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The computed cranial focal point

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ABSTRACT

Introduction: Stereophotogrammetry is a radiation-free method for monitoring skull development after craniosynostosis repair. Lack of clear fixed reference points complicate longitudinal comparison of 3D photographs. Therefore we developed the 'computed cranial focal point' (CCFP).
Methods: The CCFP was calculated in segmented 3D CT-scans of 36 adult subjects using Matlab. The robustness of the CCFP calculation was evaluated in predefined hemi-ellipsoid shapes. Finally we used the CCFP in two clinical cases to correlate CT data with 3D-photographic data.
Results: The CCFP calculation was found to be hardly influenced by incomplete or deformed surface data which resulted in small deviations (<2.5 mm). The average position of the CCFP of the skin relative to the sella turcica was at (0.0, 27.1, 19.4) mm, with CCFPσ (0.6, 4.6, 3.9) mm. The mean difference between the CCFP for the skull and skin was (−0.1, 1.9, −1.4) mm, with CCFPσ (0.5, 1.4, 1.0) mm. Using the CCFP in two cases to correlate the skin from a 3D-photo and the segmented skin from a CT-scan resulted in absolute mean differences of 0.7 and 2.3 mm, with a standard deviation of 1.1 mm in both cases.
Conclusion: The CCFP calculation is a robust method to define a reference point relative to the sella turcica based on the skin or cranial bone surfaces. The CCFP can be used to correlate 3D photographs with CT-scan data or for longitudinal radiation-free comparison of 3D-photos.

1. Introduction

Craniosynostosis is defined by the premature fusion of cranial sutures with an incidence estimated at 1 in 2000 to 1 in 2500 live births (Slater et al., 2008). Objective monitoring of the effects of craniosynostosis surgery relies heavily on the use of skull growth measurement. 3D skull measurements have become more widely used (Marcus et al., 2007, 2009; Saber et al., 2012; Delye et al., in press). These newer methods primarily rely on defining 3D parameters of the skull using CT-scans, involving radiation techniques. Because this introduces an increased radiation dose during longitudinal follow-up, alternative techniques such as 3D photogrammetry have been proposed to monitor 3D skull parameters (McKay et al., 2010; Toma et al., 2010; Schaaf et al., 2010; Wilbrand et al., 2012; Meyer-Marcotty et al., 2013). These techniques are limited to capturing the soft tissue surfaces. How well the captured soft tissue correlates to the bony skull has yet to be validated. Validation is difficult, primarily due to the lack of consistent markers to overlay and match sequential 3D photos for growth monitoring. The current golden standard for overlaying skulls uses the sella turcica, dorsum sella or a nearby structure as a skull-to-skull overlay point, based on the assumption that these structures remain immobile during skull growth (Björk, 1955). However, these structures cannot be captured on 3D photos.

We propose a new method using the 'computed cranial focal point' (CCFP). The CCFP is the point in the cranium where all the surface normals of the skin or skull tend to intersect. The CCFP can be calculated for any spherical body such as the skull or soft tissue surface of the head. The relative position from the sella turcica to the CCFP can be determined for the skin (CCFP-skin) and the skull (CCFP-skull) using CT-scans. In this study, we investigate how these points can be used for sequential photogrammetry matching, by defining the relation between the CCFP-skin and the CCFP-skull and their relative position to the sella turcica.

With the use of the CCFP, we aim for a radiation-free method to assist in objective sequential measurements of skull growth, to be

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used in craniosynostosis follow-up. This aims to reduce the need for CT-scans and thus to reduce the radiation exposure to pediatric patients with craniosynostosis.

2. Materials and methods

We developed a means of calculation of the CCFP and tested the robustness of this calculation method. Secondly, we performed an explorative patient study to define the relation between the CCFP-skin and the CCFP-skull and their relative position to the sella turcica. Finally, we used the CCFP-skin to match a CT-scan and 3D photo in two separate cases to evaluate the potential of the CCFP for matching a CT-scan and 3D photo.

2.1. Computed cranial focal point calculation

The CCFP can be calculated by determining the mean virtual intersection point of all the surface normals. All these intersection points combine to create a point cloud in the cranium with a center point and spread (CCFPσ). In-depth calculation of the CCFP can be found in Appendix A.

2.2. Method robustness test

2.2.1. Shape selection

The method robustness test was done using a set of predefined shapes as meshes (triangulated objects). Since this is a new method no predefined set of shapes to benchmark the method exists. The shapes were chosen to distinguish the effect on the CCFP and CCFPσ caused by conditions that could appear in real patients. All the shapes are spherically centered around the origin (0, 0, 0). The x-direction is from medial to lateral as seen from the left side, the y-direction from caudal to cranial and the z-direction from anterior to posterior. We used approximately 50,000 triangles per shape for optimum computation time versus accuracy.

The CCFP and CCFPσ of these shapes were calculated and compared with known values to determine the calculation accuracy. The CCFP coordinates are defined relative to the origin (0, 0, 0) in mm as x, y and z. The CCFPσ is also defined in mm as x, y and z.

One shape is a sphere with a radius of 9.6 cm. There were also four hemi-ellipsoid shapes originating from a hemi-ellipsoid with a height and length radius of 9.6 cm and a width radius of 7.7 cm (Fig. 1a). These measures were chosen to approximate the average human head size. The other three hemi-ellipsoid shapes were either asymmetrically cut to remove approximately 20% of the total surface at 15° pitch and 5° roll (Fig. 1b and d) and/or irregularly deformed up to 2.0 cm of the original (Fig. 1c and d). This is to mimic irregular skull shapes and partial missing data as could occur on a CT-scan. There were also two other shapes based on the hemi-ellipsoid, resembling trigonocephaly (Fig. 1e) and scaphocephaly (Fig. 1f).

2.2.2. CCFP outcome comparison

The sphere, full hemi-ellipsoid and the cut hemi-ellipsoid shapes have a known geometric focal point at the origin. The deformed hemi-ellipsoid shapes and the trigonocephalic and scaphocephalic shapes are constructed around the origin but do not necessarily have a geometric focal point at the origin. The position of the CCFP relative to the origin and the CCFPσ to (0, 0, 0) for the sphere is caused by polygon inaccuracy and the calculation itself. A similar comparison for the cut and full shapes give the difference caused by removing a part of the shape. Comparing the CCFP and

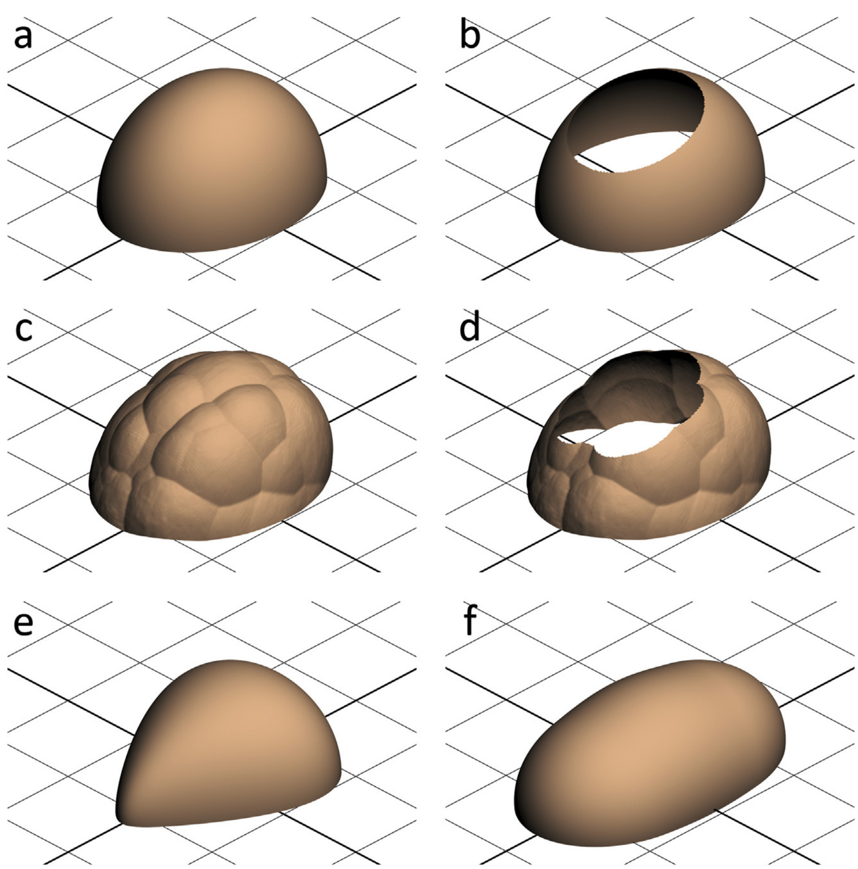

Fig. 1. A selection of the meshes used in the method robustness test: a) hemi-ellipsoid; b) hemi-ellipsoid cut; c) hemi-ellipsoid deformed; d) hemi-ellipsoid deformed and cut; e) hemi-ellipsoid trigonocephaly; f) hemi-ellipsoid scaphocephaly.