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STABILIZATION OF AN ANATOMICAL WAX MODEL OF THE COMPLUTENSE VETERINARY MUSEUM WITH THE HELP OF 3D DIGITAL TECHNOLOGIES

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Abstract

Between the 17th and 20th centuries, polychrome beeswax anatomical models played an important role in the transmission of anatomical knowledge thanks to the high degree of accuracy and realism they were able to achieve in the representation of the most delicate structures of the organism. However, due to the fragility of this material, some of these artefacts now survive in a rather precarious state of conservation. Due to the lack of consistency of some of the internal support structures, some of these figures have been damaged or their integrity has been seriously compromised. In this article we show a case of stabilisation using a polymethylmethacrylate support of a model from the Complutense Veterinary Museum, representing the head of a horse, which has suffered the loss of some parts and shows significant cracks and fractures due to the partial collapse of the internal metal framework. The methodology used was based essentially on the use of digital technologies, to minimise the handling of the work. Based on a virtual copy obtained by 3D scanning, a specific support that fits perfectly to the surface of the figure has been designed. Subsequently, some of the pieces were produced using 3D printing in order to subject them to functional and aesthetic tests and, finally, the support was manufactured using numerical control machining. The result meets the requirements of stability and minimum aesthetic impact.

***Keywords**: Computer assisted design; 3D scan; External support; Anatomical model; Computer numerical control*

Introduction

The first collections of anatomical models made of polychrome beeswax arose in the 18th century in Italy, in response to the need for teaching material that could replace cadavers, due to the difficulties in obtaining them, the problems related to their preservation and the rejection they caused among anatomy students [1]. Both the Bologna Museum of Anatomy and the Imperial and Royal Museum of Physics and Natural History, also known as the La Specola museum, are among the most outstanding examples of that time in relation to the handcrafted production of didactic artefacts for science [2]. These figures were made by sculptors in collaboration with dissectors and surgeons, who made the cadaver preparations to be reproduced [3]. In addition to wax, other materials such as bones, hair, teeth, glass eyes, etc. were often incorporated into the sculptures, as were internal support elements created with

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wood, iron or plant fibres, among other materials [4, 5]. The technique used allowed even the smallest visible anatomical details to be reproduced with great realism and precision, which is why it was so widespread in Europe, especially during the 18th and 19th centuries [6]. However, the fragility of the materials used, their handling during teaching sessions and, in some cases, poor conservation conditions led to the progressive deterioration of many of these unique figures [7].

In some cases, as in the case of the horse head analysed in this research, the internal support structures were insufficient to fulfil their function, resulting in a lack of stability of the whole that put the integrity of the work at risk. In wax figures, radiological study can provide essential information to locate these structural elements and determine their shape and arrangement, as well as the type of material they are made of, helping to determine whether they are sufficiently resistant or whether some action is required to achieve greater solidity [8].

Except in those situations in which there is a fractured piece of the sculpture and it is possible to introduce an internal fixing element, it is usual to resort to external supports so as not to damage the surface of the model. There are some previously published experiences in which support structures have been created for this type of figures, made of different materials, such as synthetic resins, polymethylmethacrylate (PMMA), polycarbonate, or foam, among others [9–11]. The elaboration of this type of structures is usually carried out using traditional techniques, which often requires the creation of moulds in those cases in which they must be faithfully adapted to the surface of the sculpture. However, the task of designing and manufacturing supports can be greatly facilitated thanks to 3D digital technologies, avoiding the application of chemical products on the model, and following the principle of minimum intervention. Firstly, 3D digitisation methods make it possible to create virtual copies of the model that can be used to study the piece and accurately determine its shape and dimensions [12–14]. Secondly, computer-aided design programmes allow the design of specific supports that are perfectly adapted to the sculpture, using the digitised 3D model. These supports can be used as auxiliary structures during restoration work [15] or to permanently stabilise the piece for display [16]. Thirdly, the creation of copies of the sculpture using 3D printers or numerical control (CNC) machines makes it possible to carry out functional or aesthetic tests to assess the most appropriate option in each case. Fourthly and lastly, manufacturing by machining accurately reproduces the shape of each piece of the support designed in the material selected.

In this study, we applied the above-mentioned 3D technologies to achieve the stabilisation of an anatomical model from the Complutense Veterinary Museum with severe structural damage by means of a support structure. The serious damage found in the model, including fractures and loss of important anatomical elements, was probably due in part to the existence of a deficient internal support system that failed to provide sufficient firmness to the anatomical structures represented, some of which are extraordinarily delicate and complex. For this reason and given the precarious state of conservation of the model, it was a priority to create a support specifically designed for this figure, which would stabilise it and consolidate the most weakened or fractured parts to prevent the loss of more anatomical elements.

Taking advantage of the aforementioned benefits inherent to 3D scanning, computer-aided design, 3D printing and CNC machining technologies, we have created a specific support for a 19th-century didactic figure representing the head and neck of a horse. During the design and production stages, no handling of the figure or application of chemical substances for the creation of moulds has been necessary at any time. Nor has it been necessary to make replicas, so the process has been made considerably faster.

Historical background

The artificial model selected for this research is an anatomical study of the head of a horse called the Nuchal Ligament (MV-670), which is a part of the anatomical ceroplastic collection, comprising forty-two sculptures of the Complutense Veterinary Museum.

In June 1829, the Scholastic Board of the Royal Veterinary School of Madrid commissioned assistant professor Cristóbal Garrigó de Nis to expand the collection of artificial polychrome wax models for the teaching of animal anatomy and pathology [17]. For his training in the art of wax, he was assisted by Pedro Pablo Sánchez Osorio, the second builder of anatomical pieces at the Royal College of Surgery of San Carlos [18]. Together they carried out the commission, which took them about nine months to complete, from January 1830 to October 1831 [19, 20].

On 31 January 1830, Sánchez Osorio informed the Scholastic Board that Garrigó had moulded three pieces, one of the eyeball and the other two of the bones of the tongue, for the piece he was executing of a horse's head with the neck, ligaments, arteries and veins "all with considerable success and application" [21]. On 19 October 1830 it was reported that the sculpture had been completed with "(...) the system of bones of the regions mentioned, the ligaments of these parts, the Eustachian tubes, the hyoid bone, the larynx, pharynx, oesophagus and trachea, the cartilaginous parts of the ears and the globe of the eye, provided on the left side with the whole arterial system, belonging to the said regions, and on the right side with the venous system with all the principal arteries (...)"[21]. The Duke of Alagón himself, professor and protector of the Royal School, stated that he was very pleased with the advantageous results that the construction of this artificial model had brought to the establishment [20].

The oldest graphic document extant showing the previous state of the figure is an early twentieth-century photograph that depicts the horse head analysed in this work in a display case in a room of the former headquarters of the Spanish Royal Veterinary School College, located in Glorieta de Embajadores in Madrid [22]. The image is in very low-resolution black and white, but it is nevertheless possible to identify the anatomical structures that make up the piece, some of which are no longer preserved or have become detached or fractured. The ears can be seen in their original position, and the same holds for the oesophagus, the carotid artery on the left side and the external jugular vein on the right, which have not been preserved. It also shows the apparently complete trachea, of which unfortunately only a few fragments remain. Furthermore, we can see that, at the time the photograph was taken, the tongue was no longer present in the figure, as the molars and premolars of both dental arches can be seen on the right side and they would have been concealed by the tongue from the angle at which the image was taken. It is not possible to distinguish the existence of the pharynx or the hyoid apparatus due to the poor quality of the image.

Materials and Methods

The anatomical model studied, Nuchal Ligament, preserved in the Complutense Veterinary Museum (Madrid, Spain), shows numerous fractures and partial or total loss of anatomical structures. In addition, the wax layer covering the different bones is cracked and has material gaps in various areas (Fig. 1).

The figure currently consists of the following bony structures: skull, mandible, cervical vertebrae and 1st and 2nd thoracic vertebrae. Both the left mandibular ramus and the molar portion on the same side have been sectioned. None of the elements of the hyoid apparatus, the chain of bones connecting the skull to the larynx and tongue, are visible.

Both ears have been fractured at the base, as has the iron pin on which the one on the right side was fixed. A fragment of the tip of the right ear is also missing.

In the orbital cavity of the right eye, the posterior portion of the superior oblique muscle of the eye and the reflection pulley can be seen. In addition, the remains of the insertions of other extrinsic eye muscles can be seen next to the origin of this muscle, which seems to indicate that the eye was probably represented in the orbit.

Of the vascular structures represented, many of them are fractured or have not been preserved. The most notable absence is the left carotid artery and the right external jugular vein.

Fig. 1. Anatomical model of the head and neck of a horse. Complutense Veterinary Museum. Madrid, Spain

Of the digestive tract, the tongue has not been preserved, nor has the pharynx or oesophagus. Fractured remains of the nasopharynx can be seen on the posterior edge of the choanae, so it is likely that the sculptors who created it had depicted it at least in this region. On the other hand, exploring the anatomical model reveals that the palate was originally represented sectioned on both sides of the midline, with its inner layers visible, which supports the fact that at the time of its creation the lateral walls of the pharynx were either not modelled or were sectioned and rebated. As for the oesophagus, remains of the adventitia are visible at some points of the trachea on both sides of the contact zone between the two.

Regarding the respiratory tract, only part of the larynx and some fragments of the trachea remain. In the larynx, the absence of the epiglottis and the corniculate process of the arytenoid cartilage, as well as the aryepiglottic folds, should be noted, with a fractured edge remaining in the area where it joins the rest of the larynx, demonstrating its previous existence. Finally, the thyroid glands and some adjacent lymph nodes have been preserved.

The greatest risk identified is related to the stability of the nuchal ligament. The latter consists of a funicular portion and a laminar portion. The funicular portion is composed of two ligamentous cords on each side of the midline connecting the external occipital protuberance of the skull with the spinous process of the 2nd thoracic vertebra. The laminar portion is composed of different fibrous laminae that join the funicular portion, along its course on the neck, to the spinous processes of the cervical vertebrae. In the anatomical model studied, the funicular portion has lost its tension, possibly due to the rostral displacement of the spinous process of the 2nd thoracic vertebra, in which it is inserted, which has caused its deformation due to the weight of the lamellar portion. As a result of this lowering, the laminar portion has folded, with numerous cracks and fractures being visible at different points, which compromises the integrity of the whole set (Fig. 2).

The existence of two large nails in the body of this vertebra, which penetrate the wooden base, seems to confirm the importance given in the past to the fixation of this piece for the stabilisation of the ligament (Fig. 3). However, the risk of fracture of this bone due to the weight it supports made it advisable to find another method of fixation that did not rely on any element of the figure.

Different methods were used to analyse the figure and find a solution to its stability problem. Firstly, a radiological study was carried out to make its internal support structure visible. Subsequently, the model was digitised using structured light scanners to obtain a high-precision 3D model of the figure. Next, an external support was designed using different computer-aided design programmes to firmly hold the sculpture. Finally, the model was created in the mechanical workshop of the UCM using computer numerical control machines.

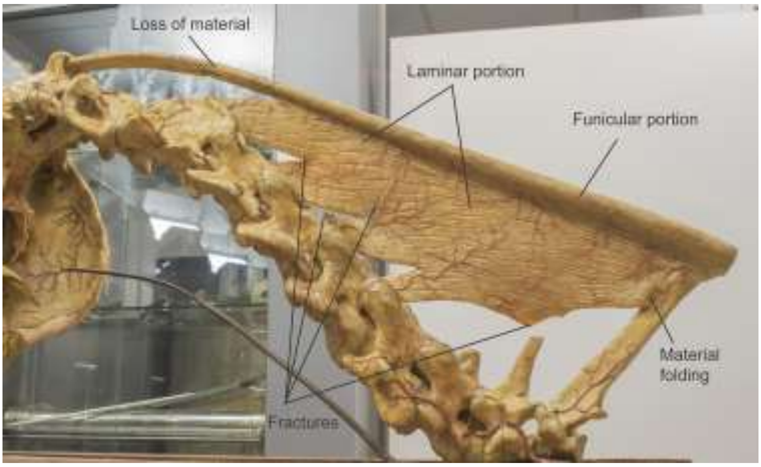

Fig. 2. Nuchal ligament with different alterations in both its laminar and funicular portions due to deformation of its internal support structure

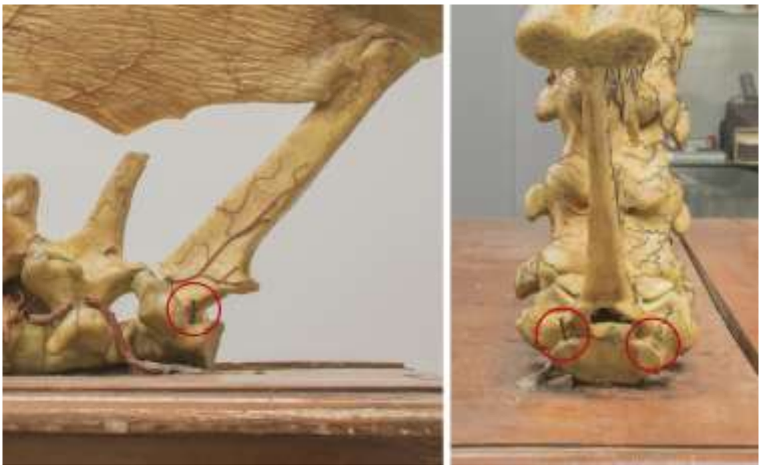

Fig. 3. Second thoracic vertebra fixed to the wooden base with nails (marked with red circles)

Radiological analysis

Since the scanning field of the X-ray machine was not large enough to cover the entire model, five radiographs were taken in a laterolateral projection of different areas of the model, with sufficient overlap to ensure their subsequent mounting. All the radiographic images were then stitched together in Photoshop CS6 (Adobe, San Jose, California, United States) to produce a single image. In this figure, three radiopaque metal rods are highlighted in yellow. Various screws and nails used to fix the figure to the wooden base are highlighted in blue, as are the bolts used to fasten the ears. The original position of the rod inside the nuchal ligament can be seen in green. The letter d indicates the original distance from the rod to the spine and d' shows the current decreased distance between the two (Fig. 4).

In the radiological image of the anatomical figure, it was possible to see different radiopaque structures that corresponded to the iron supports that were observed by visual inspection both inside the cervical spine and in the region occupied by the trachea and larynx, which were 12 and 9mm thick, respectively. It was also possible to identify a thin 2mm rod running along the entire interior of the nuchal ligament, with one end inserted into the occipital bone of the skull and the other into the spinous process of the second thoracic vertebra. The different parts of the iron structure were fixed to the wooden base by means of screws of diameters between 7 and 12mm, and other smaller ones secured the mandible to the skull. It was necessary to make tonal adjustments to the image in order to increase the contrast so that some of the metal fixation pieces that were not visible on the radiographs could be seen correctly. It was also possible to determine the shape and location of a 7 mm diameter nail, inserted in the anterior area of the nasal cavity and passing through the palate and mandible into the pedestal, as well as two more nails of lesser thickness, fixing the body of the second thoracic vertebra to the base. The latter nails were also partially visible from the outside, one on each side of the midline. Other metal structures that could also be identified in the radiographic image included the pins attaching the ears to the temporal bone and the larynx to the trachea. Finally, a thin metal wire was visible on the radiographs, coinciding with the path of the upper labial artery. This was the only metal structure that could be seen in vascular structures and was possibly used because this artery is separated from the skull and was therefore more fragile so it must have been considered necessary to provide it with an internal structure.

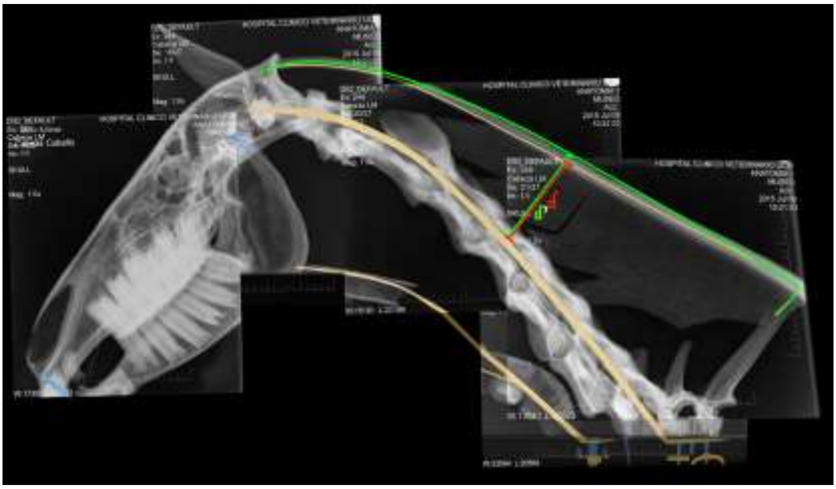

Fig. 4. Composition from five different radiographs of the model for studying the location and arrangement of the internal support structures

3D scanning

The scanning of this figure was particularly difficult, due to the large amount of fine detail it possessed and also to its size of more than one metre in length. This made us decide to use a combination of two different types of structured light scanners, plus a conventional SLR camera to capture the texture separately. The abundance of small and delicate anatomical structures made it necessary to use a high-precision device, so the Space Spider scanner (Artec3D, Luxembourg City, Luxembourg) was chosen for this purpose. This model has a point accuracy of up to 0.05mm and a resolution of up to 0.1mm. However, with this device it is almost impossible to record the entire volume at once and it is very difficult to obtain a correct alignment between some shots and others due to the dimensions of the figure and its small capture field, which ranges from 90x70mm at the closest range to 180x140mm at the furthest. For this reason, it was decided to also capture the general volume of the figure using an Eva scanner (Artec3D, Luxembourg City, Luxembourg), with a lower resolution (0.1mm) and point accuracy (0.2mm) but with a larger capture area, 214x148mm at the closest range and 536x371mm at the furthest. The purpose of using both scanners was to superimpose the model created with Space Spider with the one generated by Eva, in order to perfectly align the shots taken by the former using the mesh created with the latter as a reference. Thanks to the fact that the two devices use the same software, Artec Studio 16 (Artec3D, Luxembourg City, Luxembourg), compatibility between the two is guaranteed and it is relatively easy to combine both meshes into a single one. This results in a 3D model that is correctly aligned and represents all the small reliefs of the sculpture with high definition (Fig. 5).

Fig. 5. 3D model generated by Artec Studio 16 from data recorded with Artec Space Spider

Design of the support

The material chosen for its production was PMMA, mainly due to its high transparency, as it has a light transmission of at least 92%, an essential aspect to reduce the aesthetic impact on the figure and also due to its resistance to bending, scratching and impacts. We also considered the durability of the material and the low loss of its properties in the long term, especially its low yellowing tendency.

Firstly, the figure was analysed, so as to try to come up with a support that would stabilise the nuchal ligament and prevent its downward movement. Since it was not advisable to fix it to any adjacent anatomical structure due to the risk of damaging it and the aesthetic alteration this would entail, it was decided to create a bridge between the wooden base and the ligament, so that it would not touch any other element. It was also considered inappropriate to fix the support to the base in order not to alter its surface and also, because of the risk of any deformation of the base due to heat or humidity affecting the ligament. With these factors in mind, it was decided to create a box in which the base of the figure would rest and on whose side wall a support arm would be attached to hold the nuchal ligament. In this way, the stresses could be transmitted directly to the box without affecting any other structure of the figure or the base.

The 3D model scanned was used as a reference to create the customised support. The design was carried out in the computer-aided design software Maya (Autodesk, San Rafael, California, USA), where different aesthetic and functional solutions were tested (Fig. 6).

Different features of each support were analysed until the most suitable one was found (Fig. 7). One of the aspects that was considered necessary to bear in mind was the creation of adjustable joints in order to make it possible to adjust the position as accurately as possible in the real work and to facilitate assembly and disassembly.

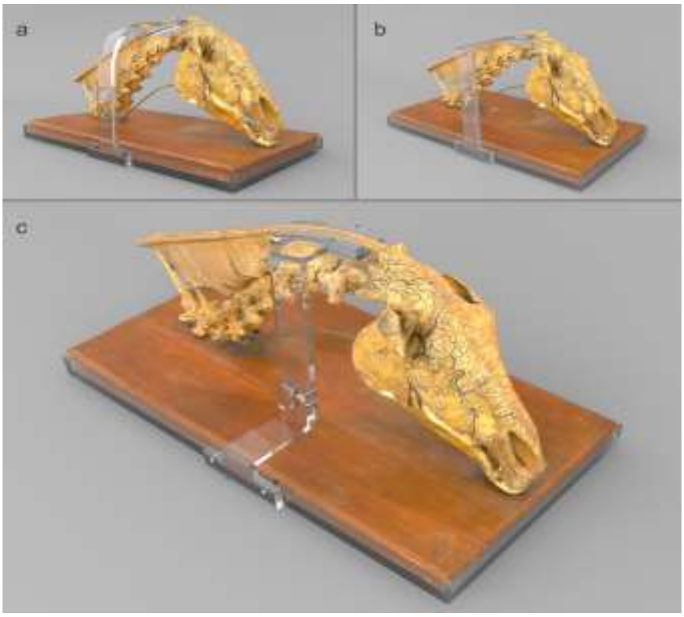

Fig. 6. 3D models of different supports considered during the computer design phase:
a) support with one-piece curved arm; b) support with one-piece right-angled arm; c) support with adjustable arm

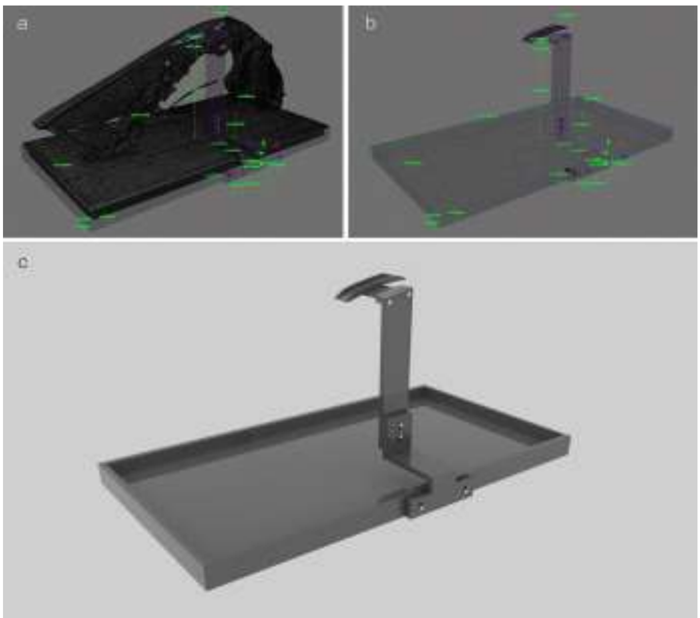

Fig. 7. 3D models of the definitive support: a) support adjusted to the anatomical figure;
b) support showing the measurements of each piece; c) infographic of the support in opaque material

The 3D model of the designed support was analysed by professors from the Department of Physics of Materials of the Complutense University of Madrid to confirm the suitability of the material chosen for its manufacture and to verify its strength and identify possible weak points. We were particularly concerned about the strength of the joints between vertically arranged parts, as the contact area was relatively small, and we wanted to ensure that the fastening of these elements would withstand the weight. The experts we consulted validated the design, although they recommended reinforcing some of the joints between parts with screws, considering the loads they would be supporting.

Once these modifications had been made, we entrusted the manufacture of all the parts of the support, except for those at the top, to the Mechanical Workshop of the Faculty of Physical Sciences of the Complutense University of Madrid (UCM). Because the parts of the support that came into contact with the anatomical model were more complex to produce and cost more, we decided to print them beforehand to confirm their shape and ensure that they would fit properly in the figure. They were reproduced in polylactic acid (PLA) on a 3D printer, Ultimaker 3 Extended (Ultimaker, Utrecht, The Netherlands) in order to mount them on the rest of the support and check that they fitted the sculpture correctly and were easy to assemble and disassemble (Fig. 8).

Fig. 8. Functional test with the upper part of the support printed in PLA

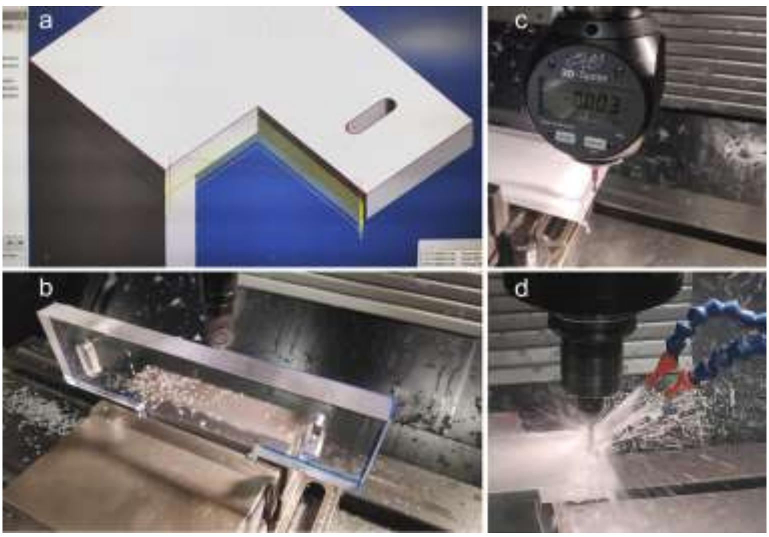

Fig. 9. CNC machining operations: a) setting the cutting areas; b) determination of the x, y and z coordinate origin; c) chamfering of the edges; d) creation of holes and slots

To print the 3D model, this was exported to an .STL file, this format being compatible with the CURA software (Ultimaker, Utrecht, The Netherlands). This is a lamination software that is used to set the printing parameters and generate the gcode file, which contains all the data necessary for the printer to build the part.

The technicians of the UCM Mechanical Workshop cut the PMMA strips and sheets to create the simpler parts that were part of the base and arm of the support, adjusting them to the right size with a universal milling machine, model FEXAC UP (FEXAC, Barcelona, Spain). The components with a more complex shape, such as the parts located at the lower and upper end of the support arm, were manufactured taking the digital files of the support as a reference and using a KONDIA B500 numerical control milling machine (KONDIA, Elgoibar, Spain) for their machining. The slots and holes for the screws were also made with this machine (Fig. 9).

The elements that make up the support were joined using chloroform, once the contact surfaces had been polished. Two 30-mm-long screws with a diameter of 5 mm were inserted into those joints that required further reinforcement.

Results and discussion

After the production of all the parts, the support was assembled separately to check the bending strength of the support arm. Once its rigidity was confirmed, it was assembled this time on the anatomical model, checking that it held the figure firmly enough (Fig. 10).

Fig. 10. Final appearance of the support: a) left lateral view; b) right lateral view; c) detail of the upper fastening piece; d) detail of the lower piece of the support

The assembly was relatively simple and at no time did the parts of the support come into contact with the anatomical model. The adjustment of the different elements allowed the structure to be adjusted to the figure, as a result of which it fitted perfectly. The screws were firmly tightened, ensuring the stability of the assembly.

No movement or deformation of any of the pieces of the support was detected after their installation. The aesthetic impact was assessed by the team of researchers, including the director of the museum, who determined that it was reasonable considering the importance of the problem it solved.

Conclusions

The digitisation of the anatomical figure made it possible to make a detailed analysis of, and –using computer-aided design software–, create a specific support to stabilise the parts of the sculpture that were at risk. This task would have been much more complex and inaccurate if only traditional methods had been used. In addition, previewing the pieces on the screen made it possible to anticipate the visual impact of each version created for the support and to decide on the best aesthetic solution for the work.

Functional testing of some of the parts of the support structure by reproducing them using 3D printing made it possible to check the ease of assembly and disassembly, as well as the adjustability of the system.

The aesthetic impact was acceptable due to the transparency of the material used to build the support and its design. In particular, the location of the support arm on the part of the model facing the inside of the showcase left it partially out of view of the viewer.

In the future, further 3D scans of the anatomical model will be carried out periodically to monitor the deformations of the nuchal ligament to determine the effectiveness of the support.

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