Skull Retrieval for Craniosynostosis Using Sparse Logistic Regression Models

Shulin Yang\textsuperscript{1}, Linda Shapiro\textsuperscript{1}, Michael Cunningham\textsuperscript{2}, Matthew Speltz\textsuperscript{2}, Craig Birgfeld\textsuperscript{2}, Indriyati Atmosukarto\textsuperscript{3}, and Su-In Lee\textsuperscript{1}

\textsuperscript{1} Computer Science and Engineering, University of Washington, Seattle, WA \{yang,shapiro,suinlee\}@cs.washington.edu
\textsuperscript{2} Seattle Children’s Research Institute, Seattle, WA \{michael.cunningham,matt.speltz,craig.birgfeld\}@seattlechildrens.org
\textsuperscript{3} Advanced Digital Sciences Center, Singapore \indria@adsc.com.sg

Abstract. Craniosynostosis is the premature fusion of the bones of the calvaria resulting in abnormal skull shapes that can be associated with increased intracranial pressure. While craniosynostoses of multiple different types can be easily diagnosed, quantifying the severity of the abnormality is much more subjective and not a standard part of clinical practice. For this purpose we have developed a severity-based retrieval system that uses a logistic regression approach to quantify the severity of the abnormality of each of three types of craniosynostoses. We compare several different sparse feature selection techniques: $L_1$ regularized logistic regression, fused lasso, and clustering lasso (cLasso). We evaluate our methodology in three ways: 1) for classification of normal vs. abnormal skulls, 2) for comparing pre-operative to post-operative skulls, and 3) for retrieving skulls in order of abnormality severity as compared with the ordering of a craniofacial expert.

Keywords: craniosynostosis, cranial image (CI), $L_1$ penalized logistic regression, fused lasso, clustering lasso (cLasso), sparse logistic regression model.

1 Introduction and Motivation

This work is focused on retrieval of CT images for patients with craniosynostosis, a common congenital condition in which one or more of the fibrous sutures in an infant’s calvaria fuse prematurely, resulting in restricted skull and brain growth. Because the brain cannot expand perpendicular to the fused suture, it redirects growth in the direction of the open sutures, resulting in abnormal head shape and in some cases, facial features. Craniosynostosis results in head deformity that can be severe if it is not corrected surgically. This condition may result in increased intracranial pressure on the brain and is correlated with developmental delays, although the cause of such delays is not currently known. It is estimated that the fusion of any one or more sutures occurs in approximately 1 in 2,000
In clinical practice, craniosynostosis is diagnosed by a physician on the basis of head shape and confirmatory CT scan. Automatic analysis of CT scans, including a measure of shape deformation, would be of great help to both doctors and medical researchers. In our previous work, we built a system that automatically generates a shape representation called the cranial image (CI) from the CT image of a patient’s skull. The cranial images are used as shape features to distinguish between skulls of patients with different types of craniosynostosis. We also proposed using logistic regression and three variations of the logistic regression model for classifying different types of craniosynostosis: $L_1$ regularized logistic regression [2], the fused lasso [9] and the clustering lasso (cLasso) [1], which is a variation of $L_1$ logistic regression. These models avoid overfitting of the regression model, and they also could select subsets of features from the cranial image that represent skull regions associated with the distinctive shape differences related to different suture fusions (e.g., sagittal vs metopic suture fusion).

It is important to note that clinicians do not need to rely on a quantitative model to make the diagnosis of craniosynostosis. However, there is a lack of criteria to quantify the severity of the abnormality for research purposes. For example, when estimating the relative effects of different surgical methods on cranial shape (i.e., pre-, post-surgery change), quantitative measurement is essential. For this reason, we have developed a system to retrieve CT images based on quantification of the severity of the abnormality of the 3D skull shape. Given an enlarged data set containing pre-operative and post-operative CT scans of subjects with three classes of craniosynostosis (coronal, metopic, and sagittal) plus a set of scans from similar-age control subjects, we conducted a set of experiments in classification, quantification, and retrieval using the three logistic regression methods proposed in [1]. Different sparse logistic regression models are compared in terms of misclassification on whether a skull has craniosynostosis or not. Then we show our retrieval results using the best model for our data - cLasso. Abnormality of the skulls of the same patient before a surgery and after a surgery is compared using the quantification criteria as well.

The rest of the paper is organized as follows. Section 2 summarizes the related literature, Section 3 gives an overview of the framework of our approach for abnormality quantification, Section 4 describes the details on how logistic regression models are used for quantification, and Section 5 shows the experimental results of our work.

## 2 Related Literature

Calvarial (skull) abnormalities are frequently associated with severely impaired central nervous system functions due to brain abnormalities, increased intracranial pressure and abnormal build-up of cerebrospinal fluid. In [3], Shapiro et al. introduced several different craniofacial descriptors that have been used in studies of two craniofacial disorders: 22q11.2 deletion syndrome (a genetic disorder) and deformational plagiocephaly/brachycephaly. They provided feature extraction tools for the study of craniofacial anatomy from 3D mesh data.