

Shape Descriptors and Automatic Severity Quantification for Deformational Brachycephaly

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Abstract

Deformational brachycephaly is a non-synostotic (or positional) flattening of the head that has largely been regarded as a cosmetic disease by clinicians. It is closely related to deformational plagiocephaly, both of which, being positional diseases, have increased in frequency considerably since the introduction of the “Back to Sleep” campaign, a largely successful attempt to prevent Sudden Infant Death Syndrome (SIDS). Most studies to date have been concerned with mapping the asymmetric deformations of brachycephaly and plagiocephaly, rather than quantifying their severity. As such, the attempts to determine whether positional skull deformations negatively impact an infant’s neurocognitive development have largely been unsuccessful, as they have lacked the standard of an objective measurement with which to correlate severity and outcome. This study proposes just such a standard for quantification, which could provide a tool not only for further research into severity and cognitive outcomes, but also for diagnosis and treatment monitoring, both of which currently are achieved largely through clinician observation and review of patient history.

1 Introduction

Deformational brachycephaly and plagiocephaly are positional diseases and therefore occur as a result of external deforming forces, including fetal positioning in the womb and supine positioning in infancy. Factors that lead to increased softness of the infant skull or a greater time spent with pressure to the skull increase the risk of a child to develop these diseases. These factors include prematurity, torticollis, male gender, and primiparity [1] [2] [3]. Positional brachycephaly and plagiocephaly (or a mix of the two) can form from any combination of these factors. Studies in the last decade have mostly focused on the effects of the supine sleeping position and attribute a greater number of deformational brachycephaly and plagiocephaly cases to the introduction of the “Back to Sleep” campaign in 1992, which greatly reduced the rate of Sudden Infant Death Syndrome (SIDS) by promoting the back or supine sleeping position. However, with a greater number of infants spending much more of their time in the supine position and

therefore receiving pressure to the back of their skulls for more time, there has been a much greater prevalence of cranial deformations [4].

Deformational brachycephaly can generally be described as the flattening of the central occipital of the head, resulting in a symmetrical but wide head shape (Figure 1a). This contrasts with plagiocephaly, which is characterized by a flattening on one side of the head’s posterior and asymmetry of the ears (Figure 1c). When the two diseases are combined, however, the difference between the two head shapes becomes much more tenebrous, as the symmetry of brachycephaly is lost (Figure 1b).

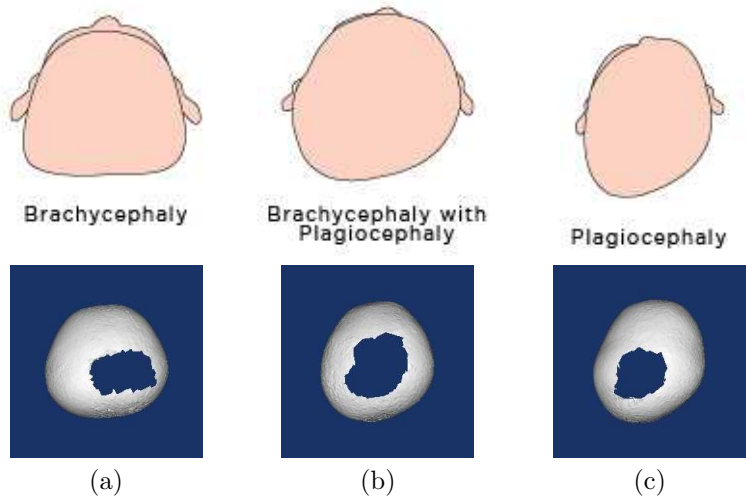


Figure 1: Diagram showing the deformation of head shape for infants with (a) brachycephaly (b) brachycephaly and plagiocephaly (c) plagiocephaly. (Top row of images taken from www.cranialtech.com, second row are similarly oriented images of patients used in this study)

Unlike craniosynostosis, which occurs when one or more sutures in the skull close prematurely [5], positional brachycephaly and plagiocephaly can generally be corrected with repositioning methods and/or a helmet or band, rather than cranial surgery [6] [7]. Studies have suggested that, without treatment, positional deformations can lead to stunted neurodevelopment and/or behavioral or learning problems [3] [8]. The results of such studies have remained inconclusive, however, in large part due to the inconsistency in diagnosis and severity quantification methods.

Current methods for classifying and quantifying deformational brachycephaly and plagiocephaly are highly subjective and incongruous. Most rely on a clinical expert to garner patient history from the observations of the patient’s mother or father and then give a diagnosis and discrete severity rating based on visual inspection of the patient. As a result, there is no standardized method for quantification; indeed, experts will often disagree on the severity of any given

case. In addition, the discrete scale varies between experts; in our research, the experts scored on a scale of 0–3, with 3 being the most severe; other studies have used expert scores on a scale of 0–4 [9]. This inconsistency and the discrete nature of the severity scores has sorely limited research into the links between severity and neurocognitive development.

This paper proposes a new and continuous severity quantification method for deformational brachycephaly. Current assessment methods and their limitations will be discussed, which will lead into the various attempts of this research to devise a classification and quantification method for brachycephaly. These attempts were met with varying degrees of success; this paper will end with analysis of the most successful and therefore recommended method for quantification of brachycephaly.

2 Related Work

While there exists very little to no literature that only deals with the classification and quantification of brachycephaly, the studies that have dealt with plagiocephaly or a combination of plagiocephaly and brachycephaly lay the relevant groundwork for methods of measuring the human head and classifying deformations. The basic problem of measuring the human head was initially tackled through cranial anthropometry [10] [11] [12]. Anthropometry labels the head into basic landmark measurements that are commonly found across all head shapes and sizes, such as the inner and outer corners of the eyes, points along the sagittal plane, etc., as shown in Figure 2. Most techniques that use anthropometry require a clinician to physically mark the location of such landmarks by hand [9] [13]. Manual measurements tend to be inconsistent, especially when taken on an infant who may be squirming or otherwise moving; in addition, such methods can be intrusive for the infant.

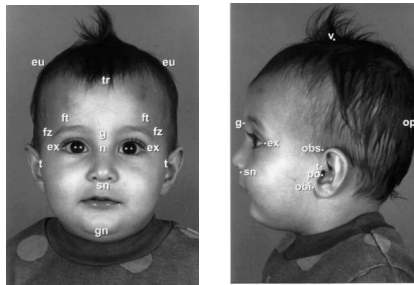


Figure 2: Anthropometric landmarks on a patient’s head. These images were published by Kelly *et al.* [12].

The approach presented by Glasgow *et al.* [9] relies on manual measurements to classify deformational plagiocephaly. First, a clinician determines the sites on the left and right sides of the head where the deformation is the most prominent.

Using a caliper, the clinician measures the diagonal distances between these sites, which are then used as occipital-frontal transcranial diameters. Their devised measure, the Transcranial Diameter Distance (TDD), is obtained by taking the difference between these two measured diameters. Infants with a TDD greater than 0.6 cm are considered severe, and correlate with infants that have an expert severity score of 2 or above; a TDD less than 0.6 cm indicates infants with mild deformations. The clinician’s judgment on the sites where the caliper is to be placed is highly subjective; in addition, correlation to the results of other studies is difficult to determine as they did not include infants with normal heads (controls) in their study.

Another technique for severity quantification of plagiocephaly and brachycephaly uses templates for matching infant heads with pre-determined shape deformations. The first template contains images of heads with no deformation (score 0), the second images of heads with mild deformation (score 1), and so on until the fourth template, which contains severe head deformation images that correspond with a score of 3 by an expert. The clinician simply matches the patient’s head shape with the most similar template and assigns the score corresponding to that template. Currently, this is the method used by practitioners who treat skull deformations using the Dynamic Orthotic Cranioplasty Band (DOC Band) helmet [14] [15].

There is also a form of manual measurement that involves a flexible band being placed around the widest circumference of an infant’s head. Vlimmeren *et al.* [2] termed the method plagiocephalometry. In this method, a thermoplastic ring is fitted around the circumference of the patient’s head, which then sets in form in under two minutes. Once the ring is set, the ears and nose landmarks are marked on the ring. The ring is then taken off the patient’s head and copied onto paper and onto a transparent sheet, using a standard copy machine. The oblique diameter difference (ODD) is calculated by taking the two diagonal diameter lengths that are drawn from points located 40° on either side of the antero-posterior line. Hutchison *et al.* [16] also use a similar technique; instead of a thermoplastic ring, a flexible strip or *flexicurve*, which requires firm pressure to fit to head shape, is used to measure each infant’s head. The subjectivity in placing the ring or strip around the widest transverse circumference is somewhat reduced in this experiment by taking three separate measurements.

Hutchison *et al.* [16] also developed a photographic method called HeadsUp, where a birds-eye view photograph is taken of each infant while outfitted in a yellow cape (to reduce confusion of the surrounding colors for analysis software), a nylon stocking cap (to flatten hair), and head circumference band. There are sliding red and green markers attached to this band to mark the nose and ears landmarks, which are placed and then the photograph is taken. Three photographs are taken for each infant; if any photograph shows significant roll or tilt to the head it is excluded from analysis. After the images are cropped to contain the headband and markers, the HeadsUp computer program analyzes each photograph and returns the cephalic index (CI) and the oblique cranial length ratio (OCLR), along with other measurements. The CI is obtained by dividing the widest head breadth by the length of the midline, then multiplying

by 100, while the OCLR is obtained by taking the ratio of the longer oblique length to the shorter oblique length, where the oblique lengths are the lines 40° from the midline, then multiplying by 100. These two measures were shown to be significant for classification. Generally, infants with an OCLR of 106% or greater had a plagiocephalic head deformation, while infants with a CI of 93% or greater had deformational brachycephaly. Zonenshayn *et al.* [17] use a very similar photographic method with an elastic headband, and calculate a cranial index of symmetry (CIS). When the photograph is taken, two black marks are drawn on the white headband, marking the nasion and inion. The CIS is then calculated by taking the two hemispheres divided by the line drawn from the nasion to inion (the midline) and inverting one of them, using the midline as the axis; the area of overlap of the two hemispheres is then doubled and divided by the total area. The CIS is this measurement expressed as a percentage. They found that the CIS for infants with plagiocephaly was less than 85%, whereas the CIS for controls was greater than 90%. Such photographic techniques have proven useful, but depend on consistency of the placement of the band and markers, and so can also produce subjectivity errors. In addition, neither of these studies reported a correlation to severity.

Data collected using 3D techniques and without the need for manually placed markers can provide more accurate and detailed information and lead to more significant measurements. Plank *et al.* use a noninvasive laser shape digitizer to obtain 3D head surfaces, but this method still requires the manual placement of markers to define a plane of anatomical reference for further calculations [7]. Lanche *et al.* utilize a stereo-camera system that creates a 3D model of the head. They developed a statistical model of the asymmetry, using principal components analysis, to quantify and localize the deformation of each patient [18] [19].

This work depends largely on the research of Atmosukarto *et al.* [20] [21]. Their work uses a 3D model of the head to automatically quantify and localize deformational plagiocephaly. Using the 3D model, the surface normals are calculated and then grouped according to azimuth and elevation angles, which isolates deformations. This research uses the same data collection as Atmosukarto *et al.*

3 Data Acquisition

3D head mesh data was obtained using a twelve-camera active photogrammetry system developed by 3dMD [22]. Each patient’s head is covered with a close-fitting cap to flatten hair. Photographs are then taken of the patient from 12 different viewpoints simultaneously; cameras are mounted on four pods in sets of three, where the top, middle, and bottom cameras capture the top, middle, and bottom views respectively from the aspect of the pod, all four of which surround the chair in which the patient sits. The software provided by 3dMD uses the acquired head photographs to produce a full 3D surface reconstruction of the patient’s head. This 3D reconstruction is then manually edited to remove noise,

resulting in a 3D mesh model of the head (Figure 3). Each 3D model is assigned a score by two human experts, and the scores are divided into four categories: score 0 indicates a normal head, score 1 indicates mild shape deformation, score 2 indicates moderate shape deformation, and score 3 indicates severe shape deformation.

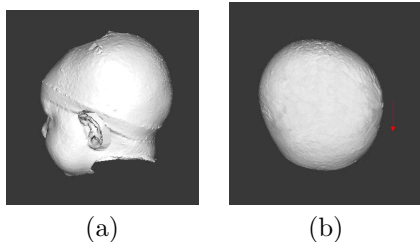


Figure 3: Example of the final 3D head mesh data: (a) Side view of patient’s head and (b) Top view of patient’s head after automated pose alignment (arrow indicates the front of the head; all such top view images shown in this paper from now on will be in the same orientation)

All 3D head mesh data are then passed to an automated rotation and alignment program developed by Wilamowska *et al.* [23] in order to ensure the same pose and orientation across images. Pose alignment performs the correctional yaw and roll angular rotations by minimizing the difference between the left and right side of the face, which gives reasonably consistent results, allowing for the fact that faces are not completely symmetrical. Then the pitch of the head is corrected by minimizing the difference between the height of the chin and the height of the forehead. Some images required additional manual alignment.

For the purposes of this project and the ultimately successful method that was devised, after pose orientation a 2D snapshot of each 3D head mesh was taken from the top view point and then converted to a binary black and white image.

4 Failed approaches to classification

This project began with the results of the automated method for quantifying plagiocephaly that was developed by Atmosukarto *et al.* [20] [21]. This method utilizes the idea that surface normals on a flat surface will lie almost parallel to each other. The surface normals for every 3D head mesh are calculated and represented in terms of their azimuth and elevation angles; as Figure 4 shows, surface normals on flat surfaces have very similar azimuth and elevation angles. The surface normal vectors of the 3D head meshes are organized into a 2D histogram according to these angles, so that groups of large numbers of vectors—and therefore flat regions on the head—are easy to distinguish (Figure 5).

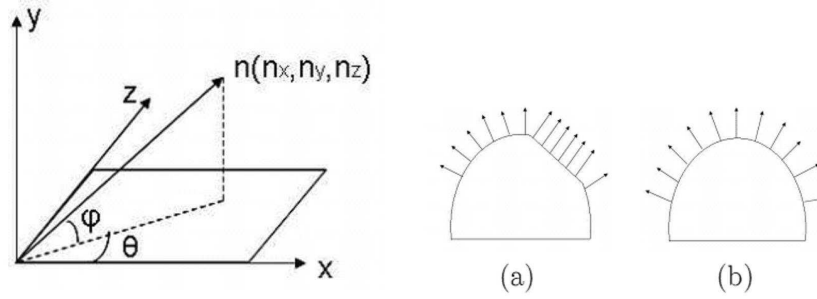


Figure 4: Image on the left shows azimuth (θ) and elevation (ϕ) angles for an exemplary 3D surface normal vector (n). Images on the right show (a) the parallel nature of surface normals on a flat surface and (b) the more spread out nature of normals on a rounded surface.

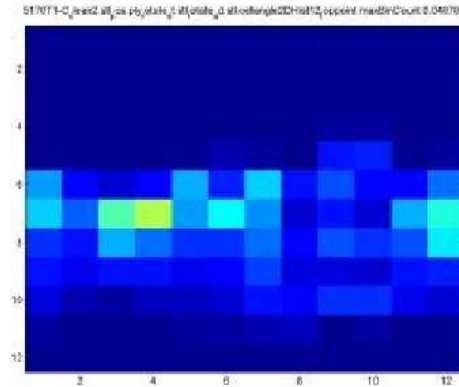


Figure 5: Example of the histogram for an affected patient. Azimuth angles run horizontally, with 0 in the middle, going to -180° on the left and 180° on the right. Elevation angles run vertically, with 0 in the middle, going up to -90° and down to 90° . Bins in 'cooler' colors represent a low number of surface normals at that azimuth and elevation, whereas bins in 'hotter' colors represent a high number of surface normals (and therefore a flat region on the head).

Using this 2D histogram, Atmosukarto *et al.* [20] [21] developed an Asymmetry Score (AS) to quantify plagiocephaly. The histogram bins that span the left posterior side of the head are summed and then subtracted from the sum of the bins that span the right posterior side of the head, which gives a representation of the asymmetry of the head (Figure 6).

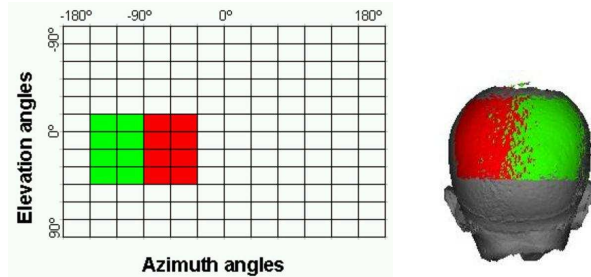


Figure 6: Highlighted bins show those that contribute to the AS; as shown on the head image on the right, the green bins in the histogram are the surface normals that span the right posterior side of the head, while the red bins span the left posterior side.

4.1 Peak areas of flatness

Visual inspection of histograms for infants both with and without brachycephaly yielded the hypothesis that affected cases would have three peak areas of flatness around the circumference of the head (Figure 7b). Or, in terms of the histogram, a horizontal transversal of the histogram along the $-15^\circ - 15^\circ$ bins would show three peak ‘hot’ areas. Intuitively, this hypothesis makes sense; brachycephalic heads are more triangular than normal or even plagiocephalic heads, which are purer ovals (Figure 7). However, in practice this did not produce consistent results. Most of the problem lies in the fact that an infant can be afflicted with both brachycephaly and plagiocephaly at once, which blurs the distinction between the two diseases. Thus, a head affected with a greater severity of plagiocephaly than brachycephaly can only have two peak areas of flatness (Figure 7a), or a head with a more equal mixture of the two can even have four peak areas of flatness (Figure 7c).

4.2 Symmetry Measurement

When a patient is affected with brachycephaly and very little to no plagiocephaly, the resulting shape deformation—especially at the very back of the head—is nearly symmetrical. Following the research of Atmosukarto *et al.*, it seemed logical that, for symmetrical brachycephaly cases, their AS would give a good indication of brachycephaly, since a symmetrical head would have an AS very close to zero. It is important to note that the decision on whether

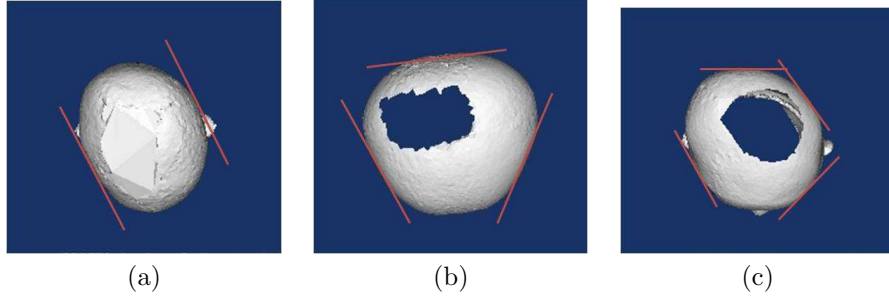


Figure 7: Red lines emphasize the peak flat areas on heads affected with (a) Plagiocephaly (b) Brachycephaly (c) Plagiocephaly and Brachycephaly.

a head affected with brachycephaly is symmetrical or not is a highly subjective judgment, and for this part of the study two researchers rated each case on whether it appeared symmetrical. The union of the sets of heads each researcher marked as symmetrical were then separated from the rest of the data set, and the symmetry of these cases were analyzed against the controls. This is obviously not an ideal technique for reproducible results, and was not meant to become a proposed method for classification of brachycephaly. The point was merely to determine the existence of affected cases that were very nearly symmetrical; if such cases existed, a diagnosing system in the form of a decision tree might be created, which would first separate affected from controls, then symmetric brachycephaly cases from plagiocephaly or combination cases, at which point a further step would be needed to separate those combination cases from plagiocephaly cases.

When symmetry analysis was performed, however, the affected cases were not shown to give results consistent with a highly symmetrical head shape. The AS was calculated for each case, giving a measure of the asymmetry of the back of the head. For the results to be significant, the AS for each brachycephaly case would have had to be very close to 0; this was not the case. Given this, and the ambiguity of whether a case was considered symmetrical, the symmetry approach was abandoned.

5 Shape Severity Quantification

5.1 Shape Descriptor

The most successful method found by this research to quantify brachycephaly uses a shape descriptor that is essentially a numerical representation of head shape; this shape descriptor is an adaption of the *Cranial Image* shape descriptor devised by Lin *et al.* [5]. First, using the binary black and white representation of the 2D snapshot of the top view of each 3D head mesh, the circumference of the head is calculated and divided by n points, or vertices. The position of these

vertices is then found by equally spacing them on the circumference, beginning with the first vertex at the exact middle of the back of the head. Since the head images are derived from snapshots of the automatically pose-aligned 3D meshes, this is guaranteed to be a consistently placed point across all the heads. Once the vertices are placed, the pairwise Euclidean distance between each pair of points is calculated, normalized, and put into a distance matrix. Normalization is achieved by dividing each distance by the maximum vertical length of the head, α (Figure 8). The vertices are numbered, beginning with the first vertex at the back of the head, for the sake of placement in the distance matrix (Figure 9).

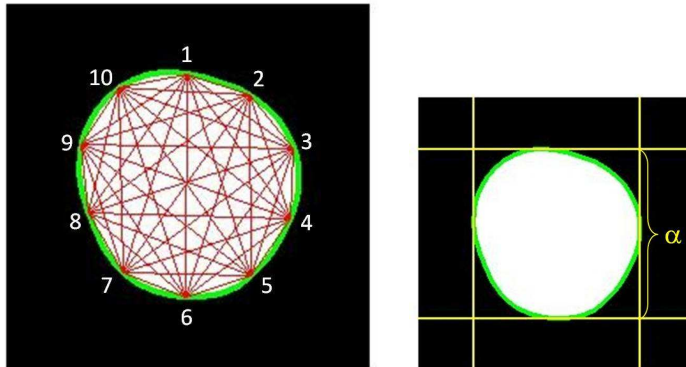


Figure 8: An example of a black and white head image, with the vertices, the circumference (in green), and all of the pairwise distances (in red) marked. The image on the right shows α , the length that was used to normalize the distances.

	1	2	...	n
1	0	$pdist(1,2)$...	$pdist(1,n)$
2	$pdist(2,1)$	0	...	$pdist(2,n)$
\vdots	\vdots	\vdots	\ddots	\vdots
n	$pdist(n,1)$	$pdist(n,2)$...	0

Figure 9: Diagram showing the structure of the distance matrix. The bin characterized by the i th row and the j th column is the euclidean pairwise distance between point i and point j . The main diagonal of the matrix is, of course, zero, because the distance between a point and itself is zero.

This research calculated distance matrices for $n = 10, 50$, and 100 points. As will be further discussed later on in this paper, there was not a significant difference in the results obtained from any of these sizes. Figure 10 shows all three sizes of distance matrix for one patient.

The distance matrix in all cases is symmetrical about the main diagonal,

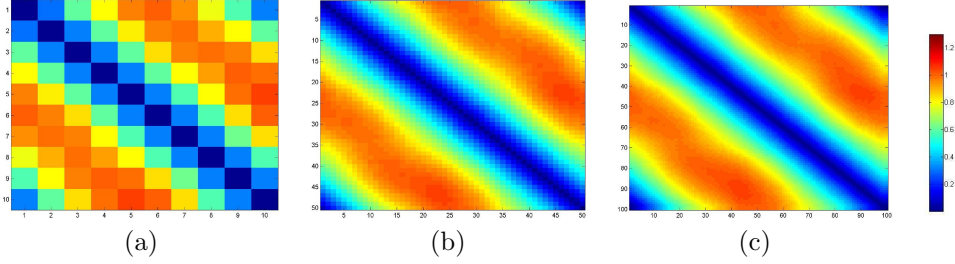


Figure 10: (a) $n = 10$ points (b) $n = 50$ points (c) $n = 100$ points. ‘Hotter’ colors in these images represent greater values (i.e. longer distances on the head), while ‘cooler’ colors represent small values.

which is logical—the distance from point 2 to point 8 would of course be the same as that from point 8 to point 2. Since it was unnecessary and would possibly even lead to confusing or skewed results, during analysis the lower triangle of the distance matrix was discarded. The values in these bins were replaced by a constant that was significantly higher than the values in any of the distance matrices, in order to distinguish the main diagonal—which is always zero.

Visual inspection showed that the distance matrix for an affected patient is noticeably different from that of a normal patient (Figure 11). Intuitively, these images make a lot of sense; a normal head is similar in shape to an oval, which is longer than it is wide. Thus the distance matrix for a control has two ‘hot spots’ in its distance matrix image; these represent the length of the head (the distances between the cluster of points at the very back and those at the very front of the head), which is the maximum distance. The heads of affected patients are more circular, and so their maximum distance is less noticeable. Something else to note from Figure 11 is the image for the patient with a mixture of brachycephaly and plagiocephaly; the diagonal line of ‘hot’ colors is noticeably unbalanced, which alludes to the asymmetric deformation due to plagiocephaly.

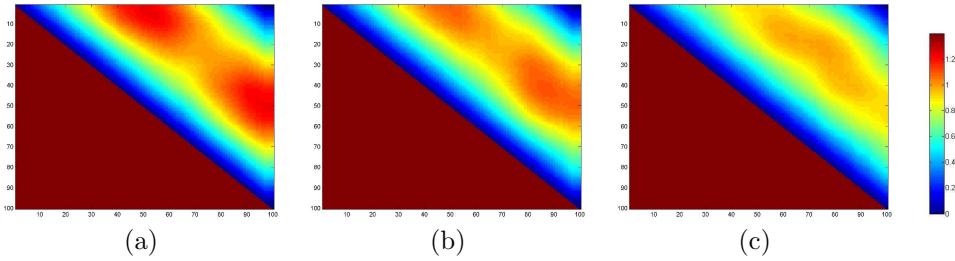


Figure 11: Upper triangular distance matrices (size 100) for (a) a control (b) a patient with brachycephaly and plagiocephaly (c) a patient with brachycephaly.

5.2 Severity Score

5.2.1 Less successful attempts at a Severity Score

Before the most successful quantification method was devised, there were a few attempts to manipulate the distance matrix shape descriptor and obtain a severity score to quantify brachycephaly. These attempts were met with limited success, but at the very least returned interesting and thought-provoking results. There are two methods in particular that merit a slight discussion.

The idea behind the first method was to correct the cephalic index (CI) devised by Hutchison *et al.* [16] for the case when a head is affected by both plagiocephaly and brachycephaly. The CI is a more or less successful method to classify brachycephaly because it measures the squareness of the head—generally, heads with brachycephaly are roughly as wide as they are long. It is easy for the CI to be thrown off by plagiocephaly, however, because the asymmetry of plagiocephaly skews the length of the head to one side. Using the distance matrix shape descriptor, the distances between the vertices that divide the head into fourths—starting with vertex 1—were isolated. These distances create a sort of diamond on the head, or a rotated square, which does not change significantly when a head has an asymmetric plagiocephaly deformation. The original hypothesis was that the ratio of the length and width of this diamond would be very close to 1 for brachycephaly cases; however, this did not provide clear separation between the cases and the controls. The distances parallel to the length and width of this diamond and originating within the confines of the diamond (Figure 12) were then isolated, and the sum of these diagonal distances did provide a score that significantly separated the affected cases from the controls. Figure 13 graphs the distances sum for all cases against the CI, showing the case-control separation as well as the marginally more successful classification rate. The diagonal distances sum provides a decent spread of severity, where severity increases as the sum decreases, but it is not ideal.

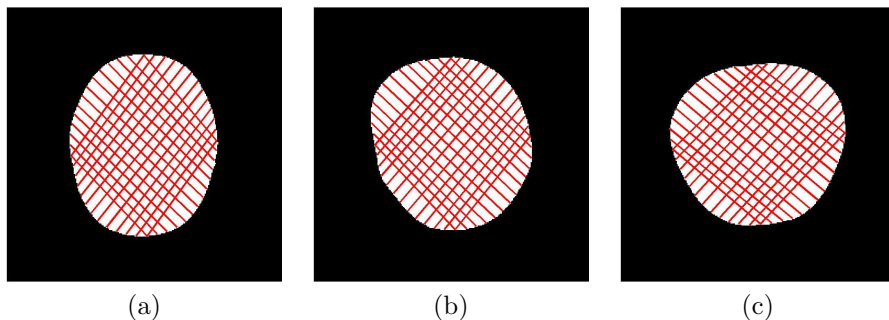


Figure 12: Diagonal distances (making a diamond shape) drawn on (a) a control (b) a patient with brachycephaly and plagiocephaly and (c) a patient with brachycephaly.

In simplistic terms, this shows that the distances across brachycephalic heads

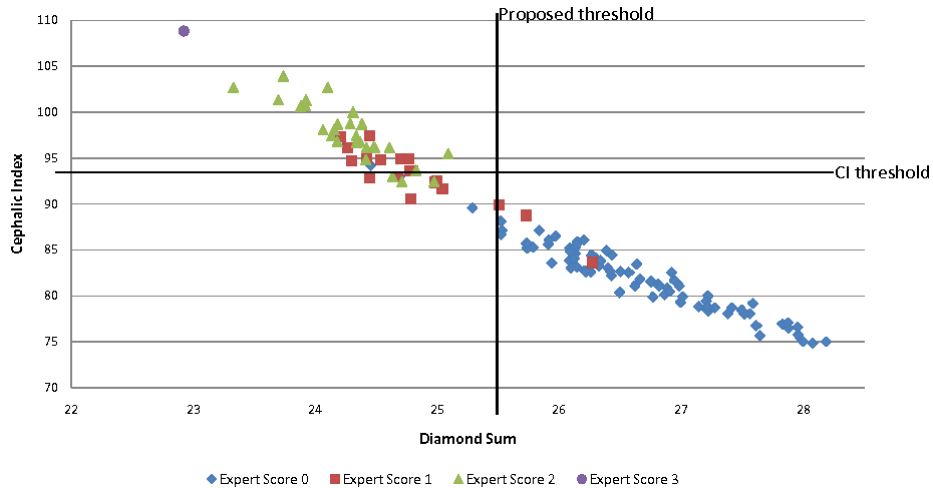


Figure 13: Sums run along the horizontal axis, while the CI is the vertical axis. This graph shows a decent spread of severity of case and a slightly lower false negative rate than the CI.

are shorter. The second method springs from this idea, because it implies that the distance matrices for cases with brachycephaly will in general contain smaller values than those for controls. The sum of each row in the distance matrix was taken, resulting in a vertical vector. The images of these vectors for all cases are quite interesting, because they show a marked difference between cases of brachycephaly and controls—in general, the row sum vector images for controls are depicted in ‘hotter’ colors than those for affected cases (Figure 14). These images are also interesting because they reflect any asymmetry due to plagiocephaly; as can be seen in Figure 14b the bottom half of the image contains a horizontal line in a ‘hotter’ color as compared to the rest of the image, which represents the longer distance that spans the lopsided deformation due to plagiocephaly. To obtain a severity score, the maximum value in this vector was determined. Figure 15 graphs this maximum row sum for all cases against the CI and shows a very similar separation to that given by the diamond distances sum.

These methods, while somewhat successful, do not have a strong scientific basis and so would not ultimately prove valuable in further research. The most successful technique undeniably arose from the ideas that these methods provoked, but it uses an established algorithm in computer vision to accomplish a similar task—with more successful results.

5.2.2 Successful Severity Score

The values in the distance matrices were put through principal component analysis (PCA) to isolate the variations between large values in the matrices for

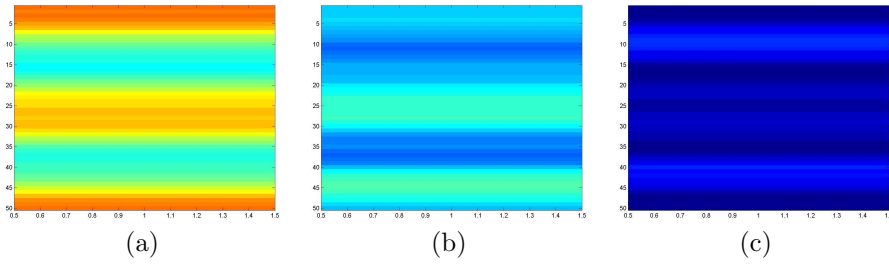


Figure 14: Row sum vector of the distance matrix in image form for (a) a control (b) a patient with brachycephaly and plagiocephaly and (c) a patient with brachycephaly.

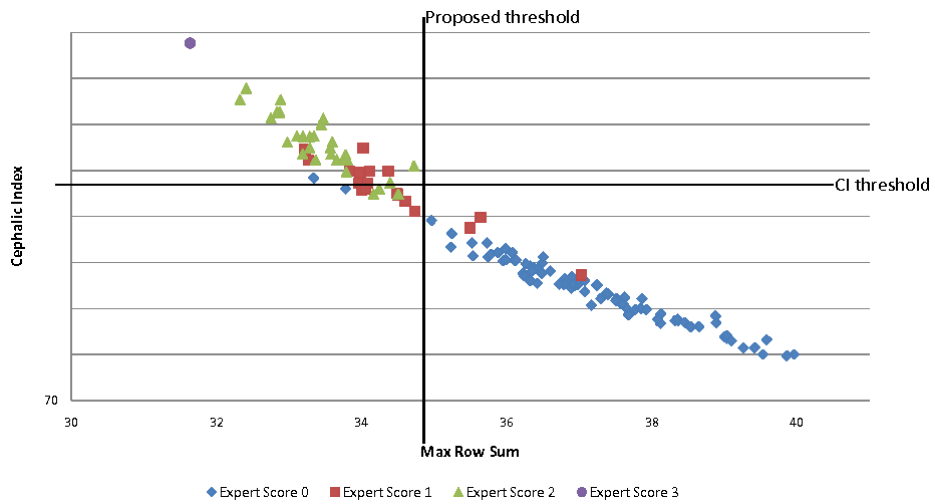


Figure 15: Maximum row sum is the horizontal axis, while the CI is the vertical axis. This graph is almost identical to the one above, showing the diamond sum against the CI.

controls and the smaller values in those for cases. The resulting eigenvectors pick out these variations quite well; the first eigenvector in particular does an excellent job isolating the variations that were noted above, where the matrices for normals have much higher values, specifically in the very top and right areas of the matrix (Figure 16).

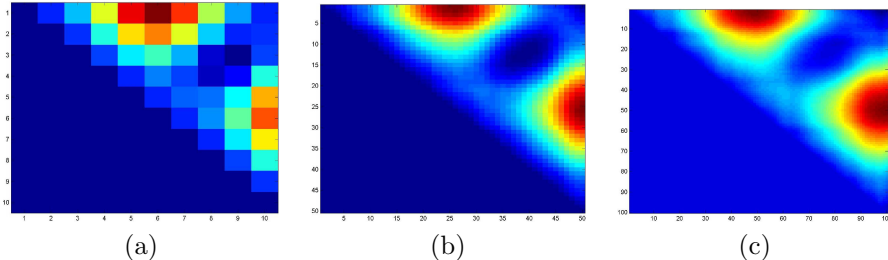


Figure 16: Images of the first eigenvector that resulted from PCA on distance matrices of size (a) 10 points (b) 50 points and (c) 100 points.

Each distance matrix image was mapped using only this first eigenvector, projecting the image into one-dimensional space. The weight of each distance matrix in this space is the *severity score* for each case, where severity is quantified by increasingly negative scores. This essentially obtains the variation of each distance matrix from the ‘normal’ or control image, since the first eigenvector characterizes the average control distance matrix image.

6 Shape Severity Localization

When used as a shape descriptor, the distance matrix gives positional information regarding the maximum length of the head. The maximum values in the distance matrix were determined and the distances on the head corresponding to these values were drawn on the head images. This is useful for visualization; Figure 17b shows the distance matrix for a patient with a mixture of plagiocephaly and brachycephaly and the maximum distances (the ‘hot spot’ in the distance matrix) drawn on the head, which clearly demonstrates the shift in the maximum length of the head. For this affected patient, it is skewed to the left, rather than the straight vertical midline of a control (Figure 17a). In direct contrast, the localization image for the patient with brachycephaly shows that the maximum length of the head is in fact the width (Figure 17c).

7 Evaluation

This study worked with a case control data set of 127 infants that was derived from a larger data collection of 254 cases. Of this entire set, 154 were patients referred as having some deformation—while the rest were referred as normal—and of the affected, 50 were diagnosed with brachycephaly and given the same

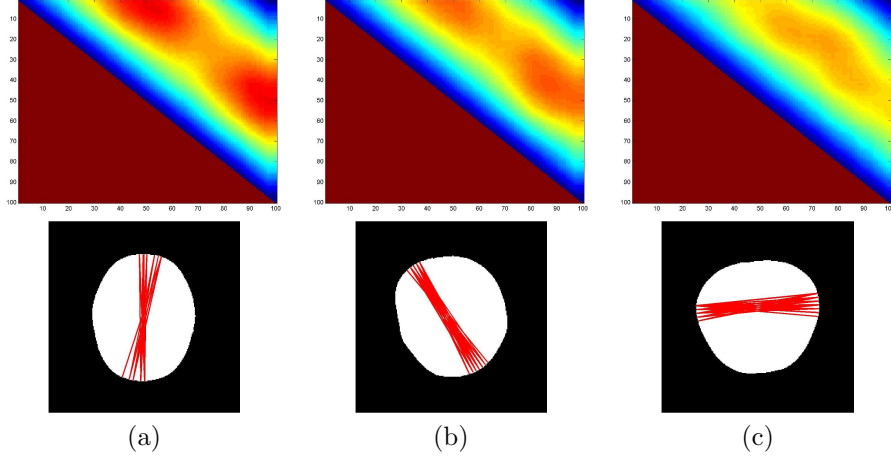


Figure 17: Distance matrix (size 100) and corresponding localization images for (a) a control (b) a patient with brachycephaly and plagiocephaly (c) a patient with brachycephaly.

severity score by both experts. As a side note, it is problematic that there is no ‘gold standard’ for determining brachycephaly. The groundtruth for these experiments was the expert score, and as the two experts that quantified each case in the data collection did not always agree with each other, human subjectivity error was minimized by eliminating the cases in which the experts did not agree. Patients that were referred as normal but were given an agreed expert score of 1 or higher for brachycephaly were also discarded. Two additional patients were eliminated during the study because of technical difficulties regarding their 3D head meshes. Thus the final set included 127 infants, with 78 controls and 49 cases of brachycephaly. The breakdown of the expert scores for the cases is as follows: 19 score 1, 29 score 2, and 1 score 3. Most of these cases were also affected with varying degrees of plagiocephaly.

The severity scores obtained through PCA for 10, 50, and 100 point distance matrices were compared both to the expert scores (Figure 18) and the CI (Figure 19) devised by Hutchison *et al.* [16], as this is currently the predominantly used classification score for brachycephaly. As mentioned previously, there is hardly any difference in results between the different sizes of distance matrices.

There is a strong correlation coefficient between the severity scores and the expert scores; for 10 and 50 points it is 0.85 and for 100 it is 0.84. Figure 18 also shows this strong linear relationship; it is negative, but keep in mind that with this severity score, severity increases as the score becomes more negative, so it is in fact a positive relationship and demonstrates that the severity score is a good measure of severity. In addition, Figure 19, depicting the correlation of the severity score to the CI, shows that the severity score in fact classifies slightly better than the CI, as there is a visibly smaller number of false negatives.

The optimal threshold for the severity score was calculated by maximizing

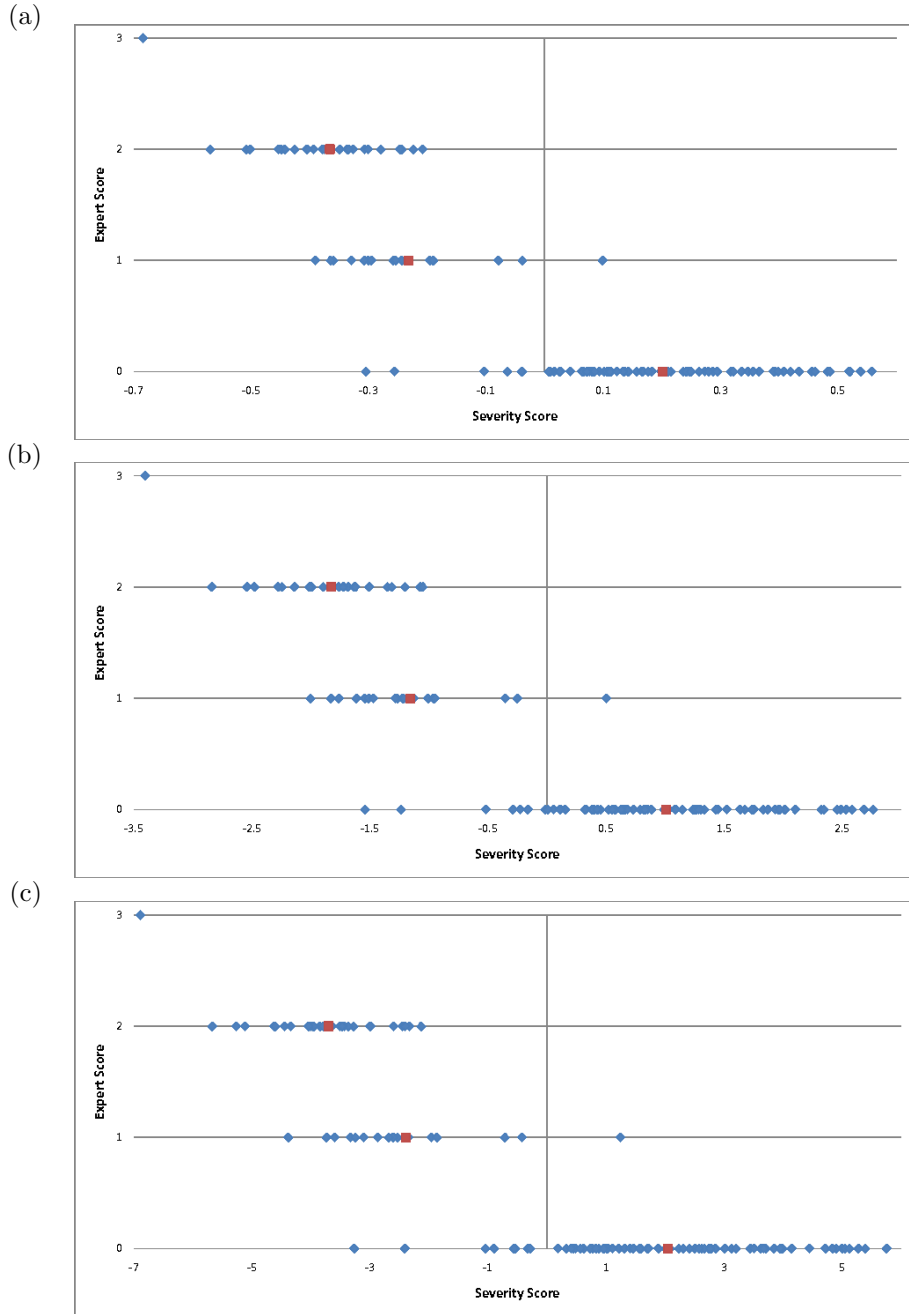


Figure 18: Severity score Vs. expert score, (a) 10 points (b) 50 points and (c) 100 points. The series of red squares represents the mean of the severity scores for each expert score subset.

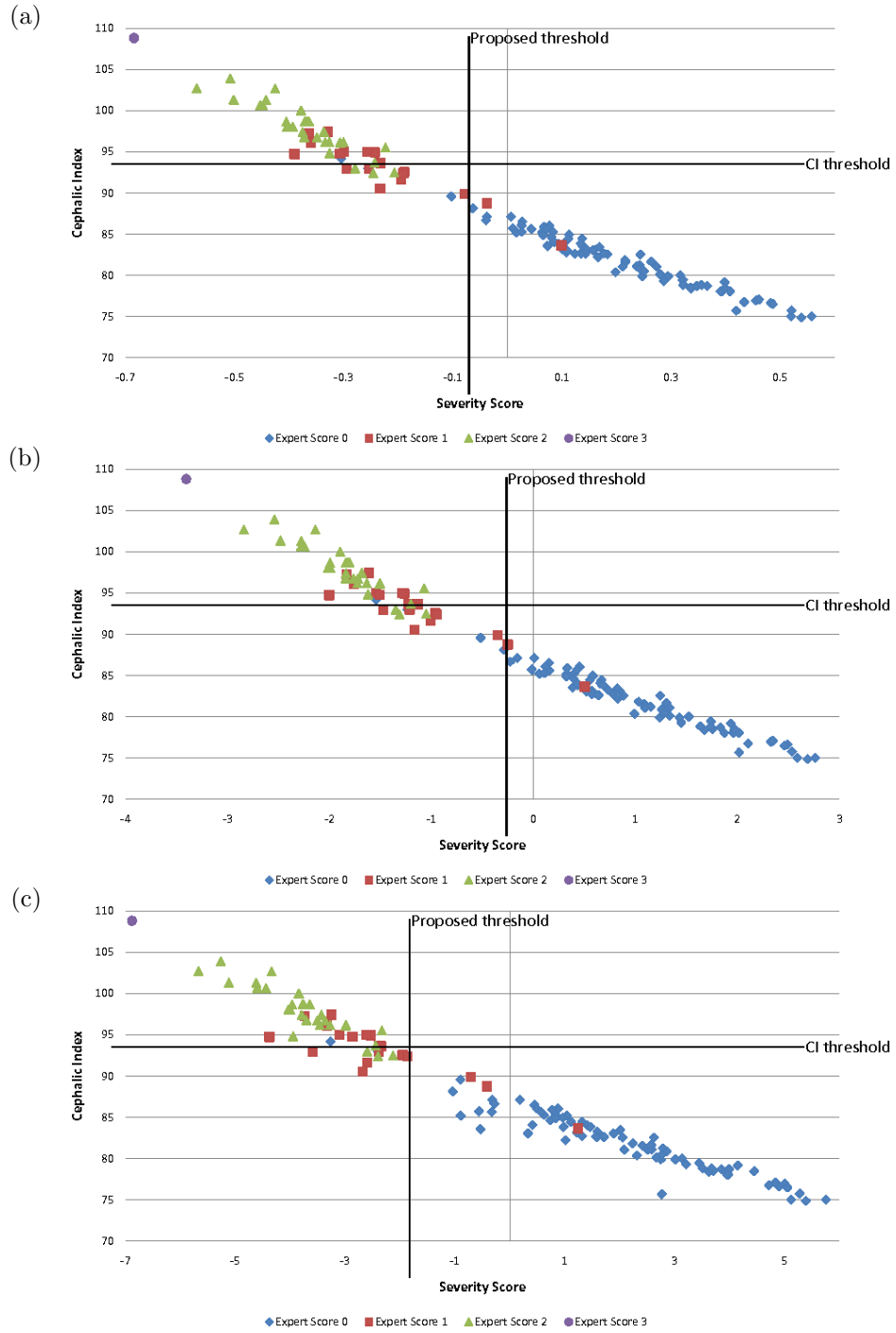


Figure 19: Severity score Vs. CI, (a) 10 points (b) 50 points and (c) 100 points.

the true positive vs. false positive rate; the ROC curves for each size of distance matrix is shown in Figure 20. For 10 points, the threshold is -0.0786, for 50 points it is -0.2524, and for 100 points it is -1.8639. Using SVM 10-fold cross validation, the classification rate for the severity score across all sizes of distance matrices was 96.063%.

The fact that severity increases as the severity score decreases actually makes intuitive sense; the score measures the deviation of each patient’s distance matrix from the average normal distance matrix, which is characterized by the two ‘hot’ spots of maximum distances. The normal cases deviate from this positively, as the maximum distance on their heads is the length, whereas brachycephaly cases deviate from it negatively, as their heads do not necessarily reach a maximum length.

8 Conclusion

This paper presents a new, continuous shape severity score for quantifying deformational brachycephaly. Since it is derived from an automatically pose-aligned 3D head mesh, it allows for greater objectivity and consistency of measurements across all cases. In addition, it will be more easily reproducible for future experiments, and could provide a standardized measure for further research not only in measuring head shapes but also into links between head deformations and neurocognitive development.

Future research into this method could widen the results to include other head deformations, such as plagiocephaly. It was beyond the scope of this project, but it is highly likely that the other eigenvectors returned by the PCA analysis would give much more information regarding other head shapes beyond brachycephaly; it is worth investigating.

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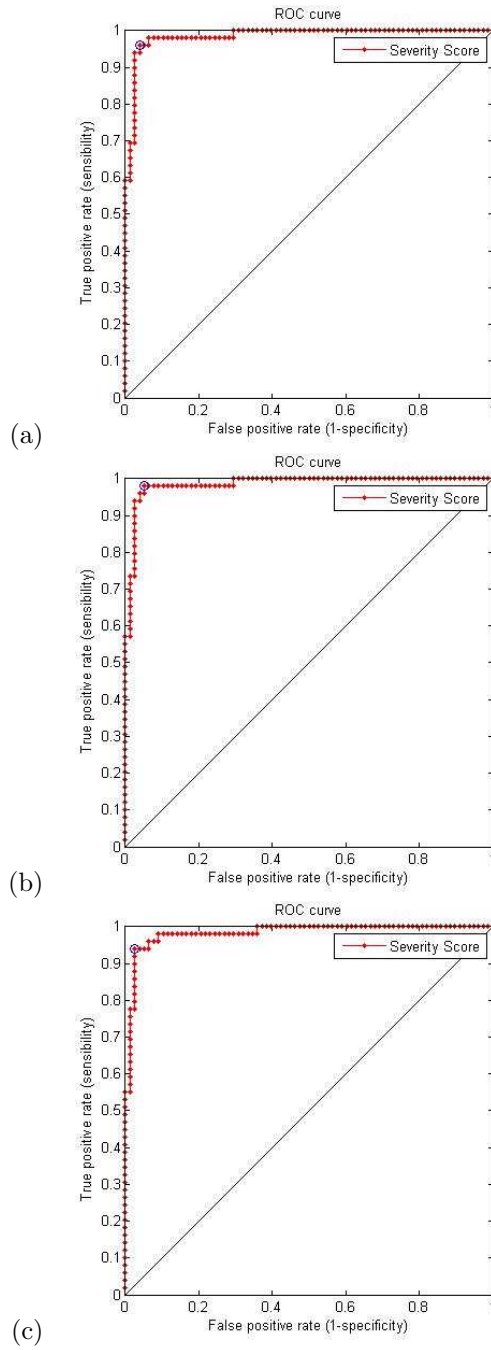


Figure 20: ROC curves for severity scores calculated from (a) 10 point (b) 50 point and (c) 100 point distance matrices.

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