Automatic 3D Shape Severity Quantification and Localization for Deformational Plagiocephaly

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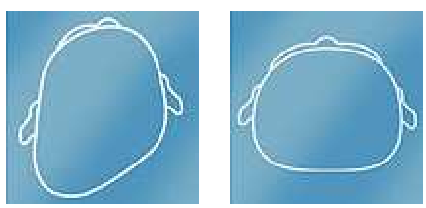
ABSTRACT

Recent studies have shown an increase in the occurrence of deformational plagiocephaly and brachycephaly in children. This increase has coincided with the "Back to Sleep" campaign that was introduced to reduce the risk of Sudden Infant Death Syndrome (SIDS). However, there has yet to be an objective quantification of the degree of severity for these two conditions. Most diagnoses are done on subjective factors such as patient history and physician examination. The existence of an objective quantification would help research in areas of diagnosis and intervention measures, as well as provide a tool for finding correlation between the shape severity and cognitive outcome. This paper describes a new shape severity quantification and localization method for deformational plagiocephaly and brachycephaly. Our results show that there is a positive correlation between the new shape severity measure and the scores entered by a human expert.

Keywords: 3D Shape Quantification, 3D Shape Analysis

1. INTRODUCTION

Deformational plagiocephaly (also known as positional plagiocephaly, or non-synostotic plagiocephaly) refers to the deformation of the head characterized by a persistent flattening on the side, resulting in an asymmetric head shape and misalignment of the ears. Brachycephaly is a similar condition of deformation of the head, however the flattening is usually located at the back of the head, resulting in a symmetrical but wide head shape (Figure 1).



(a) (b)

Figure 1. Deformation of head shape for infants with (a) Plagiocephaly and (b) Brachycephaly (from www.cranialtech.com)

Deformational plagiocephaly is caused by persistent pressure on the skull of a baby before or after birth. Recent studies[1] have highlighted that the increased occurrence of deformational plagiocephaly can be traced to the "Back to Sleep" campaign, which was launched in 1992. This campaign advised parents to place their babies on their backs to sleep to reduce the risk of Sudden Infant Death Syndrome (SIDS). Another possible factor that can lead to deformational plagiocephaly is torticollis, a muscle tightness in the neck resulting in a limited range of head motion that causes infants to look in one direction and to rest on the same spot on the back of the head. Premature babies are also at a higher risk of developing deformational plagiocephaly as their skull bones are softer.[2]

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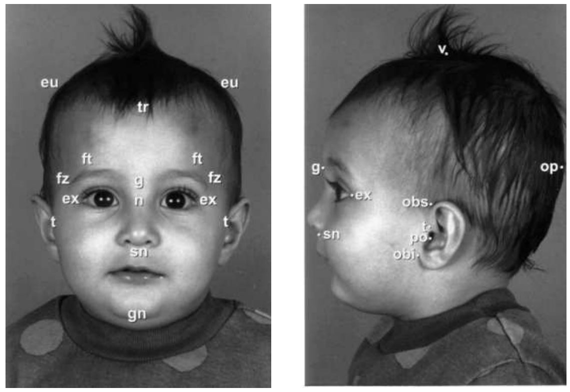


Figure 2. Anthropometric landmarks on patient's head. These images were published by Kelly et al.[7]

It is important to note that deformational plagiocephaly and brachycephaly are different from craniosynostosis, a condition in which premature closure of the cranial sutures leads to abnormal head shapes. While craniosynostosis often requires surgery for correction, plagiocephaly and brachycephaly can often be corrected using repositioning methods. However, if left untreated, children with either of these abnormal head shape conditions may experience a number of medical issues in their lives, ranging from social problem due to abnormal appearance to delayed neurocognitive development.[3]

Current shape severity assessment techniques for deformational plagiocephaly and brachycephaly are very subjective and tend to produce inconsistent scores, resulting in a lack of standard for the severity quantification of the two conditions. Most existing techniques rely heavily on clinical expert opinions to classify the degree of severity of the condition into discrete score ranges. Using continuous scores that reflect the degree of severity would allow researchers to investigate other issues, such as the correlation between shape severity and cognitive outcome for patients with deformational plagiocephaly and brachycephaly.

This paper describes a new shape severity quantification and localization method for deformational plagiocephaly and brachycephaly. We first discuss current assessment techniques and their limitations. We then describe our data acquisition process. Next we describe our new method of computing a shape severity measure and explain how it can be used to identify the flat regions on the patient's head. Finally, we analyze the results of our experiments on 46 patients and provide a summary and suggestions for future work.

2. RELATED WORK

There are a number of different methods to assess and measure the severity of deformational plagiocephaly.[4] Early measurement techniques for plagiocephaly began by using anthropometric landmark measurements.[5–7] These landmarks identify certain points on the head that are commonly found across all head shapes. The points include inner corner of the eyes, outer corner of the eyes, point along the sagittal plane etc. as shown in Figure 2. These techniques involve taking physical manual measurements on the patient's skull.[8,9] The approaches use calipers to record various measurements on the head. In one approach, the clinician determines the area with the greatest prominence both on the right and left side of the head and measures diagonally the distance from these sites to the back of the head. The smaller length is subtracted from the larger resulting in an asymmetry number called the Transcranial Diameter Difference (TDD).[8] Skulls with TDD values greater than 0.6cm are considered severe and correlate with skulls that scored 2 or more by an expert. Skulls with TDD values less than 0.6cm are considered mildly deformed. This technique produces discrete classifications that do not truly reflect the continuous trend in severity of the shape deformation. In addition, taking manual measurements is very time consuming and intrusive especially for young infants and tends not to produce consistent results. Finding the area to place the calipers is still subjective and affects the overall score.

Another technique for measuring the severity of shape deformations due to plagiocephaly and brachycephaly involves having clinical experts qualitatively match the shape of the patient's head to a set of templates. The templates contain images of heads with varying degree of shape deformation severity. The technique uses four templates: 1) normal head shape [score 0], 2) mild shape deformation [score 1], 3) moderate shape severity [score 2], and 4) severe shape deformation [score 3]. When assigning the severity score for a patient, a clinical expert matches the patient's head shape to the most similar template and assigns the score corresponding to that template. This technique is currently employed by practicians using the Dynamic Orthotic Cranioplasty Band (DOC Band) helmet as a treatment method.[10, 11]

Instead of taking physical measurements directly on a patient's head, some techniques take the measurements from photographs of the patient's head. This approach is less intrusive for young patients, but it is still time consuming and can be inconsistent as technicians must manually place landmarks on the photographs. Hutchison *et al.*[12, 13] developed a technique called HeadsUp that involves taking the top view digital photograph of infant heads fitted with an elastic head circumference band. The elastic band is equipped with adjustable color markers to identify landmarks such as ear and nose position. The resulting photograph is then automatically analyzed to obtain quantitative measurements for the head shape, including cephalic index, head circumference, distance of ear to center of nose, oblique length and ratio. Their results showed that the cephalic index (CI) and Oblique Cranial Length Ratio (OCLR) can be used for quantification measurement of shape severity, as the numbers differ significantly between cases and control. Zonenshayn *et al.*[14] used a headband with two adjustable points (nasion and inion of the head) and used photographs of the headband shape to calculate the Cranial Index of Symmetry (CIS). These methods require consistency in setting up the band and placing the markers, which may lead to non-reproducible results. In addition, this is a 2D technique, but plagiocephaly and brachycephaly are three dimensional deformations.

Vlimmeren *et al.* introduced a new method called plagiocephalometry to assess the asymmetry of the head. The method uses a thermoplastic material to mold the outline of a patient's head. The ring is positioned around the head at the widest transverse circumference. Three landmarks for the ears and nose are marked on the ring. The ring is then copied onto a paper and transparent sheet made to keep track of follow-up progress.

Measurement techniques that use full 3D head shape information can provide more detailed and accurate shape information. Plank et al.[15] use a noninvasive laser shape digitizer to obtain the 3D surface of the head. This system provides more accurate shape information, but still requires the use of markers to define an anatomical reference plane for further quadrant placement and volume calculations. Lanche *et al.*[16, 17] used a stereo-camera system to obtain a 3D model of the head and developed a statistical model of the asymmetry to quantify and localize the asymmetry at each patient's head. The model was obtained by first computing the asymmetry of a patient's head by deforming a symmetric 'ideal' head template to the patient's head to obtain point correspondences between the left and right sides. Principal component analysis was then performed on the vector of the asymmetry values of all patient's head to obtain a statistical model.

Our method uses a 3D model of the head without the need for markers. The method uses the surface normal vectors of all the 3D points on the head to find and quantify the flatness severity.

3. DATA ACQUISITION

The input to the plagiocephaly severity quantification and localization methodology is a 3D mesh model of a human head. The head mesh data is obtained through a data acquisition pipeline. A patient's head is covered with a close fitting cap to flatten the hair. The data acquisition process starts by taking photographs of the patient from twelve different viewpoints simultaneously, using a twelve-camera active photogrammetry system developed by 3dMD.[18] The software provided by the system uses the acquired head photographs to produce a full 3D surface reconstruction of the patient's head. The resulting 3D surface mesh contains 3D point coordinates and the connectivity information between the points. The mesh model is then manually edited to remove artifacts such as clothing and noise, resulting in a final 3D mesh model of the head (Figure 3). Each of the obtained head mesh data were assigned a score by a human expert. The scores were divided into three categories: score 0 indicates a normal head, score 1 indicates a head with mild shape deformation, and score 2 indicates a head with moderate shape deformation. The human expert also noted in some cases the type of deformation: plagiocephaly or brachycephaly.

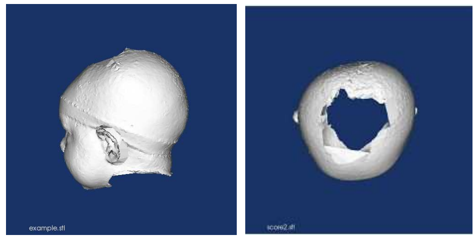


Figure 3. The final output of the data acquisition process is a 3D mesh model of a patient's head: (a) Side view of the head, (b) Top view of the head (the arrow indicates the front of the head). The head mesh model is used as input to the shape severity quantification and localization method.

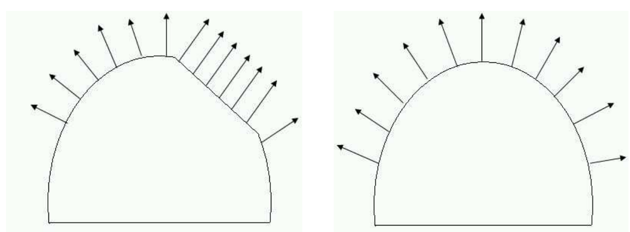
4. SHAPE SEVERITY QUANTIFICATION

4.1 Shape Descriptor

Given a point on a 3D surface mesh, a vector that is perpendicular to the tangent plane at that point is called a *surface normal* vector. Our shape severity quantification method uses the idea that surface normal vectors of points on a flat region of a head will all point in the same direction, whereas a rounded surface will have surface normals that point in many directions (Figure 4). Surface normals can be computed as the vector cross-product of two non-parallel vectors on a surface. Given the surface normal vector $n(n_x, n_y, n_z)$ of a 3D point, the azimuth angle θ of n is defined as the angle between the positive x-axis and the projection of n to the x plane. The elevation angle ϕ of n is defined as the angle between the x plane and n (Figure 5).

$$\theta = \arctan(\frac{n_z}{n_x}) \qquad \phi = arctan(\frac{n_y}{\sqrt{(n_x^2 + n_z^2)}})$$

where $\theta = [-\pi, \pi]$ and $\phi = [-\frac{\pi}{2}, \frac{\pi}{2}]$.



(a) (b)

Figure 4. (a) The surface normal vectors of points that lie on a flat surface tend to have similar azimuth and elevation angle and will create a peak in the 2D angle histogram. (b) The surface normal vectors of points that lie on a more rounded surface have more varying angles and hence will be spread out in the histogram bins.

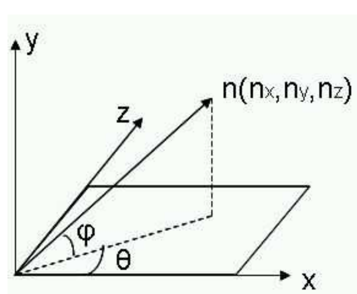
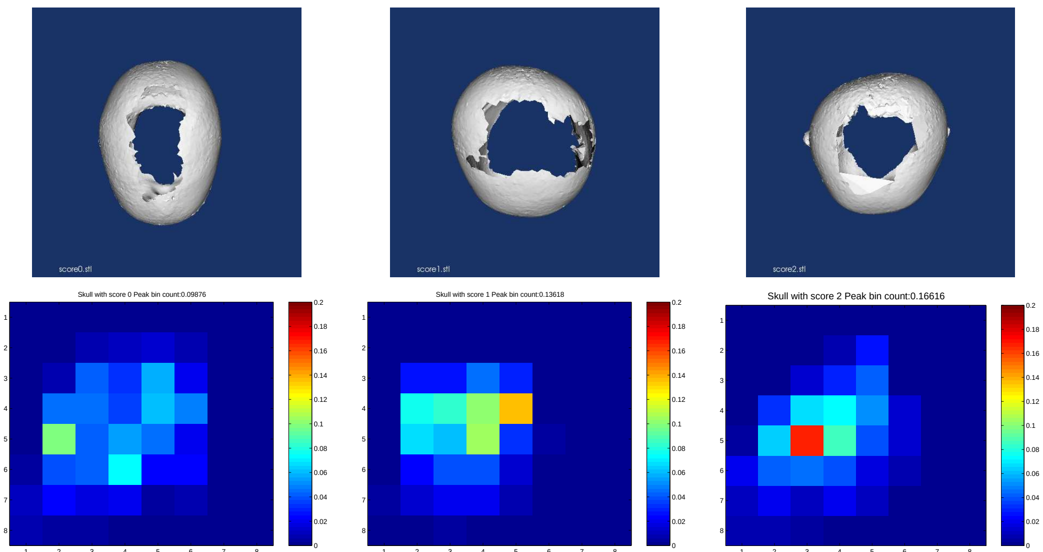


Figure 5. Azimuth and elevation angle of a 3D surface normal vector.

Once the surface normal vectors of all the 3D points in the mesh model are calculated, the algorithm constructs a 2D histogram of the azimuth and elevation angles to create a shape descriptor for the head. At the current time, we construct our 2D histogram with 8 bins for each dimension, resulting in 64 bins in total. Using 8 bins for angles is common in digital image analysis, as the angle calculations are not highly accurate.

Since the surface normal vectors of points that lie on a flat surface will be almost parallel, they will have similar azimuth and elevation angles. Thus flat parts of the head will show up as peaks in the 2D histogram. In comparison, the surface normal vector of points that lie on a rounded surface will have many different angles and hence would tend not to fall into the same histogram bin.

Figure 6 shows the 2D histograms of three different heads with increasing degree of deformation severity. The 2D histogram bin values are mapped by a color map in which high values in the bins are colored in warm colors (red, orange and yellow), while low values in the bins are colored in cool colors (blue, cyan and green).The 2D histogram of the normal head, a head that was labeled 0 by a clinical expert, has a low peak in the histogram (Fig. 6(a)). The head with a mild shape deformation (labeled 1 by a clinical expert) has a higher peak value in the 2D histogram (Fig. 6(b)), while the head with a more moderate shape deformation (labeled 2 by a clinical expert) has an even higher peak in the 2D histogram (Fig. 6(c)).



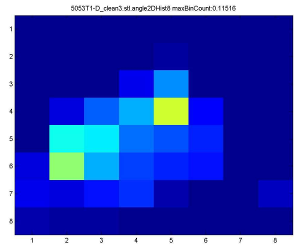
(a) Expert score 0 (b)Expert score 1 (c) Expert score 2

Figure 6. 2D Histograms of azimuth and elevation angles of surface normal vectors on 3D head mesh models (shown from the top view). As the severity of flatness increases, the peak in the 2D histogram becomes more prominent.

4.2 Severity Score

Using the acquired shape descriptor, we constructed a severity quantification algorithm. To calculate a shape severity score we first sort the histogram bins in increasing order of bin count, and assign each bin a rank, so that the bin with the highest count is assigned rank 1 and the bin with the lowest count is assigned rank 64 (8x8 bins). We then perform a simple clustering procedure based on the bin ranks. The seeds for the clustering algorithm are bins whose counts are above a threshold t. For our experiments, we used $t = 0.10$.

The clustering algorithm is similar to a region growing that starts its first seed at a bin of rank 1 (the bin with the highest bin value). For a seed of rank i, a cluster is formed for the seed bin by checking the seed bin's immediate eight neighbors and adding the adjacent bins that are of rank $i+1$, $i+2$, up to $i+8$ in sequential order. The process is repeated for each seed bin with value above threshold t and that have yet to be included in a cluster. Figure 7 shows an example of the clustering algorithm result on the 2D histogram of a head with a human expert score of 1. Note that considering only the 8 neighbors of each seed keeps the clusters small. If we grow the region further, then too many bins are included, which results in false positives.



61	63	62	64	39	44	58	57
56	50	54	32	26	38	52	60
46	45	30	18	7	40	55	47
35	21	9	6	1	17	49	48
41	3	4	8	10	14	51	59
20	2	5	11	13	15	31	36
19	22	16	12	25	43	29	23
24	27	28	34	37	53	42	33

(a) (b)

Figure 7. Example of clustering algorithm results on 2D histogram (a) based on the bin rank (b). Two clusters were found.

Each cluster returned by the algorithm represents a potential flat spot on the patient's head. The final shape severity score is obtained by summing the squares of the bin counts that are in the returned clusters and multiplying that sum by the number of such bins. If $B = \{b_1, b_2, ..., b_n\}$ is the list of bins from all the clusters, and $count_i$ is the count for bin b_i

$$score = n * \sum_{i=1}^{n} {count_i}^2$$

5. SHAPE SEVERITY LOCALIZATION

Using the 2D histogram of the azimuth and elevation angles as a shape descriptor also allows us to obtain positional information indicating where the flatness occurs on the head. This is done by finding points whose surface normal vector's azimuth and elevation angle correspond to the histogram bin with high counts. We again used a threshold of 0.10 to identify bins that have high values. Points whose azimuth and elevation angle fall into these bins are marked and subsequently displayed to the user. Figure 8(a) shows the top view of a head scored 2 by the human expert, and Figure 8(b) shows our localization on the back view. The flatness occurs on the right side of the head.

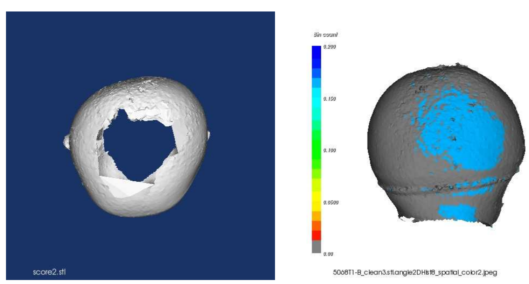


Figure 8. (a) Top view of head model, (b) localization of flat areas on the head (rear view with the flat areas marked).

6. EVALUATION

To evaluate the performance of our shape severity quantification method, we designed a case control study of 46 infants. The groundtruth for our experiments were the scores assigned by a human expert to each of the head data. Of the 46 head data, 14 heads were assigned label 0 by an expert indicating a normal head shape, 17 were assigned a score 1 indicating a mild case of head deformation, and 15 were assigned a score 2 indicating a moderate case of head deformation. The human expert also noted the type of deformation: plagiocephaly or brachycephaly in some cases. Each infant was photographed using the stereo camera system setup. The photographs were then passed to the data acquisition pipeline described in the data acquisition section (Section 3), resulting in a 3D head mesh model of each infant.

The shape severity scores obtained by the quantification algorithm were compared to the human expert scores. The correlation coefficient between our shape severity scores and the human expert scores was 0.62, indicating a positive but weak relationship. Analysis of the results showed that the heads labeled as mild cases (score 1) were assigned a wide range of values by our severity measure, but the skulls labeled as normal (score 0) were mainly assigned low values and those labeled as moderate (score 2) were mainly assigned higher values by our measure. Figure 9 shows the correlation between our shape severity scores and the human expert scores for each of the infant head. The mean shape severity score for each of the human expert score categories are indicated with a red dot. The figure shows that there is a linear trend in the shape severity score that directly correlates to the human expert score.

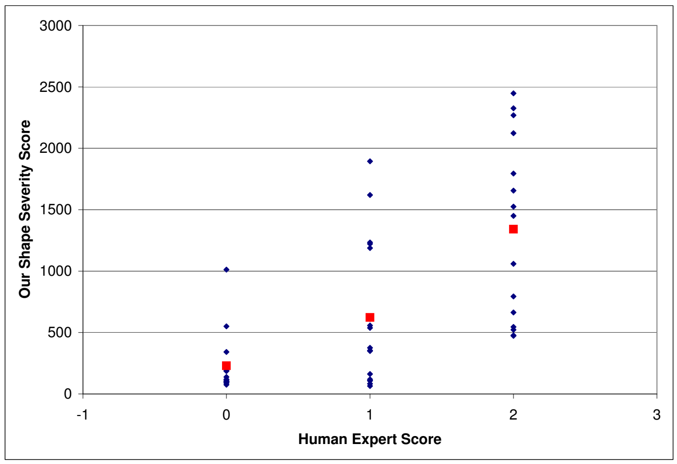


Figure 9. Graph showing the correlation between our shape severity score and the human expert scores for each of the infant data.

When the mild heads were removed from the study, the correlation coefficient increased to 0.72. Given these results, we relabeled the heads as normal (score 0) and abnormal (score 1 and 2) for the purpose of classification. We trained a random forest classifier using our shape severity scores assigned to the two classes: normal and abnormal. Using 10-fold cross validation, the classification rate was 76.087%.

Our shape severity measure was designed to look for flat areas of the head. It not only produces a continuous measurement of flatness but also shows where the flat areas are located on the head. The evaluation of our methodology used huma expert scores measured in discrete scales of 0, 1, and 2. In this case, there was only one expert score for each head data. The expert, in fact, noted on three of the head labeled 0 that they had mild or subtle asymmetry. Those three heads received higher shape severity scores than the other normal heads. Furthermore, two of the heads that the expert labeled 1 had been diagnosed as normal by the referring doctor and these were in the low range produced by our shape severity measure, similar to those labeled 0. The craniofacial specialists on our team feel that our shape severity measure shows promise for use in medical research and that experiments on a larger set of subjects and with multiple human expert evaluations are warranted.

7. CONCLUSION

In this paper, we have presented a new shape severity quantification and localization method for deformational plagiocephaly. This quantification provides a more objective and reproducible measurement that can be used for research in the area. The use of continuous measures instead of discrete, allows researchers to investigate the correlation between shape severity and other outcomes, such as neurocognitive disorders.

Medical experts agree that the shape spectrum of the affected cases tend to be very wide, hence a better scoring system is needed. A new scoring system is being designed to include an overall head shape score and ratings for different parts of the head. In addition, to ensure objectivity and consistency in the scores, more than one expert is needed for groundtruth measurements.

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