Transactions on Additive Manufacturing Meets Medicine
Trans. AMMM, 2023, Vol. 5, No 1, Article ID 816, 4 Pages

Original Research Article

Development of an additively manufactured skull model for the neurointerventional simulator HANNES

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Abstract: Neurointerventional procedures, such as the treatment of acute ischemic strokes using mechanical thrombectomy, require fast and skilled action. However, proper alignment and navigation of treatment instruments pose a challenge. This paper describes the development and manufacturing of a skull model that enhances the existing neurointerventional simulator HANNES, by providing a representation of the skull structure in X-ray imaging. The partially additively manufactured anatomical model enhances the realism of the simulator, as it can be used as an orientation for the targeted alignment of the treatment instruments during different neurointerventional treatments.

I. Introduction

An acute ischaemic stroke is caused by reduced blood flow to the brain, often due to a blood clot [1]. As a result, the brain is not supplied with enough oxygen [1]. This condition presents a life-threatening state that requires immediate treatment [2]. In addition to the medication-based treatment, the mechanical thrombectomy has become a standard treatment approach for patients with occlusions in large and medium vessels (LVO, MeVO) [3, 4, 5, 6]. It involves the endovascular removal of the blood clot that obstructs blood flow, using a catheter [7]. One of the challenges of this procedure is the orientation and navigation of the instruments within the blood vessel system. Orientation relies, among other techniques, on the visualization of bones within X-ray imaging. Mastering the complex treatment procedures of mechanical thrombectomies demands significant expertise.

The simulator HANNES (Hamburg ANatomical NEurointerventional Simulator) [8] can be used for the training of neurointerventional procedures, such as the mechanical thrombectomy [9], without the need for animal experiments. The simulation model includes a modular vessel tree based on patient original data [10]. To enhance the realism of the mechanical thrombectomy training on HANNES, a skull model has been developed. In the following the aspects of development, production and application will be more specified.

II. Development of the skull model

The development of the skull model was performed based on the standard VDI 2221. After defining all requirements for the development, several concepts were elaborated. For example, as reported by Hoffmann et al. cortical areas have a comparatively higher X-ray density compared to cancellous areas of the skull [11]. The interior of bones mostly consists of cancellous bone, whereas the outer bone shell consists of cortical bone [12].

Regarding the X-ray imaging of the skull, this results in a contrasting difference between the cortical outer shell and the inner cancellous bone parts. The final concept takes this into account by designing a fabrication of the skull bones from two different materials. The interior of the bones will first be additively manufactured and then encased with a layer of another material. Compared to the outer material, the additively manufactured core is to be made of a less radiopaque material. The additive manufacturing of the core is expected to result in a realistic reproduction of the complex bone geometries, which in turn will be transferred to the outer layer. For a good compatibility to the vessel tree of HANNES, the skull model was divided into a total of five components. Figure 1 shows the basic structure of the final concept. In order to be able to insert or exchange individual segments of the synthetic blood vessel tree in the skull model, it was decided to divide the skull along the frontal plane into an anterior and a posterior skull component. The fact that the two components each consist of several bones was neglected by defining them as firmly fused with each other. Further subdivisions into several components were made in order to keep the adaptation effort of future modifications and extensions of the skull model as low as possible.

In addition to the anterior and posterior components, a skull base was defined which serves as an interface between the cervical arteries and the cerebral vessels of the simulator. Furthermore, the skull base connects the anterior and posterior components of the skull. In addition to the bony structures of the skull, the concept considers the integration of the top four cervical vertebrae as an additional component, which can be coupled to the posterior skull via an interface. Beside the optical expansion, the spinal column serves as a support for the vertebral arteries of the simulator. Finally, it was decided to define the mandible as an additional component, which can be connected to the anterior skull via an interface. The orientation of the skull is determined by a skull holder which is attached to the posterior skull.

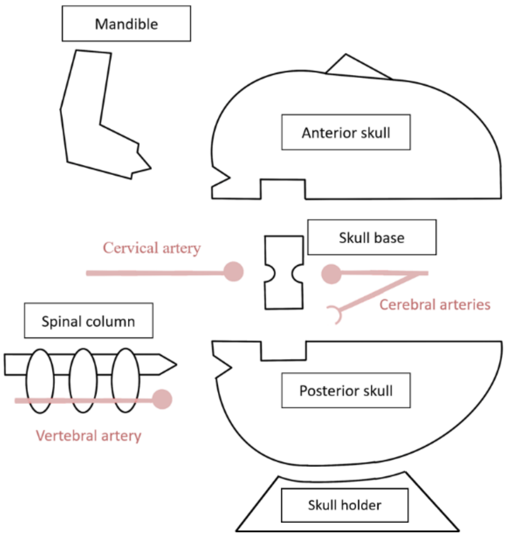

Figure 1: Schematic representation of the skull concept.

The construction of the skull model was performed using the CAD-Software CATIA (Dassault Systèmes, Somerville, Vélizy Villacoublay, France). The anterior and posterior components of the skull were constructed using an STL model obtained from a CT scan sourced from the embodi3D.com online database. Due to the high degree of geometric dependencies of the skull base and the spinal column in relation to the vessel tree, the construction of both components is based on the patient-original datasets of the HANNES vessel tree. For the implementation of the concept, some adjustments had to be made to the original data sets. In particular, these include adjustments that were necessary to realise the interfaces between the individual components. Furthermore, it had to be taken into account that there is sufficient space to exchange the vessel models. This resulted in the necessity to enlarge the foramen magnum. Finally, the bones belonging to each component were fused together to form a common single unit. The final construction of the skull model in CATIA, including the skull holder, is depicted in the upper graph of Figure 2.

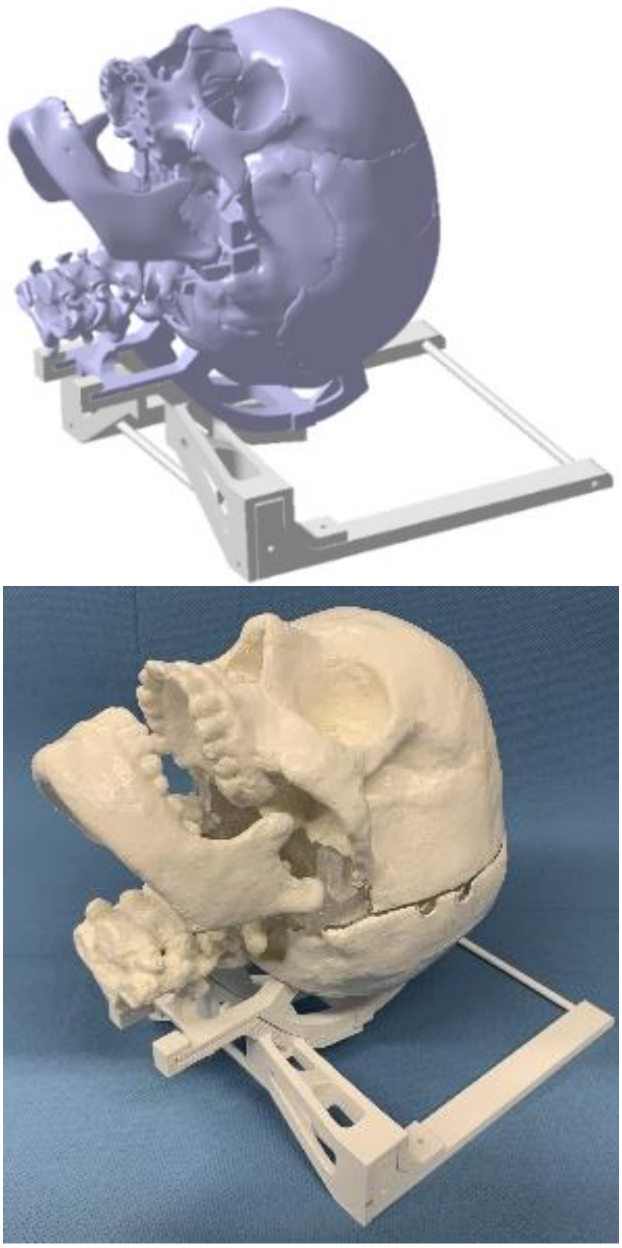

Figure 2: Skull model in CATIA (upper graph) and after manufacturing (lower graph).

III. Manufacturing of the skull model

In the production of the bony structures of the skull model, a special focus was placed on the authentic representation within the X-ray imaging. Accordingly, the fabrication of the bones was executed in three phases. First, the individual components were manufactured additively using the stereolithography (SLA) process on a Formlabs Form 3 (Formlabs Inc., Somerville, Massachusetts, United States) printer. This was done using the Clear V4 material from Formlabs.

Afterwards, the support structure was removed, the prints were washed out with isopropanol and cured under UV light. The fabricated parts, except for the skull base, were then manually coated with two layers of Cellona plaster fabric (Lohmann & Rauscher International GmbH & Co. KG, Rengsdorf, Germany). Plaster was used for the coating since it has a significantly higher X-ray attenuation compared to Clear V4 and can be applied well after printing [13, 14]. To enable the teeth to be completely encased in plaster fabric, they were each fabricated individually and then cemented into the mandible. Each tooth was scaled down by a factor of 0.7 so it received its final size after the plaster fabric had been applied.

During the replacement of individual vessel segments, small amounts of water may leak into the skull. Therefore, the plaster fabric of the skull was sealed with two layers of clear varnish (Hornbach Baumarkt AG, Bornheim, Germany). Finally, the skull holder was fabricated using the fused deposition modelling process on an Designjet Color 3D printer from HP (HP Inc., Palo Alto, California, United States) and attached to the posterior skull component using adhesive. The manufactured skull model is depicted in the lower graph of Figure 2.

IV. Results and discussion

To verify the results, the skull model was connected to the vessel tree of the simulator. In this process, it was observed that the removable anterior half of the skull provided sufficient space for inserting the vessel models. The vertebral vessel models could be well integrated into the spinal column. Afterwards, the representation of the skull model was checked in the X-ray imaging. The resulting image can be seen in Figure 3. The areas covered with plaster fabric are significantly more radiodense compared to the interior of the bones allowing clear visualization of the outlines of the bone structure.

The Hounsfield Units (HU) of the skull model were examined by a computed tomography using a SOMATOM go.Open Pro (Siemens Healthineers AG, Erlangen, Germany). The bone interior consisting of Clear V4 had HU values of 110 ± 14 and the outer plaster fabric layer had HU values of 551 ± 101. Here, the relative difference between the two materials appears to be sufficient for a high-contrast representation of the bone outlines. The visible bone outlines can be used for the training with the simulator HANNES to better assess the current position of the treatment instruments in relation to the simulated anatomy. The teeth of the skull model appear unrealistically radiolucent. It seems that the plaster fabric coating is not sufficient in this regard, and therefore, a complete fabrication using only plaster should be considered for future improvements.

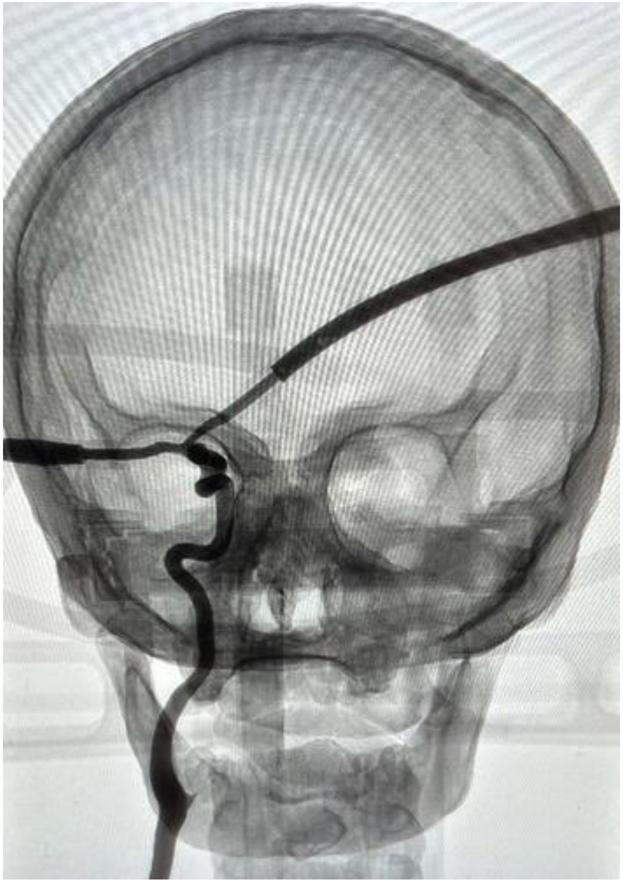

Figure 3: Frontal view, of the skull model connected to the HANNES simulator in X-ray imaging.

IV. Conclusions

To enhance the realism of the simulator HANNES, particularly during mechanical thrombectomy training, a skull model was developed and manufactured. The development of the spinal column was performed based on the original patient data of the vertebral artery.

Deriving and adapting patient data proved suitable for this application, ensuring high geometric compatibility with the vertebral artery. The SLA manufacturing from Clear V4 and subsequent encasing with plaster fabric enabled a qualitatively realistic representation of the skull bones to be implemented in X-ray imaging. In the future, the skull model will be an integral part of the HANNES simulator and thus support the training sessions conducted on the simulation model.

ACKNOWLEDGMENTS

The authors would like to thank the Federal Ministry of Education and Research – BMBF for funding the project COSY-SMILE-2 (16LW0165K).

AUTHOR'S STATEMENT

The project is funded by BMBF. The authors state no conflict of interest. Consent was obtained from all persons involved in this study.

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