in the leg and back areas. On the right leg, at the ankle and at the knee, they have reached a considerable size. The increase in the opening causes the whole to destabilise, generating a gradual overturning towards the heavier side of the figure. In the case of the left leg, the same happens just at the level of the tibia. Other critical points of the model are to be found on the back, at the level of the lumbar and trapezius muscles. The fracture here is now very significant in size (Fig. 2). These areas are critical and have caused significant deviation. In order to reduce the progression of the change in position and to avoid total collapse until intervention takes place, a temporary support structure has been placed as a preventive measure in order to ensure stability.

3.2 3D documentation

The registration strategy was carried out by rotating around the model and proved to be very suitable, as it made it possible to capture the entire volume with high quality. The elimination of outside elements by means of the manual tool made it possible to obtain images with very precise, clean results. This phase has been decisive, as the quality of the mesh and the fidelity of the details largely depend on this preliminary process.

Regarding the detailed analysis of the scans that make up each fragment, this has made it possible to identify parts with slight deviations. Sometimes, due to the high brightness of the wax model, the scanner lost the reference and duplicated small parts. The problem has been solved by breaking down each scan and selecting the deviating frames to remove them. Once the fragments were perfectly clean and free of duplicated areas, the manual rigid mode alignment gave very accurate results (Fig. 3a, b, f and g). On the other hand, one of the most important processes for obtaining a model with maximum precision has been the global registration. This option has allowed all the aligned fragments that make up the model to be precisely aligned, as if they were a single fragment. The identification of the deviations and the final result could be observed in great detail thanks to the X-Ray vision (Fig. 3c and h). Regarding the analysis of the maximum error, on the one hand it revealed the precision of each fragment scanned after the global registration, and on the other hand, it served to eliminate those frames that were far from the optimum quality values. All values higher than 0.2 have been eliminated in order to obtain maximum volumetric fidelity. Finally, hard fusion was the

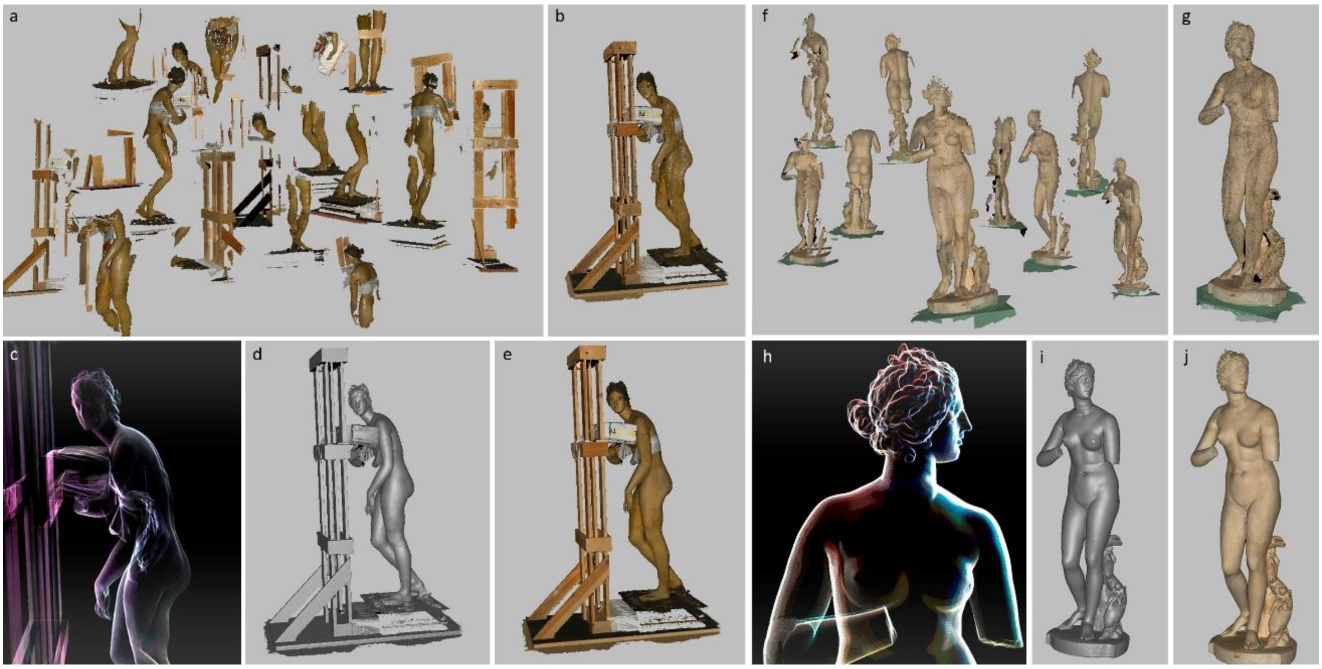

Fig. 3: Wax Venus de' Medici: a) Scans; b) Alignment made; c) Global registration; d) Mesh; e) Final texture; RABASF plaster Venus de' Medici: f) Scans; g) Alignment made; h) Global registration; i) Mesh; j) Final texture.

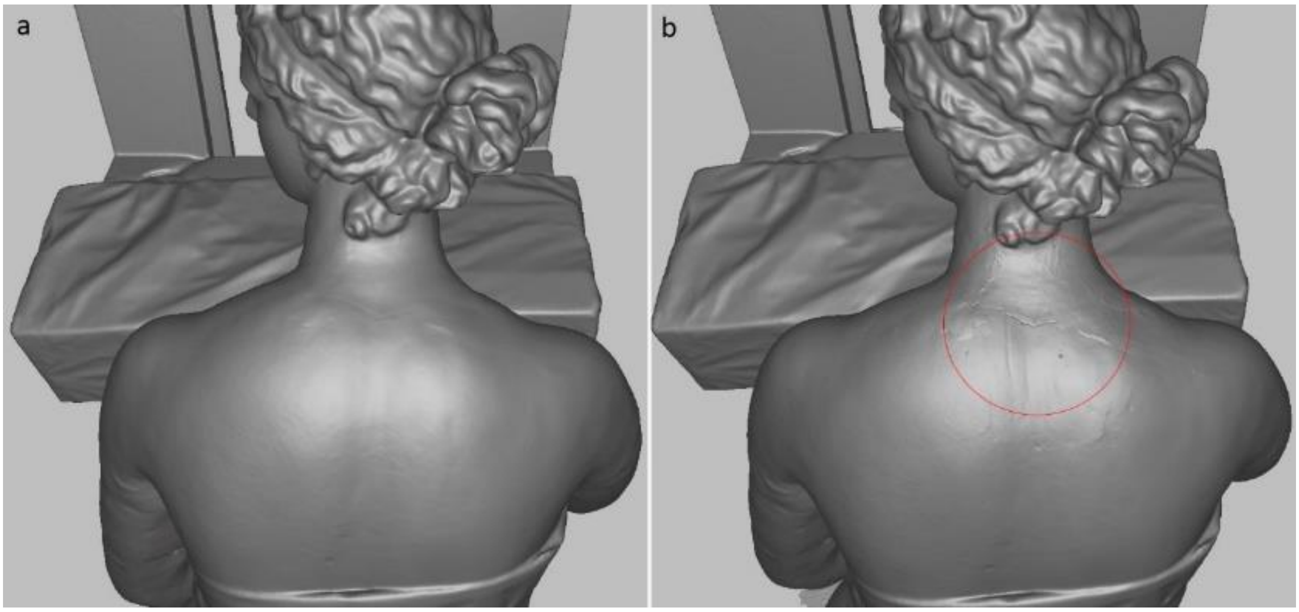

Fig. 4: Wax Venus de' Medici: a) Mesh obtained with the Eva scanner; b) Application of the mesh obtained with Space Spider on the neck part.

process in which all fragments aligned with a spatially dispersed point cloud were converted into a single solid polygonal model (Fig. 3d and i). The 0.2 resolution applied in the combined scans by both devices has yielded surprising results. Regarding the colour texture, the result obtained has been truly remarkable (Fig. 3e and j).

The registration obtained in both sculptures by combining the Artec Eva scanner for the general registration (Fig. 4a) and the Artec Space Spider for the details of cracks and fractures (Fig. 4b) has made it possible to produce a very high resolution model, providing a mesh of 60 million polygons in the case of the wax Venus de' Medici, and 55 million in the case of the Venus de' Medici of the RABASF, which more than meets the level of resolution necessary to develop the objectives proposed in this research.

3.3 Comparative volumetric analysis of the two sculptures

The high level of resemblance between the wax Venus and the classical Venus de' Medici suggested that the artist of the wax Venus may have used some of the numerous existing plaster casts of the Hellenistic sculpture. In order to test this hypothesis, the 3D models of the wax Venus de' Medici and the plaster Venus de' Medici from the RABASF were superimposed (Fig. 5).

During the alignment of the meshes, it was found that both figures do not globally coincide in shape and orientation, as the wax Venus has a smaller vertical dimension and is also significantly deviated to the right in relation to the plaster Venus. Taking linear measurements, the height of the plaster Venus was determined as 1513.60 mm and that of the wax Venus as 1453.05 mm, there being a height difference of 60.55 mm between the two sculptures.

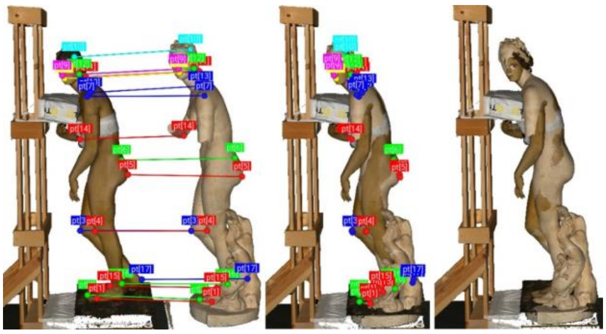

Fig. 5: Process of manually aligning the works at common points.

Since the discrepancies found could be compatible with a hypothetical deformation of the anatomical model due to the fact that beeswax is more susceptible to losing its consistency under the effect of high ambient temperatures in the exhibition room, the different anatomical regions were compared individually to see if they matched. Numerous partial linear measurements were taken to compare both figures (Fig. 6), significant differences in different areas being found (Tab. 1).

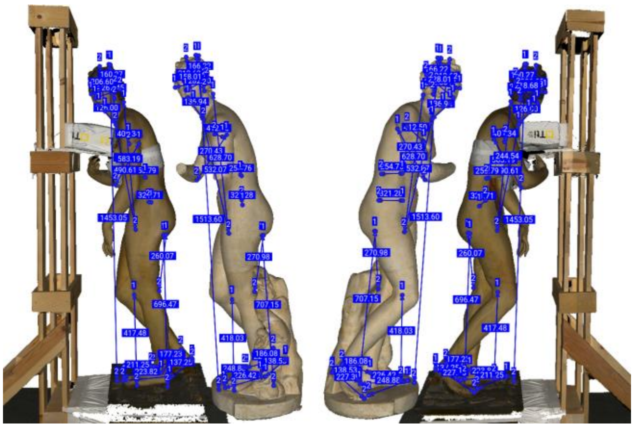

Fig. 6. Linear measurements of the proportions of each work.

Tab. 1: Comparative measurements between the two sculptures.

Linear distance considered	Wax Venus (mm)	Plaster Venus (mm)	Difference (mm)
Height of the figure	1453.05	1513.60	60.55
From the pubis to the base	713.57	718.71	5.14
From the pubis to the sternal manubrium	490.61	532.07	41.46
From the pubis to the nape of neck	583.19	628.70	45.51
From the sternal manubrium to the head	267.45	282.50	15.05
From the sternal manubrium to the lower lip	126.00	136.94	10.94
Height of the head	206.60	212.62	6.02
Height of the head	144.03	158.01	13.98
Distance between shoulders	409.34	412.50	3.16
Waist width	258.79	254.76	4.03
Hip width	321.71	321.28	0.43
From the left knee to the base	417.48	418.03	0.55
Distance between the big toes	211.25	248.88	37.63
Length of the right foot	227.80	227.39	0.41
From the armpit to the right elbow	244.54	270.43	25.89

However, given that the formal resemblance was very high in some specific areas of both sculptures, each of the main anatomical regions was superimposed on the two 3D models to check whether their shape and dimensions were similar (Figs. 7 and 8). For this analysis, the parts modified by the sculptor to show the anatomy of the internal organs, which only exist in the wax model, were not taken into account. After performing this procedure, it was observed that there were some areas of the anatomy that coincided quite closely, such as the segment comprising the pelvis and lower limbs (Fig. 7), with the exception of the feet and ankles, which are different in orientation, and also the buttocks and posterior region of the thighs, which are somewhat more prominent in the plaster sculpture, the maximum difference at these points being of between 8 and 12 mm. A great similarity was also found between the two thoracic regions except in the area bordering the neck, which is more forward-leaning in the wax Venus.

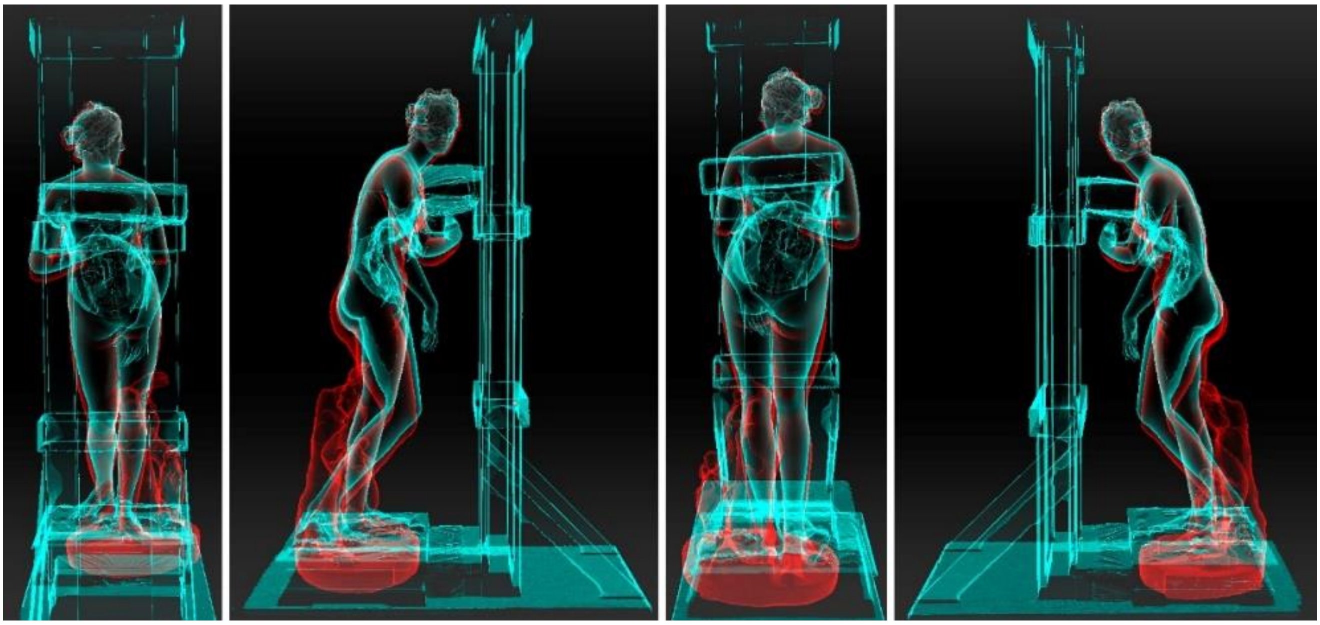

Fig. 7: Alignment of the works with the matching part of the head; Red: plaster Venus; Turquoise: wax Venus.

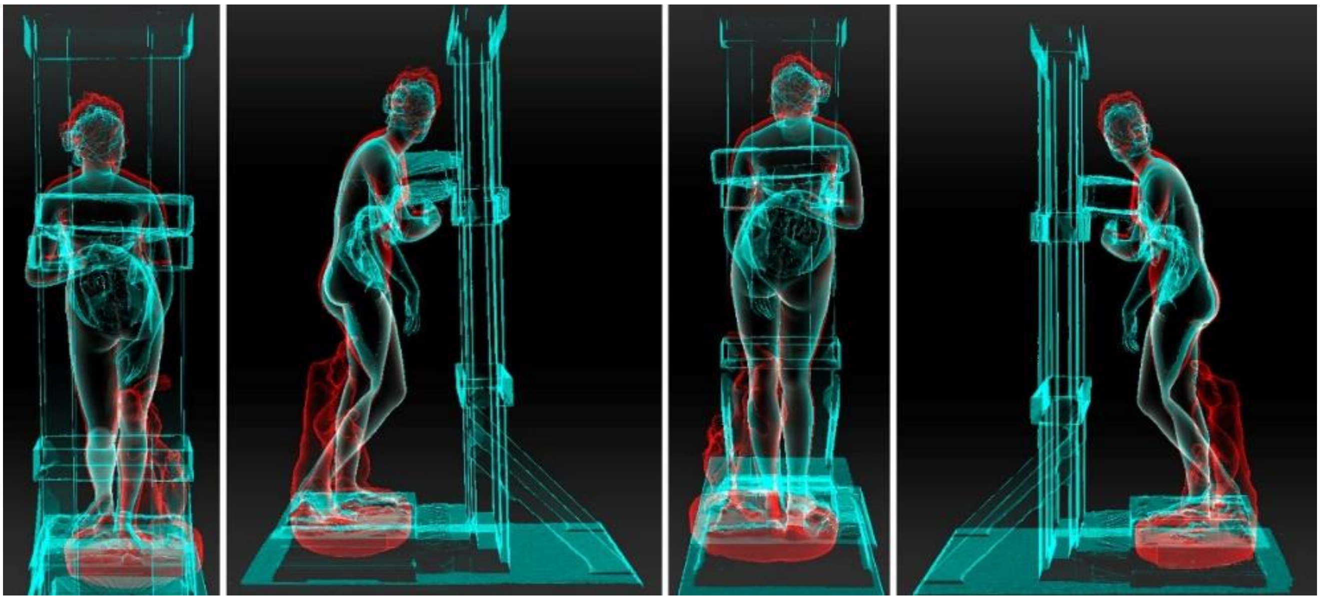

Fig. 8: Alignment of the works with the matching part of the legs; Red: plaster Venus; Turquoise: wax Venus.

Another notable difference between the two figures has to do with the overall shape and size of the torso, with a large difference in height between the two when the meshes were aligned (45 mm smaller in the wax Venus), in contrast with the rather similar width. However, as mentioned above, the shape and dimensions of the thorax and pelvis were separately very similar in both works, both in shape and volume, which shows that the loss of height has occurred at the expense of the abdominal region, the area of union between these two structures.

However, clear inequalities were found when the 3D models were superimposed in some regions. In the head, a clear difference in volume was found, with the wax Venus being smaller in size. The different measurements show a discrepancy of approximately 10 mm in thickness across the entire volume of the head of the wax Venus. After calculating the area, the wax Venus yields a surface area of 187833.63 mm2 and the plaster Venus one of 197183.04 mm2. This means that the head of the wax Venus is 10 mm thinner than that of the plaster Venus. However, it was noted that the shape of both heads was apparently identical, suggesting a proportional reduction in size. To check this, the area was scaled to match the size of the plaster head. It was necessary to apply a scale factor of 1.04 to match the height of both heads, after which it was possible to appreciate a fairly high formal coincidence *between the two, except for a slight reduction in* transverse dimension, from left to right, of the head of the anatomical model (Fig. 9). Also noteworthy is the different treatment given to the eyes in the wax figure, possibly with the intention of making the gaze more realistic.

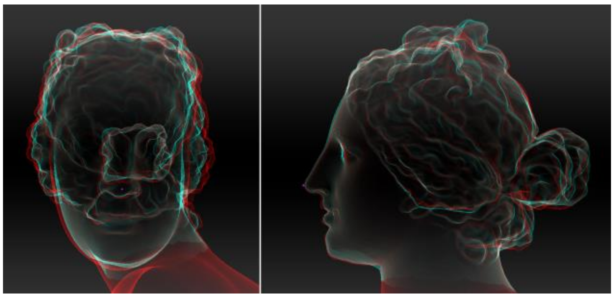

Fig. 9: Superposition of both heads, scaling the wax sculpture to check the considerable similarity between them.

Finally, although the morphological coincidence is considerable in the segment that includes the pelvis, thighs and legs, there is a clear deviation in the position of the left foot, which is located 37 mm further to the right in the wax Venus (Fig. 10a). However, when reorienting and superimposing the left feet of both sculptures in isolation, their formal coincidence is very high (Fig. 10b and c).

In order to corroborate the measurements and proportions analysed with greater accuracy, the surface morphology of both sculptures was examined using the *surface distance mapping* tool. To do this, first of all, a general calculation was made (Fig. 11) for the whole piece. The surface distance map of the wax Venus and the plaster Venus shows an error range of -27.3 mm to 25 mm. Secondly, the parts (head, arms, torso, legs) were calculated by matching them in the two works (Fig. 12).

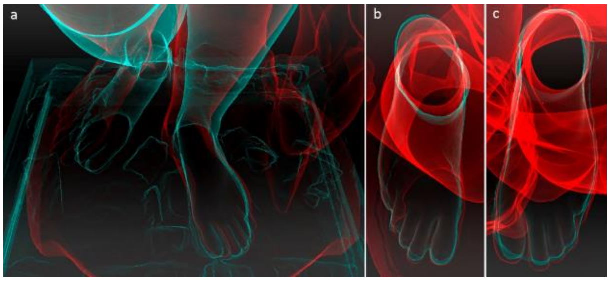

Fig. 10: a) Location of the left feet of the two sculptures; b) Superposition of the right foot; c) Superposition of the left foot.

In order to analyse each area of the sculpture more accurately, a maximum error range of 10 mm has been established. In the case of the head, the

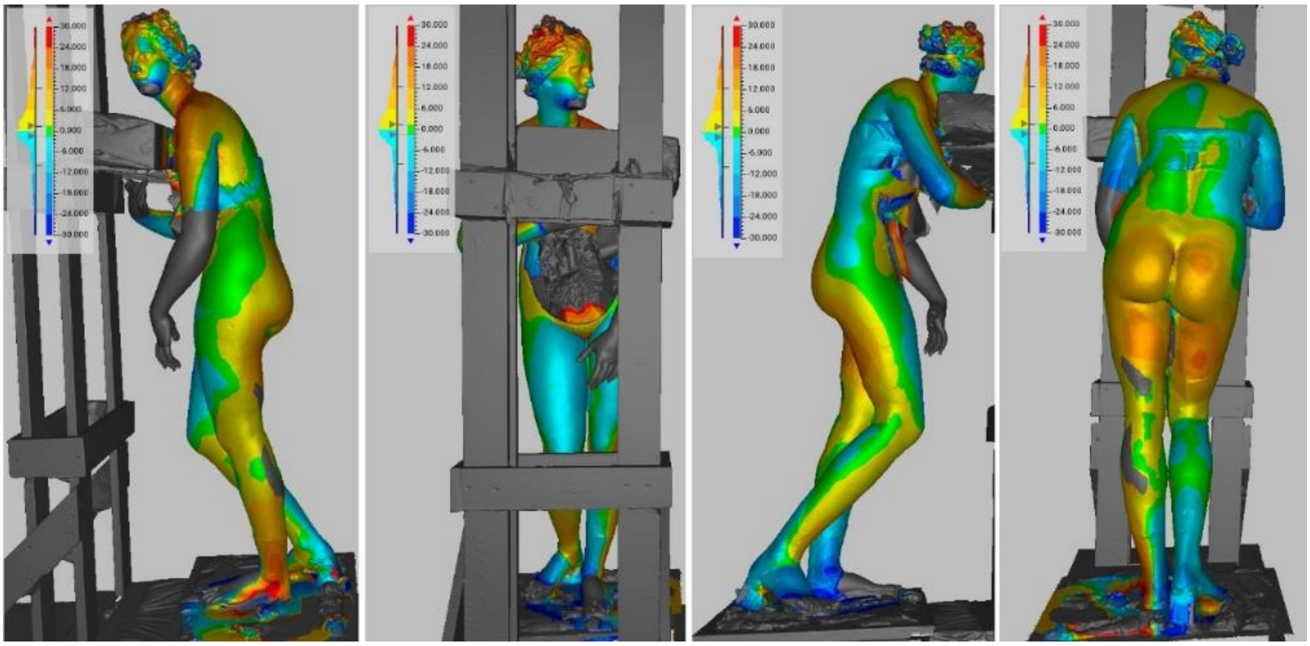

Fig. 11: Surface distance maps; Error scale: 30 mm.

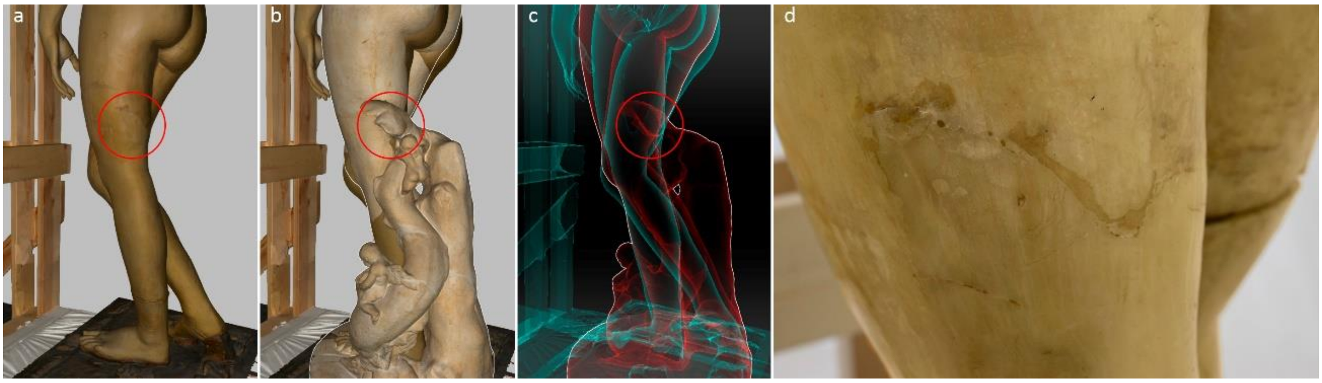

Fig. 12: a) Wax Venus, thigh area; b) Superposition of the lateral support of the RABASF Venus; c) X Ray vision in the coinciding area of the thigh of both figures; d) Detail photograph of the thigh area.

error range is of between -3.6 mm and 9 mm. In the area corresponding to the torso, the error range is of between -8.2 mm and 8.4 mm. Finally, in relation to the leg parts the error range lies between -6.4 mm and 8.2 mm.

Another of the findings is an irregularly delimited area on the thigh of the wax Venus, whose shape and dimensions correspond to the area where the lateral support is attached to the lower limb in the plaster figure (Fig. 12).

It was also possible to locate some linear marks that were compatible with the typical marks produced in the areas where the moulds are joined during casting, which the sculptor does not always manage to fully conceal. More specifically, they were detected in the lower cervical area and on the back at shoulder height, both in the plaster figure and in the wax figure, coinciding in both shape and location (Fig. 13). In the figure produced by Lacaba, some cracks can be seen and these could be due to a weakened joint (Fig. 16).

3.4 Analysis of the state of conservation and monitoring

The superimposition of both sculptures, matching the part of the feet, this being the area that was least altered by the deviation, has revealed some important data. The wax Venus de' Medici has suffered a deviation towards the right side (Fig. 14). The distance maps applied revealed a deviation of approximately 82.45 mm (Fig. 15).

The angle from vertical to the line formed between the sternal manubrium and the centre of the heel of the supporting leg was of 3.05 degrees counterclockwise for the RABASF sculpture and 2.19 degrees clockwise for the Javier Puerta Anatomy Museum figure.

A comparison of the matching parts of the two sculptures has shown that the part of the legs up to the knees has hardly any deviations. However, at the level of the lower thighs, one can already see a

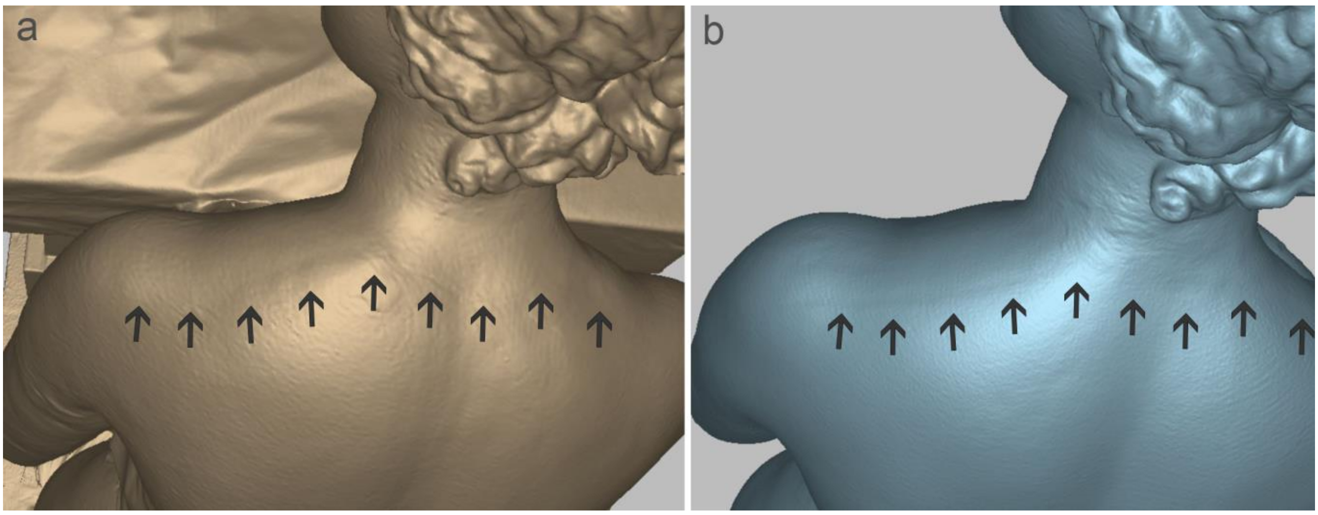

Fig. 13: Coincidence of the linear marks due to the union of the moulds in the same location: a) Wax Venus de' Medici; b) RABASF plaster Venus de' Medici.

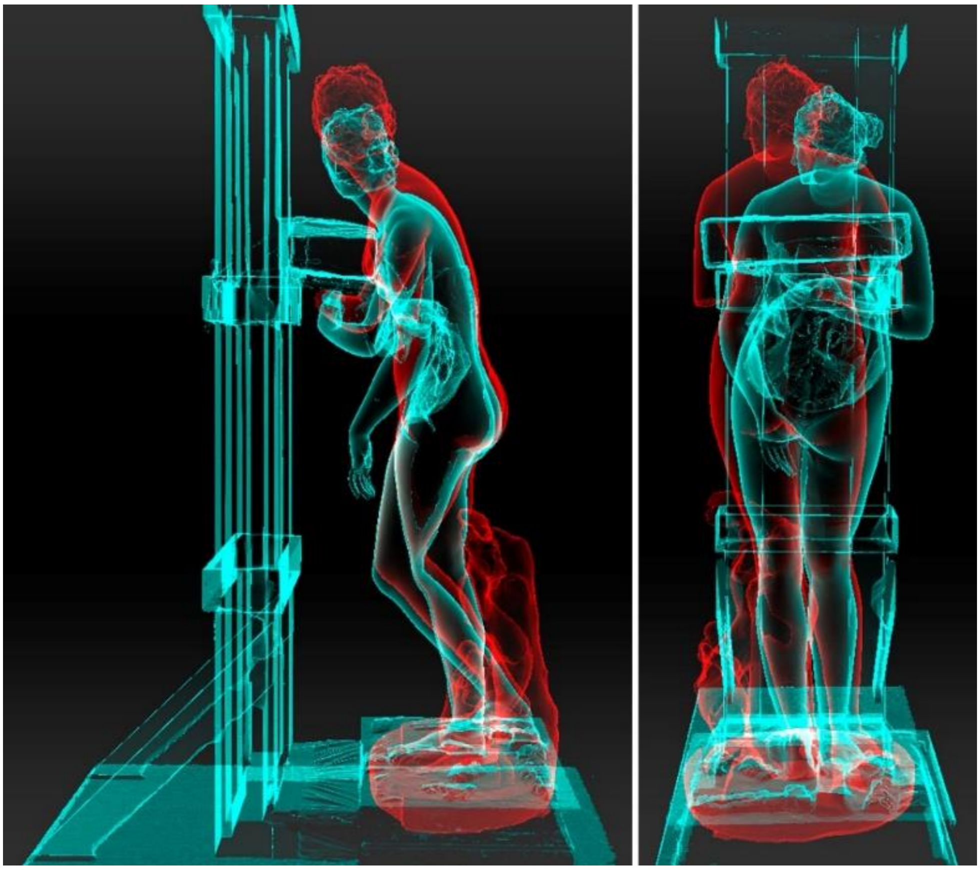

Fig. 14: Sagging and deviation of the wax sculpture; Red: RABASF Venus; turquoise: wax Venus.

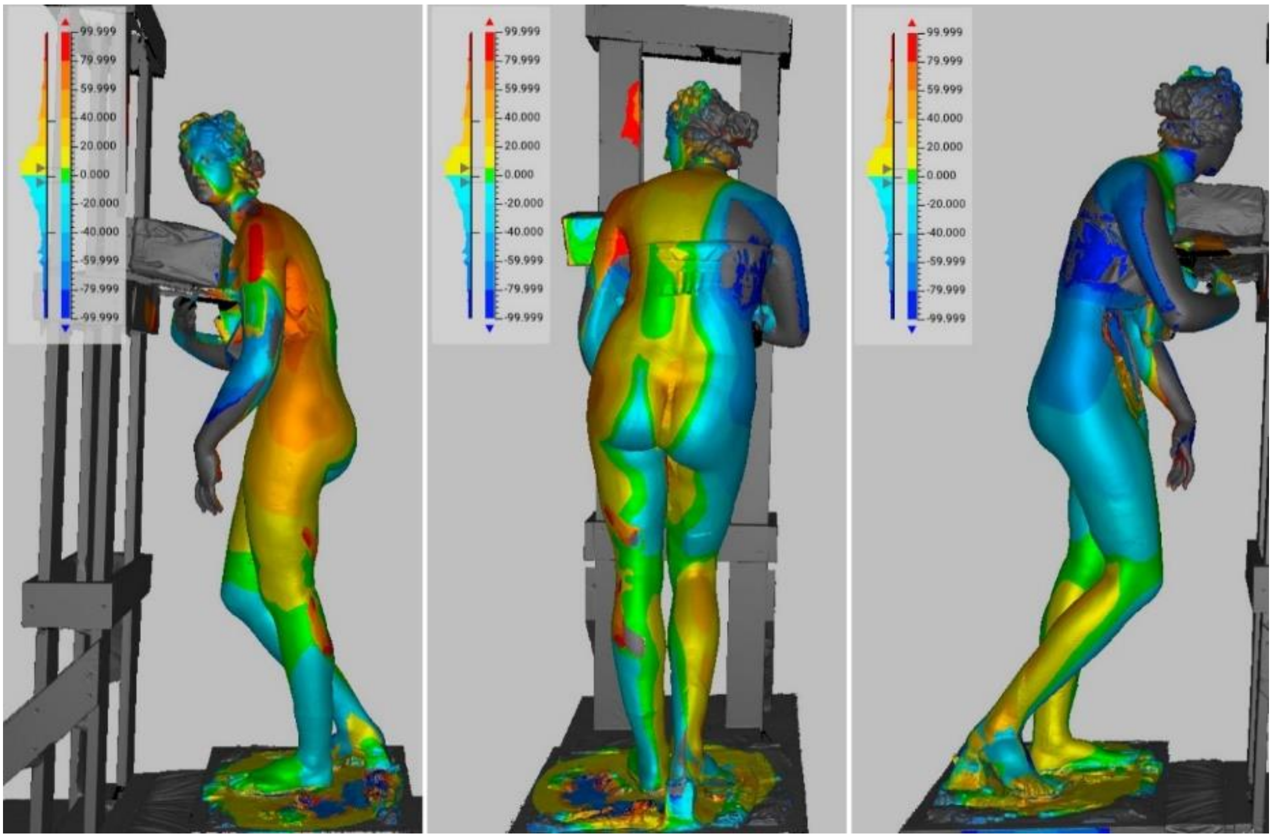

Fig. 15: Surface distance maps; Error scale: 100 mm.

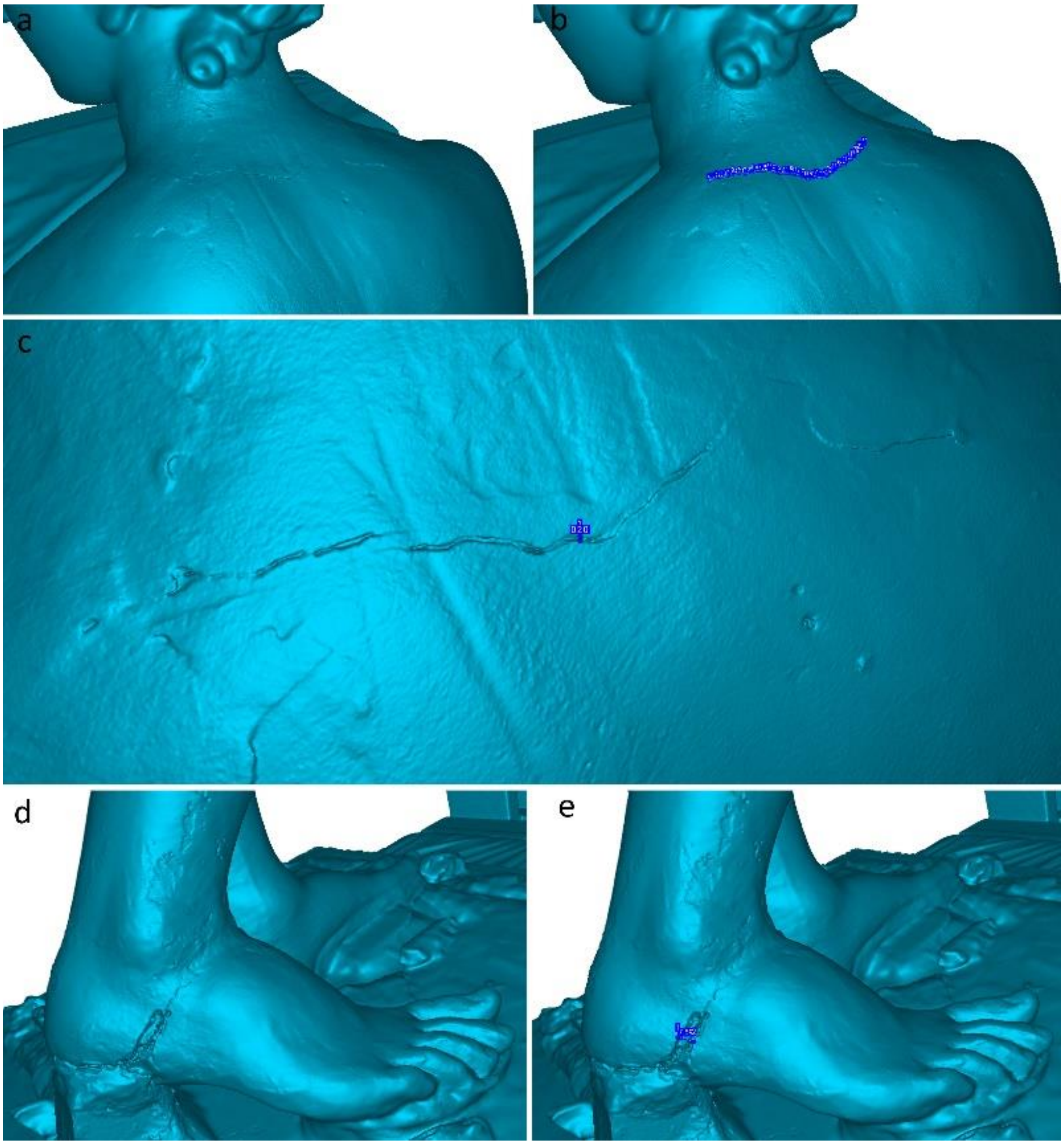

Fig. 16: Spot measurement of fractures and cracks: a) Crack on the back at the level of the trapezii; b) Geodesic measurement of the crack on the back at the level of the trapezii; c) Linear measurement of the width of the crack on the back at the level of the trapezii; d) Fracture of the right foot at the level of the ankle; e) Linear measurement of the width of the fracture of the right foot at the level of the ankle.

Tab. 2: Linear and geodetic measurements of the different fractures, cracks and fissures.

Linear and geodesic distance	Length in mm	Width in mm
Fracture of the right foot at the level of the ankle	101.79	2.34-7.59
Fracture of the right foot at the level of the knee	469.13	3.54-8.80
Fracture of the left foot at the level of the tibia	257.76	1.78-3.98
Fracture on the back at the level of the lumbar spine	331.22	0.87-2.99
Crack on the back at the level of the trapezii	77.34	0.52-0.78

16-mm deviation and, at the location of the upper thighs, a deviation of 35 mm. In the pelvic region there is a deviation of 53 mm and in the side region one of 71 mm. Finally, the right arm shows an 82-mm deviation.

Regarding the measurement of the different fractures and cracks, the very high quality of the 0.1 mm mesh obtained with the Space Spider scanner has made it possible to obtain geodesic and linear measurements of the values of each alteration (Fig. 16). With this, first of all, the extension of each crack and fracture has been obtained and, secondly, so has the width of the crack (Tab. 2). The results found are essential for one to be able to monitor the state of conservation over the following years until intervention takes place.

4. *Conclusions*

Regarding the construction method used, some of the results obtained in this study support the hypothesis that Ignacio Lacaba may have made this work from moulds of a copy of the classical Venus de' Medici. On the one hand, thanks to the historiographical study carried out, we know that the RABASF owned a plaster copy made a few years earlier. The existence of such a reproduction greatly facilitated the production process, as it made it unnecessary to model the figure except for the areas in which the internal anatomy was to be shown. On the other hand, the proximity in time with which both sculptures were created and the physical proximity between the Academy of San Fernando and the Royal College of Surgery of San Carlos, for which the anatomical model was made, make a collaboration between members of both institutions more likely.

Other indications suggesting a relationship between the two pieces have been found during the visual analysis, by means of which it has been possible to detect the presence of some of the marks resulting from the joints of the moulds that have been preserved in both sculptures with the same shape and arrangement. The high coincidence between the joints of both sculptures could point to the use of the same moulds for the creation of both figures.

Another piece of information that also seems to support the use of moulds from the plaster copy is the identification on the back of the thigh of the wax figure of a surface area that is clearly demarcated by a crack and is slightly darker and more irregular, coinciding in shape and location with the marks described and documented photographically in the restoration report of the plaster copy of the RABASF. That document explained how the support of the base and part of the pedestal had been sectioned and separated from the rest of the figure with the probable intention of making a reproduction using moulds to avoid complications with the attachments. If Lacaba had made the wax sculpture using moulds of the plaster figure, he would necessarily have had to fill in the gap in the contact area of the support, as this was not reproduced in the anatomical Venus. The existence of this trace on the wax sculpture would therefore be compatible with its creation by moulding, since if it had been modelled, no such mark would have been left.

Another finding that supports the use of moulds of the plaster Venus for the execution of the didactic model lies in the remarkable morphological coincidence between the two works when they were examined and compared region by region. The similarity between the two figures has been demonstrated by comparing the virtual models obtained by the 3D scanning of each of them. These three-dimensional meshes have made it possible to obtain a large number of linear measurements, as well as the superimposition of the different regions of both sculptures for verifying their volumetric similarity.

Although there are overall differences that are mainly due to the greater inclination of the wax anatomical model, possibly because of its structural weakness and the fragility of the construction material used, there is a clear formal coincidence between different isolated regions of the two sculptures. However, there are some discrepancies in specific areas that may be due to different reasons.

Some of the differences found between the two works, such as those observed on the buttocks or the arms, may be a result of the deformation of the thin layer of beeswax in the didactic model. Others may have originated when the pieces were assembled. This could be what explains the shortening in torso height of the wax Venus at the expense of the abdominal region, as there are no visible deformations, cracks or other alterations at this level that could justify this smaller size. This modification in the middle part of the torso may have been motivated by the need to adapt the size of the abdominal cavity to that of the anatomical structures, or it may have been a rectification performed to adjust it more successfully to the internal support structure.

As for the deviation of the left foot of Lacaba's Venus, this does not seem to be due to deformations following the creation of the work, as there are no compatible signs to support this option. We therefore think that it may have been an aesthetic decision on the artist's part, or perhaps an attempt to compensate for the absence of the support base that did exist in the classical Venus by shifting the centre of gravity, or it may also have been due to an adaptation to the poorly designed underlying structure.

The last of the notable discrepancies in morphology detected between the two Venuses has to do with the proportional reduction in size of the anatomical wax model in relation to the plaster copy, as has been verified by superimposing the 3D models and by means of linear measurements between different points of the latter. One possible explanation could be that the head was created with a different method to that of the rest of the figure, as no such reduction has been observed in other parts of the body. Since the head is also composed of beeswax, it is not likely that it would have decreased to the extent detected, even if other components had been added to it. It is typical, however, that the clay reduces in size as it loses water during the drying process. This suggests that the head may have been made by the clay stamping method, applying a layer of clay to the surface of the mould of the classical Venus to obtain a clay positive from which moulds could later be obtained for casting in wax. The loss produced by this procedure could be compatible with that found for the wax head (4% on average).

Determining the construction method of the wax Venus in the "Javier Puerta" Anatomy Museum and verifying that it was most probably created by means of casting, using moulds obtained from a plaster copy of the classical Venus, are steps of great importance for establishing the extent of the deviation of the figure from the moment of its creation, since it is possible to compare the respective inclinations of both works to determine the change in position. In this study, this comparison has been carried out using scanned models of the two figures, which method has made it possible to accurately establish the angle of separation between them.

In relation to the progressive inclination of the Wax Venus, several possible causes were identified during the study. These include the use of a material that is very sensitive to environmental changes, especially high temperatures, such as beeswax, the possible weakness of the internal framework or its inappropriate design, the absence of the support that joins the base to the left leg of the figure, which does exist in the classical Venus, and the lack of a fixed wall in the anterior thoracic-abdominal region to show the internal organs.

This change in position of the model is causing the appearance of deformations and cracks that put the integrity of the sculpture at risk, so it has been necessary to stabilise it by means of an external support structure and to monitor these alterations as well as the degree of inclination of the work while a definitive intervention strategy is being designed.

Finally, about monitoring the state of conservation of the wax sculpture, the high precision and resolution of the geometry recorded employing the structured light scanners have allowed a rigorous and precise knowledge of each of the existing fissures, cracks and fractures, as well as the monitoring of this damage using various linear and geodesic measurements. The tools used will serve as a preventive conservation measure to detect possible structural changes.

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