Travel depth: a new measure of depth for brain surfaces

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Abstract. Depth is an important measure characterizing the folded surface of the brain. Our goal is to define and compute a depth that is useful for morphometry and feature extraction. We define travel depth from a point on a surface as the shortest distance from that point to a reference surface along a path that does not run through the interior of the surface. Travel depth was originally used to measure the depth along the surfaces of proteins. Here we have modified this measure to match the needs of brain image analysis. The result is a smooth, accurate, and efficiently computed depth map, for use in morphometry and for extraction of features from a folded surface. Example features include fundi and pits from sulcal folds of the human cerebral cortex as imaged in magnetic resonance image (MRI) data.

1 Introduction

The surface of the human cerebral cortex is highly folded, and much of the surface is buried deep within these folds. Depth is an important measure characterizing this folded surface, and an accurate measure of depth is useful for morphometry and feature extraction. In morphometry, depth does not only establish position relative to the outside of the brain, but might serve as an indicator of developmental stage [1, 2]. In feature extraction, some anatomical features can be defined based on their depth, such as sulcal fundi [3–5] and sulcal pits [1, 2, 6]. In this article we will briefly review prior cortical depth measures, introduce a definition of depth that is more accurate and meaningful for brain image analysis called "travel depth" and demonstrate this measure of depth for cortical surface meshes.

2 Prior measures of brain surface depth

The FreeSurfer software [7] extracts surface meshes corresponding to the human cerebral surface. The software computes a "convexity" measure along the surface that is a function of the displacement of surface mesh vertices after inflating the mesh [8]. Since vertices in the sulcal folds are displaced in proportion to

their depth, deeper vertices are assigned higher convexity values. However, if we use convexity as a measure of depth, points on a gyrus (ridge on the cerebral surface) could also be assigned nonzero depth values. In [1], depth is defined as the relative distance between two reference surfaces: the closed surface and the opened surface. Those surfaces are constructed using a morphological closing and a morphological opening on the white matter. However, this definition of depth is based on Euclidean distance and permits paths that penetrate the surface and enter white matter.

3 Defining travel depth

Travel depth is a depth measure for proteins, defined as the shortest distance that a solvent molecule would travel from the convex hull of the protein without penetrating the protein surface [9, 10]. The principal idea of the algorithm lies in the classification of a surface into "visible" and "hidden" areas. A point on the surface is considered visible by another point if they can be connected by a straight line without intersecting the volume enclosed by the surface. In other words, there is a "line of sight" between the two points that does not run through the interior of the surface. A point is considered hidden from another point if it is not visible and can only be reached by a path running either along the surface or connecting points of the surface without intersecting the enclosed volume. The travel depth for a given point on the surface is then the minimum distance to a reference surface, originally the convex hull, along such paths (Fig. 1).

The algorithm itself takes the following steps, illustrated in Fig. 2. As an initialization step, the algorithm constructs a reference surface from a target surface to be measured. The reference surface lies outside of the volume enclosed by the target surface ("target volume"). This reference surface is the convex hull for proteins, and a "wrapper" surface for brains (described below). The algorithm computes Euclidean distances from each target vertex to all reference vertices via straight paths that do not intersect the target volume. Target vertices that do have direct paths to reference vertices serve as the new set of reference vertices for subsequent iterations, replacing the vertices of the initial reference surface. In the first iteration, the lengths of these paths are recorded as initial depth values for the target vertices. In subsequent iterations, propagation results in an increase in their depth values. The algorithm terminates if all target vertices have a finite depth value with a high enough "confidence" score, computed from the depth values of the reference vertices (see [10] for more details about the confidence score). Otherwise, this step is followed by geodesic propagation along the target surface, with propagation length proportional to the confidence score. The algorithm then reverts to further Euclidean propagation and the cycle repeats for a maximum number of iterations, so the algorithm could terminate even if there are some vertices remaining with low confidence scores. In this case, a final geodesic propagation is performed to impart a depth value to all target vertices.

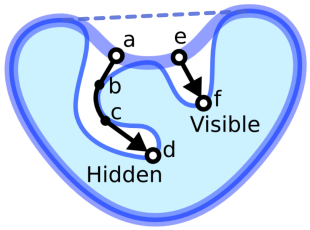

Fig. 1. Schematic diagram illustrating how travel depth is measured for a hidden point (d) and a visible point (f) from points (a and e) on a wrapper surface as opposed to a convex hull (dashed line).

4 Computing travel depth for brain surfaces

The only input required for computing travel depth is a VTK (www.vtk.org) surface mesh on which it is to be computed, and the mesh is assumed to be connected and closed. In the present study we have adapted this measure of depth for use with brain surfaces derived from magnetic resonance images (MRI). One of the primary changes was to replace the convex hull. This is an inappropriate reference surface from which to begin measuring depth because the shape of the brain is concave in places, resulting in some gyri that do not touch the convex hull. For example, in Fig. 3, the gyri of the medial temporal lobe are assigned positive depth, resulting in an unreasonably high depth for the folds of that region. Since the convex hull is not suitable for application to brain images, we define and construct a different reference surface that we call the wrapper surface. The wrapper surface has to be chosen such that the top of a gyrus has zero depth. We compute a wrapper surface as follows. We create a volume image representing the interior of the mesh, dilate this image with a probe of radius r, then erode it with the same probe. We have empirically set the probe radius to 5mm. The wrapper surface mesh is an isosurface of this morphologically closed image volume, created using the marching cubes algorithm [11].

Also, in the case of proteins, there is evidence supporting their representation as smooth, curved surfaces [12], and vertices that are close enough to the reference surface may be considered to be visible. This hypothesis on the surface smoothness cannot be made for brain surfaces, so all vertices are immediately considered to be potentially hidden.

5 Results

Fig. 4 shows a comparison between travel depth (top) and FreeSurfer convexity (bottom). The new wrapper surface used for travel depth lies closer to the medial temporal lobe, so the gyri in this area have a depth value equal to zero as one would want. Convexity, on the other hand, leads to non-zero and even negative values for vertices on these gyri. To compare travel depth and convexity, we

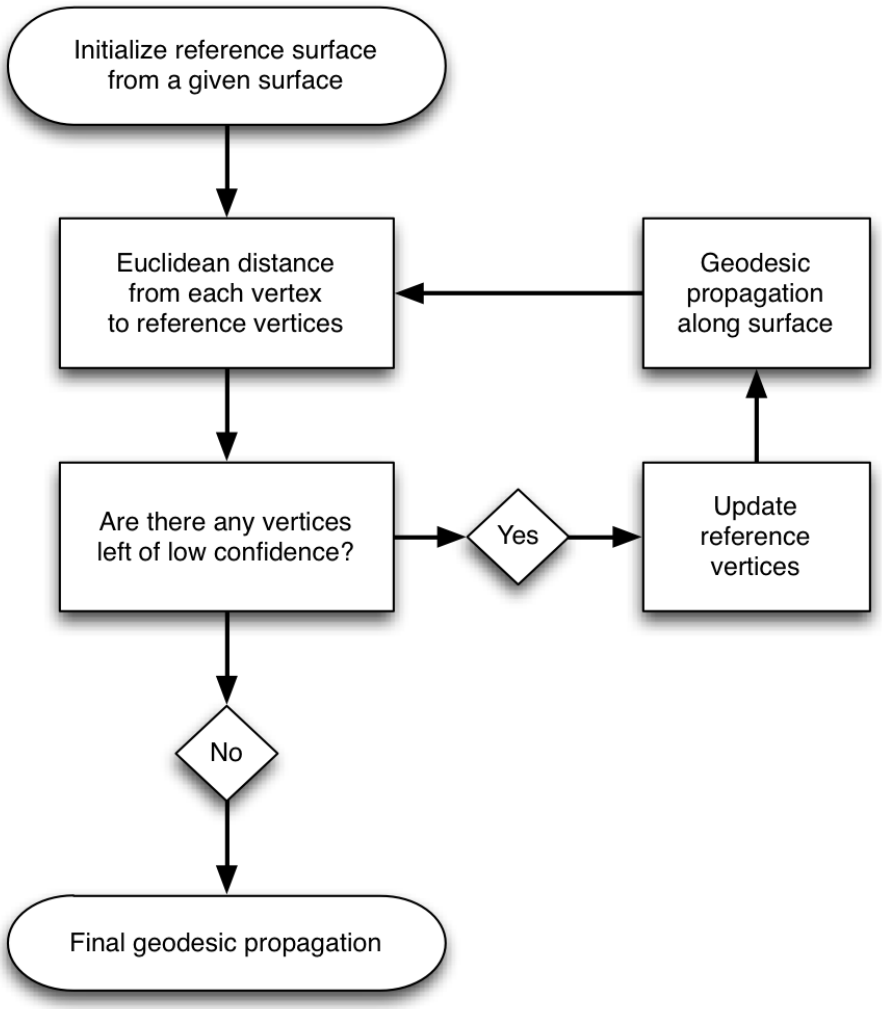

Fig. 2. Flowchart outlining the steps to compute travel depth.

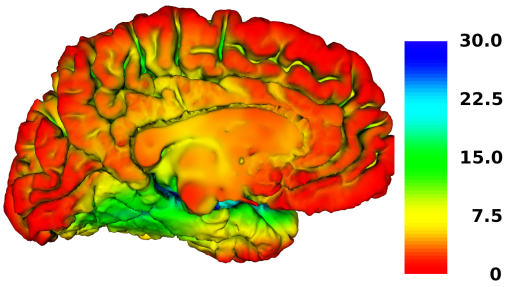

Fig. 3. Example travel depth measured from the convex hull. This depth map was computed on a surface mesh of the left cerebral cortex (medial view).

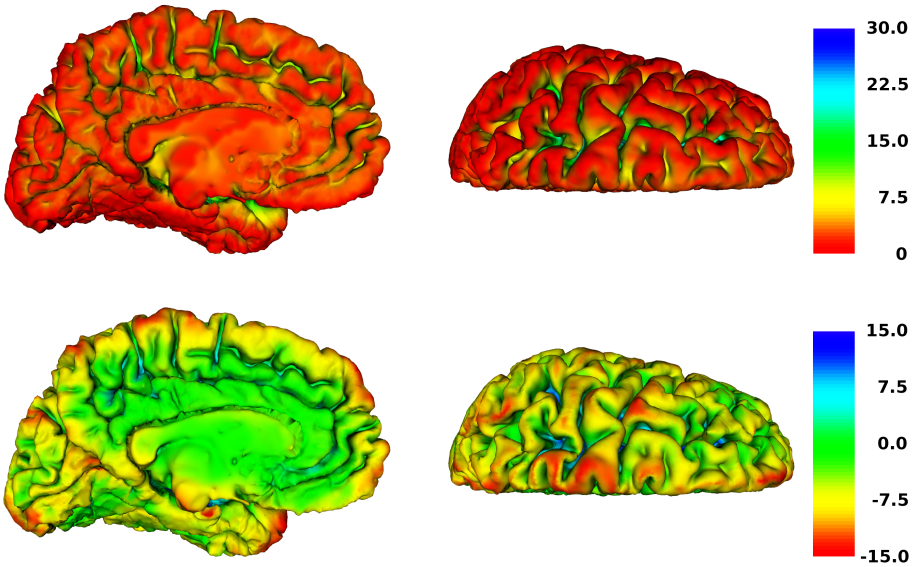

Fig. 4. Travel depth (top row) measured from a wrapper surface (as opposed to the convex hull in Fig. 3) vs. FreeSurfer convexity (bottom). The left and right columns show the medial and top views of the left cerebral cortex. (Note: the colors assigned to travel depth and convexity are different because the convexity values extend below zero.)

computed both measures for cerebral surface meshes extracted by FreeSurfer from 11 T1-weighted brain MRI volumes (of the 21 healthy volunteers in the publicly available Multi-Modal MRI Reproducibility Resource [13]). To see how well convexity corresponds with travel depth, we examined small values of both and measured their distances to the wrapper surfaces. Table 1 contains the mean and standard deviations of (1) travel depth and convexity values over all the meshes, (2) percentage of vertices with small travel depth or convexity values that are close to the wrapper surface, and (3) percentage of vertices close to the wrapper surface with small values. We defined close to the wrapper surface as within $\epsilon = 0.1mm$, and small values as smaller than ϵ for travel depth and smaller than $c_m + \epsilon$ for convexity, where c_m is the smallest convexity value for all the vertices in the mesh. By definition, all the vertices that are close to the wrapper surface have a small travel depth and vice versa. Likewise, almost all the vertices (97.71%) that have a small convexity value are also close to the wrapper surface. However, only 6.89% of the vertices close to the wrapper surface have small convexity values. Fig. 4 clearly illustrates this discrepancy for one hemisphere. The surface-based travel depth algorithm has been shown to be fast compared to volume-based algorithms [10]. On a brain mesh with 150,000 vertices and 300,000 triangles, the algorithm takes around 200 seconds when the wrapper surface is provided. The generation of the wrapper surface takes an additional 20 seconds for a probe radius of 5 mm.

Table 1. Comparison of travel depth and FreeSurfer convexity for brain surfaces.

	Travel depth (SD)	**Convexity** (SD)
Average value across vertices	6.85 mm (0.28)	0.00 mm (0.00)
Vertices with small value close to wrapper	100% (0)	97.71% (0.91)
Vertices close to wrapper with small value	100% (0)	6.89% (0.33)

6 Future work

When constructing the wrapper surface from which depth is measured, it is important to carefully set the probe radius for morphological closing. If the radius is too large, the wrapper surface will be similar to the convex hull, and if the radius is too small, the wrapper surface will be too close to the original surface and the travel depth will be close to zero even inside folds. We used an empirically determined radius but are interested in determining an optimal probe radius directly from the individual brain image or from a large data set of many brain images. We are also working on improving the construction of the wrapper image by using a Fourier transform of the volume image and a frequency filtering, similar to a method used to generate protein solvent accessible surfaces [14]. With this technique, we hope to avoid the time-consuming computation of the morphological closing. Alternatively, we could avoid morphological closing by

implementing a surface-based technique that would avoid approximation errors due to volume sampling.

7 Conclusion

We have introduced an accurate and meaningful measure of depth for brain surfaces, called "travel depth." Originally used to measure the depth along the surfaces of proteins, travel depth had to be modified so that gyral folds of the cerebral cortex would have a depth equal to zero. The result is a smooth, accurate, and efficiently computed depth map, for use in morphometry and the extraction of sulcal features such as fundi and pits. We have released open source software for computing travel depth as part of the ********* automated brain morphometry and labeling project (http://www.**********).

Acknowledgements

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References

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