A Lobar-Based Curvature Analysis of Normal and Polymicrogyria Brain Surfaces in Children

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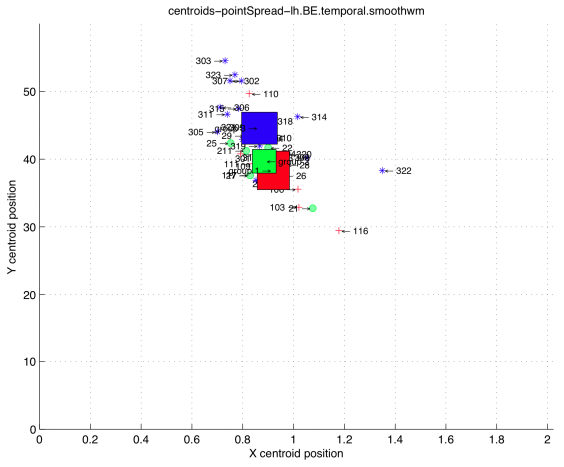
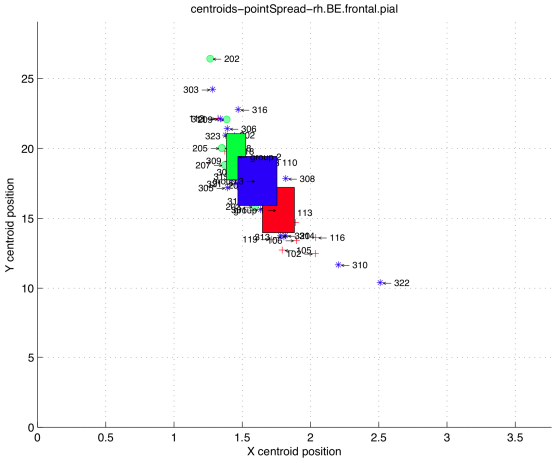
INTRODUCTION: Polymicrogyria (PMG) is a developmental malformation of the human brain, and given that its presentation can be localized, multifocal, or generally diffuse, offers challenging image classification problems. In the simplest case, PMG malformations are characterized by an excessive number of abnormally small gyri. This paper presents findings from a surface curvature analysis on comparative PMG and normal groups, calculated across brain surface lobar regions. Surfaces are created from MRI volumetric data as processed by FreeSurfer. We present a robust post-processing curvature-pipeline that analyzes curvature distribution profiles for a large battery of curvature functions across surface regions. Given an a-priori set of classes, we present statistical curvature-based properties based on our analysis that can allow for useful group-wise statistics and aid in future curvature-based image recognition.

METHODS: A total of 43 subjects (23 normal: age 1 year to 18 years; mean 8.0 years; std 4.8 years – and 20 PMG: age 2 years to 18 years; mean 8.2 years, std 4.9 years) were identified in a retrospective study of existing Hospital database records. T1 weighted image volumes were processed by FreeSurfer and per-hemisphere gray/white 'smoothwm' and outer 'pial' mesh surfaces reconstructed. These surfaces were analyzed for point-by-point principle curvature values using a Gauss-Bonnet scheme, resulting in a solution for the intrinsic curvature (or Gaussian) $K=k_1k_2$ and the mean extrinsic curvature $H=\frac{1}{2}(k_1+k_2)$. Since these curvatures are functions of the principal curvatures k_1 (maximal curvature) and k_2 (minimal curvature) at each vertex, we can solve also for k_1 and k_2 from the Gauss-Bonnet K and H. Additional curvature functions including the Curvedness, $C = \sqrt{(\frac{1}{2}(k_1^2 + k_2^2))}$, Sharpness, $S = (k_1 - k_2)^2$ and Bending Energy $B = (k_1^2 + k_2^2)$ which were also evaluated for all surface points, as too was the cortical thickness. Each hemisphere was subdivided into the following lobar regions: frontal, parietal, occipital, and temporal, and each PMG subject MRI was visually examined by a radiologist and the regional involvement of the malformations recorded. In our data set, PMG involved was localized to given regions. This resulted in three classes of data per lobar region per hemisphere: group 1:"PMG-involved-in-region", group 2: "PMG-not-involved-in-region", and group 3:"completely normal". Under this regime, the membership of the "PMG-involved" and "PMG-not-involved" classes varies across regions. The curvature analysis considered for each region for each subject the histogram distribution of curvature function values, where the curvature function $c \in \{K, k_1, k_2, H, S, C, B,$ Thickness$\}$. Each histogram plot was reduced to a single point for its positive and negative curvature lobes – this single point being the geometric centroid of the given lobe. This essentially characterized each spread function with a weighted mean/average occurrence point. The set of all centroid points for all subjects was then grouped together, and some simple clustering performed. All the centroids for a given class on each region were again averaged, and a 2D standard deviation calculated in the mean and occurrence directions. This defined a rectangular region in the mean/occurrence space defining the first deviation of each group (in effect performing a conceptual/graphical Kullback-Leibler divergence). These regions were examined for clean separation, and all classes that separated at this first-deviation border were deemed to show significant statistical group differences.

	LH-smoothwm																	
	Frontal						Parietal						Temporal					
	neg			pos			neg			pos			neg			pos		
	1-3	1-2	2-3	1-3	1-2	2-3	1-3	1-2	2-3	1-3	1-2	2-3	1-3	1-2	2-3	1-3	1-2	2-3
K					■													
K1		■			■						■							■
K2	■	■			■			■			■							
H		■									■					■		
S				■	■					■						■		■
C					■						■							
BE				■	■					■	■					■		■
Th					■	■												

RESULTS: Subjects were grouped by hemisphere $\{rh, lh\}$ and by region $\{frontal, parietal, temporal, occipital\}$, and curvature distributions analyzed on both the white matter surface ('smoothwm') and the outer cortical surface ('pial'). In our PMG cohort, the numbers of subjects presenting per hemisphere and per lobe were *lh*:{14, 12, 9, 1} and *rh*:{11, 9, 7, 2}. Since too few PMG cases were observed in the occipital region, these were not considered in this analysis. The Table above shows for each lobar region (in this case, the left hemisphere) on the gray/white surface (the 'smoothwm') and for each curvature function, which first order mean/occurrence deviation regions separated cleanly. Each column indicates whether significant separation was observed between specific groups where group 1 was "PMG-involved-in-region", group 2 was "PMG-not-involved-in-region", and group 3 was "completely normal". We note immediately that across all regions the Sharpness and Bending Energy were group-wise most sensitive to differences between groups. On left, we show sample results from the *B* curvature function on the left hemisphere temporal gray/white (smoothwm) surface, and on right the same function on the right hemisphere frontal pial surface. Each point corresponds to a centroid position of the positive histogram for a single subject's *B* curvature function over the indicated hemisphere lobe, with the red points corresponding to group 1, green to group 2, and blue to group 3. The first deviation area for each group's weighted mean and occurrence is shown by the colored boxes. Note how on left, group 1 separates cleanly from group 3. On right, for a different hemisphere, surface, and lobar region, group 1 shows significant separation from group 2, and a slight overlap with group 1. Based on the the results from all the curvature functions, across all regions, we noted that the Bending Energy extrinsic curvature was a particularly powerful differentiator between normal and abnormal surfaces. We also observed that, contrary to conventional wisdom, PMG seems to be more general in presentation than expected. In subjects with localized areas of observable PMG involvement, our curvature analysis has demonstrated that non-involved lobar regions that otherwise appear normal, show statistically significant curvature distribution deviation from baseline data.





CONCLISION: PMG surfaces are measurably different from normally shaped brains. A analysis of curvature properties over lobar regions has shown that most extrinsic measures of curvature are useful markers for tagging these differences. Interestingly, we have shown that PMG brains seem to show global surface distortions despite localized initial presentation: PMG surfaces are not "normal" in non-affected regions but show statistical separation from normal surface curvature. Based on the results of this statistical lobar-based analysis, we hope to further analyze curvature distribution functions as useful markers for tracking brain surface development.