

# Specific Parametrization Model of Skull on Structure and Thickness

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Received date: 05/04/2025

Accepted date: 27/06/2025

Publication date: 27/10/2025

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**Keywords:** biomechanics, finite element analysis, ballistic, parametrization, python

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Published by Société de Biomécanique

## 1. Introduction

Helmets protect soldiers from ballistic impacts, saving lives. However, testing is expensive and raises ethical concerns when using Post-Mortem Human Subjects (PMHS) for model validation. Skull structure and thickness influence the mechanical response of both bone and brain during trauma. To account for these factors, person-specific Finite Element (FE) skull model is necessary for helmet and head impact testing. We developed a mathematical model to capture inter/intra skull variability. This model reconstructed skull using only five parameters, all retrievable from a sagittal plane scan and skull width. This significantly reduced the number of inputs required to generate a patient-specific model.

## 2. Materials and Methods

This study developed a method for global skull parametrization, including morphology and thickness. Additionally, personalization of bone layers, namely cortical and trabecular bone, was integrated into the model.

### 2.1 Global model

To parameterize skull, geometric contours were collected from 13 PMHS (12 males and 1 female) and two additional specimens for validation (Delille, 2007). Specimens were chosen from brachycephalic, dolichocephalic, and mesocephalic categories, representing different skull morphologies based on length-to-width ratios.

Each PMHS skull was scanned using a non-contact 3D scanner (VIVID 910, resolution: 0.1 mm) with 22 acquisitions per specimen. A statistical analysis identified eight curves with 30 points distributed proportionally across the calvaria (Figure 1.a). Coordinates along the anteroposterior and transversal axes were distributed across the skull length, corresponding to a% and b%, respectively. Transversal and longitudinal coordinates were normalized using four exterior parameters to adapt the model to each individual. They are defined as L (skull length),  $x_{0,a}$  (coordinates at b = 0%),  $l_{55}$  (width at a = 55%), and  $h_{55}$  (height at a = 55%, b = 55%) (Figure 1.a). Additionally, base plane was aligned with Frankfort plane, shifted to sinus.

This normalization allowed calculation of equation for each a-curves (Figure 1.b). Then, all curves were then expressed as a function of the one at a=55%. Finally, the model could be described as follow:

$$\begin{aligned}
 X_{b,a} &= f\left(\left|X_{b,55}\right|, x_{0,55}, l_{55}\right) \\
 Y_a &= \frac{a}{9} L \\
 Z_{b,a} &= f\left(\left|Z_{b,55}\right|, h_{55}\right).
 \end{aligned}$$

To transfer data into FE model, all model points must be converted into nodes. Using initial equations and polynomial interpolation on Python, a model was constructed to determine  $n$  adjustable points (Figure 1.c).

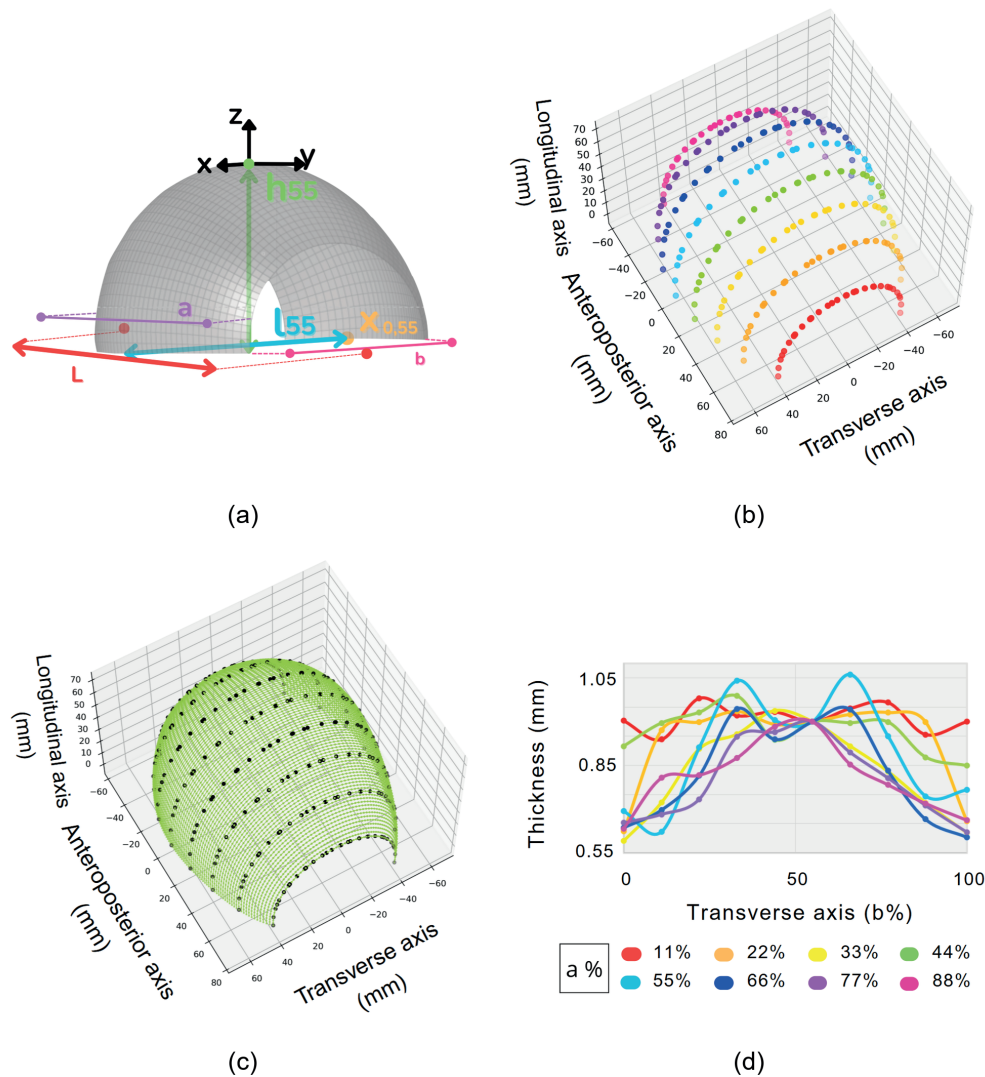


Figure 1. Skull model. (a) Referential, (b) a-Curves, (c) Final model and (d) Thickness.

## 2.2 Total Thickness

An equivalent method was used to determine total bone thickness. Eight curves, each defined by 10 points, were normalized and expressed relative to the center curve at  $a=55\%$  (Delille, 2023) (see Figure 1d). By correlating curves and interpolating points, the model could reconstruct total thickness using only one parameter (frontal thickness,  $th_f$ ). Consequently, the model incorporated all total thickness data, consistent with the structural shape.

## 2.3 Micro-structure

To determine internal bone personalization, a study was conducted on four skulls and 220 samples (Karkar, 2018), with one additional skull used for validation. Samples

were scanned by  $\mu$ CT (Skyscan 1172, resolution:  $10\mu\text{m}$ ), for determining the proportion of each layer (external/internal table and diploe). Then, they were correlate to total thickness which was used on global parametrization.

## 3. Results and discussion

### 3.1 Results

Using Python 3.12.7, the model provided a central calvaria parameterized with 5 inputs to generate  $n$  points. To evaluate our model, errors were calculated between the model-predicted coordinates and the corresponding PMHS coordinates. A point-by-point comparison showed errors below  $5\%$  for the two skulls not included in the database.

Using skulls from the model database, the median error between each model and the corresponding PMHS total skull thickness was quantified at 16.4%.

Study about bone layers thickness allowed to determine the percentage of cortical and trabecular bone with the following equations (Karkar, 2017):

$$t = \frac{1}{3.05} * (3.5 - 0.225) * t_{tot}$$

$$t_{ET} = \frac{2.05}{3.05} * (3.5 - 0.225) * t_{tot}$$

$$t_{dip} = 1.225 * t_{tot} - 3.5$$

with  $t_{tot}$ ,  $t_{ET}$ ,  $t_{IT}$ ,  $t_{dip}$ , representing total, external/internal table and diploë thickness, respectively. Those equations defined proportions of each tissue layer. Combined with parameterized structure, model predicted skull points with their thickness and tissue distribution.

### 3.2 Discussion

The model was successfully transferred into FE software by converting points into nodes and assembling them as shell elements in Altair® HyperMesh® using Python. The global parametrization captured inter- and intra-individual variability, scaling both skull geometry and total thickness. This study focused on the central calvaria. However, to apply the model in FE simulations of mechanical skull response, extremities must be incorporated. Additionally, the model remains a simplified geometric representation intended to capture overall individual variability, which constitutes a limitation of the present study.

### 4. Conclusions

In conclusion, the study successfully developed a parameterized skull with 5 parameters, focusing on geometric contours and bone thickness. The model showed high accuracy, with geometric errors under 5% and thickness errors averaging 16%. The transfer to FE software demonstrates the model's potential for personalized skull design.

### Acknowledgements

This work was conducted as part of a Ph.D. thesis, supported by the Direction Générale de l'Armement (DGA), Agence Innovation Défense (AID), the French Ministry of the Interior (CREL), and the Hauts-de-France Region. The authors thank them for their financial support.

### Conflict of Interest Statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

### Contributor Roles

**CL:** Conceptualization, Methodology, Writing original draft, Visualization, Writing-review & editing; **NP:** Supervision, Writing-review & editing; **OM:** Supervision, Writing-review & editing; **BB:** Supervision, Writing-review & editing; **FL:** Supervision, Visualization, Writing-review & editing; **SR:** Supervision, Writing-review & editing; **RD:** Supervision, Conceptualization, Methodology, Writing original draft, Writing-review & editing.

### Funding

This project was funded by the Direction Générale de l'Armement (DGA), the Agence Innovation Défense (AID), the Ministry of the Interior, and the Hauts-de-France region.

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