A Method for the Creation of Normative Paediatric Skull Models: a Pilot Study

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Abstract—Today, no objective standardized planning procedure exists for the preoperative planning of open cranial vault reconstruction of patients suffering from craniosynostosis. The use of a normative skull model, which will serve as a reference, will enhance the standardized planning procedure. Since no normative skull models of the Dutch population exist yet, a method was developed to create normative skull models of this population.

Methods: Steps include the creation of volumetric data and threshold determination, creation of mesh data, registration, rendering and normalization.

Results: A normative skull model represented as point cloud was created based on the CT scans of three patients.

Conclusion: The presented method enables the creation of normative skull models, using three CT data sets containing skull images. Therefore, this method is suitable for the creation of normative skull models of the Dutch population.

Index Terms—Craniosynostosis, Normative skull model, Open reconstruction planning, Ray casting, Registration

I. INTRODUCTION

Craniosynostosis is the premature fusion of one or more sutures on the newborn’s skull. Prevalence of craniosynostosis is between 1:2100 and 1:2500 births[1], [2]. As a result, growth perpendicular to that suture will be hindered and growth at other sutures creates a deformation of the skull. As a result increased intracranial hypertension can exist, potentially leading to mental retardation and malfunction of the eyes, ears and respiratory system. Well known forms of craniosynostosis are scaphocephaly, plagiocephaly and trigonocephaly.[1], [3], [4] Treatment of craniosynostosis is primarily surgical[5].

Children over 6 months are subjected to open cranial vault reconstruction techniques[6]. Even though open remodeling techniques have long history, no objective standardized planning tools exist. Therefore, the reconstruction is subjective and dependent on the surgeon’s experience and preference[7], [8].

With the help of normative skull models a standardized planning tool for open cranial vault reconstruction could be developed. Studies have presented methods for the creation of normative skull models. Saber et al. presented the first study in which they created normative skull models as surgical tools[7]. Marcus et al. showed that ray casting is an accurate reproducible and comprehensive method to obtain craniofacial morphometric data[8], [9]. To our knowledge no normative skull models exist of the Dutch population. Eventually, this method will be used to create of normative skull data, with as main goal to create normative skull models of the Dutch population.

II. METHODS

For the development of the procedure, Matlab 2014a and its Graphical User Interface (GUI) were used[10], together with the iso2mesh Toolbox[11] and the Geom3d toolbox©. The flowchart in Error! Reference source not found. demonstrates the steps of the procedure: preparing volumetric data, creation of mesh data, registration, 3D ray casting and normalization.
Fig 1. Workflow for the creation of normative skull data

A. Creating Mesh data

To enable the registration and ray casting the volume data is converted to vector data. Using the GUI the appropriate threshold is chosen, allowing segmentation of the skull and the creation of a mesh representing the skull. The function `volume2mesh` obtained from the iso2mesh Toolbox is used to create a tetrahedral volumetric mesh[11]. This function initially creates a triangular fully closed iso-surface, based on the selected threshold. Finally, the tetrahedral elements are filled with sub-volumes. The maximum face surface is set to 5 mm$^2$, the maximum size of the volume element is set to 100 mm$^3$ and the angle size in the ray casting is set to $2^\circ$.

B. Registration

To create comparative data, all mesh data should be similarly oriented and scaled. Therefore, registration is needed to place the local skull coordinate system onto the world coordinate system. Three non-aligned reference points are needed to constrain the coordinate system in the right orientation. In this method, a fourth point is used to place the skull in a symmetrical orientation within the world coordinate system.

Björk et al. describe the Sella Turcica as stable landmark within the skull during growth[12]. Also, the Sella-Nasion line appears to be appropriate for the determination of the skull orientation[13]. The reference points...
in the registration method consist of the Nasion, the center of the Sella Turcica and the symmetrical oriented anterior Clenoid processes of the Sella Turcica.

The registration consists of three operations: translation, scaling and rotation.

\[ W'p = sR_w(sW(s(p - t_W)))(1) \]

The first step of the registration includes the translation. In this method all skulls are oriented in such that the Centre of the Sella Turcica is positioned at \(X,Y,Z = [0,0,0]\). Therefore, the translation matrix consists of the coordinates of the Centre of the Sella Turcica.

\[ t_W = \begin{bmatrix} X_{SellaCentre} \\ Y_{SellaCentre} \\ Z_{SellaCentre} \end{bmatrix} \] (2)

In order to compare measurements between different skull meshes, all data should be scaled to the world coordinate system in mm. The scaling vector is obtained from the voxelvolume, which is included in the DICOM information. Therefore, the scaling vector is:

\[ s_W = \begin{bmatrix} 1/\Delta X_{voxel} \\ 1/\Delta Y_{voxel} \\ 1/\Delta Z_{voxel} \end{bmatrix} \] (3)

The rotation of the mesh data is accomplished in three steps (See Fig 2). First, the line connecting the Centre of the Sella Turcica and the Nasion is placed onto the y-axis. To do this the coordinates are rotated around the x-axis counter clockwise with angle \(\alpha\). Subsequently, the coordinates are rotated counter clockwise over the z-axis. The angles are computed with the following equations:

\[ \alpha = \cos^{-1}\left(\frac{Y_{Nasion}}{\sqrt{Y_{Nasion}^2 + Z_{Nasion}^2}}\right) \] (4)

\[ \beta = \cos^{-1}\left(\frac{Y_{Nasion}}{\sqrt{Y_{Nasion}^2 + Z_{Nasion}^2}}\right) \] (5)

In case that the Nasion is positioned in the other quadrant \((x_{Nasion} < 0 \text{ and/or } Y_{Nasion} < 0)\), angles with values \(\pi\) and/or \(2\pi\) respectively are added. The rotational matrices are:

\[ R_x(\alpha) = \begin{bmatrix} \cos \alpha & \sin \alpha & 0 \\ -\sin \alpha & \cos \alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \] (6)

\[ R_y(\beta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \beta & -\sin \beta \\ 0 & \sin \beta & \cos \beta \end{bmatrix} \] (7)

Finally, the right and left anterior Clenoid process of the Sella Turcica are used to rotate the caudal-cranial plane into a vertical orientation (See Error! Reference source not found.). These anatomical structures are always symmetrically located inside the skull[14].

Both angles \(\alpha\) and \(\gamma\) are computed with the following equation (equation for the left point is given):

\[ \sigma = \cos^{-1}\left(\frac{X_{NasionLeft}}{\sqrt{X_{NasionLeft}^2 + Y_{NasionLeft}^2}}\right) \] (8)

All coordinates are rotated clockwise with angle:

\[ \theta = \frac{1}{2} \Delta = \frac{1}{2} (\sigma - \gamma) \] (9)

The rotational axis is:
Fig 4 shows the result of the registration.

C. 3D Ray Casting

For the creation of normative skull data comparative information about the measurements of all skulls should be available. This information is obtained by ray casting. Hereby, the center of the Sella Turcica (located at $X, Y, Z = [0,0,0]$) is used as origin. Lines are created using spherical coordinates, in which $\theta$ represents the polar angle, $\sigma$ the azimuthally angle and $r$ the radial distance.

The Geom3d toolbox© with its intersectLineMesh3D function finds the intersection of the lines with the faces of the mesh (See Fig 5). This function returns the distance $R$ from an intersection to the origin. Also, the $x, y, z$ –coordinates of the intersection are given. For the full analysis, $\theta$ should have the range $0 \rightarrow 180^\circ$ and, $\sigma$ the range $0 \rightarrow 360^\circ$. It should be noted that the function finds intersections over the infinite line, defined by the spherical coordinates and $r = \infty$. Therefore, to obtain full analysis the interval of $\theta$ can be reduced to $0 \rightarrow 90^\circ$. Step size is chosen $2^\circ$. A full dataset of metrical information of the skulls is created and can be represented in point cloud images (See Fig 6).

All redundant information is omitted. This includes all intersections for $z<0$. Also, intersections are sorted in which the inner and outer cortical layers are separated (See Fig 7). Each line contributes to zero or at least two intersections within the data (inner and outer layer). For $\theta = 0$, four or more intersections are present. In that case only the outer four intersections are selected. These intersections are present in two determinants: $R < 0$ and $R > 0$, for which the origin $R = 0$. The intersections are sorted into the inner and outer layer dataset and separated based on the concerned determinant.

A. Normalization

The last step in the method is the normalization of all metrical data. For each spherical coordinate the mean is computed. During this computation a record of empty cells is kept. Therefore, the amount of data contributing to the mean is known. The mean is computed with the following equation:

$$\mu_i = \frac{\sum_{\text{con} \text{tributing data}} \text{data}_i}{\text{con} \text{tributing data}}, \text{ with } i = x, y \text{ or } z \quad (11)$$

RESULTS

CT-scans of three male/female patients of 16 months old were included in this study. The normative skull data was obtained represented in a point cloud (See Error! Reference source not found. 8).
III. DISCUSSION

A. Clinical application

Open cranial vault reconstruction techniques are performed in Craniosynostosis patients[5], [6]. However, no objective Dutch reference material is available for the planning of these reconstructions in children with Craniosynostosis. As a result, the planning remains subjective [7], [8]. Open cranial vault reconstructions are performed at the preferable age of 9 to 12 months [15]. Therefore, a database should be created containing cranial CT-scans of patients within these age groups. Normative skull models can be created and used as reference for the planning of a reconstruction. As a result, objective planning of the reconstruction is possible.

B. Method limitations

During the registration, all mesh data are rescaled based on the voxelvolume. The rescale factors are obtained from the DICOM information and based on the pixel spacing and slice thickness. However, information does not suffice for CT-scans in which voxels are not closely aligned or spacing between slices is present. Hence, such CT-scans were excluded.

For the registration three reference points within the Sella Turcica were used. These points are located within a close range to each other (around 2 mm) which increases the inaccuracy. Preferable would be to use points that are located at greater distance from each other. Ricketts et al. describes the Frankfort line as another appropriate reference to determine the orientation of the skull[13]. For this line both auditory meati should be located. Yet, these anatomical references were not always recognizable on CT-scans and therefore not appropriate for this method.

C. Additional research

Several improvement suggestions can be made reporting the method. First, the registration study needs to be validated. The reference points are manually selected. Thus, an inter-observer and intra-observer study is recommended.

The presented method uses ray casting for the assembly of normative data. Marcus et al. have shown that ray casting is an accurate, reproducible and comprehensive method to obtain morphometric data of the skull[8], [9]. Yet, the ray casting in the method of this article does not consider the difference in distances between the intersections and origin. As a result, the point cloud is not evenly distributed over the entire skull. The density of the points will decrease with increasing distance. To improve, a method allowing an even distribution of intersections should be developed.

Further, the parameters representing the maximum face surfaces and volume elements in the mesh function and the angles between the lines in the ray casting are arbitrary. The accuracy of the reconstruction increases with the decrease of the parameter values. However, the process time increases with the accuracy. It is not clear which values are appropriate. A parametric study should be considered, finding a balance between accuracy and process time. It should be noted that the accuracy of the reconstruction will vary due to differences in slice thickness and pixel size.
IV. CONCLUSION

With the presented method it was possible to create normative skull data, using three CT data sets containing skull images. Using a database with CT-scans, this method is able to create normative skull models of different populations.

REFERENCES


