3D SHAPE ASYMMETRY ANALYSIS USING CORRESPONDENCE BETWEEN PARTIAL GEODESIC CURVES

Ola Ahmad⋆† Philippe Debanné⋆† Stefan Parent† Hubert Labelle† Farida Cheriet⋆†

†Centre de recherche du CHU Sainte-Justine, Montréal, Canada
*École Polytechnique de Montréal, Canada

ABSTRACT

Analyzing the asymmetry of anatomical shapes is one of the cornerstones of efficient computerized diagnosis. In the application of scoliotic trunk analysis, one major challenge is the high variability and complexity of deformations due to the pathology itself, and to changes of body poses, for instance, torsos acquired in lateral bending poses for surgical planning. In this paper, we present a novel and fully automatic approach to analyzing the asymmetry of deformable trunk shapes. Our method detects the symmetry plane/axis of the shape and a set of reflective geodesic curves; the method then uses parts of these geodesics to compute point correspondence between any reflective pair. We present a preliminary study on scoliotic torsos in neutral standing and lateral bending poses. Our results show that matching parts of reflective curves is robust against non-isometric deformations. The proposed method can extend to other applications, such as maxillofacial surgery planning.

Index Terms— 3D Shape Asymmetry, Reflective Geodesic Curves, Correspondence, Graph Laplacian, Scoliotic Trunk Shape.

1. INTRODUCTION

Shape asymmetry analysis is increasingly important in many medical applications, such as computer-aided diagnosis (CAD), surgical planning, and surgery outcome assessment, as it can often emerge from a pathology or anomaly. For example, tumors can be localized by investigating by the asymmetry of human body organs [1]. Brain lesion detection has been drastically improved by the integration of shape asymmetry analysis [2, 3, 4]. Facial asymmetry has an important role in maxillofacial surgery planning as it is associated with beauty and aesthetics [5] but also with various disorders and anomalies [6, 7]. Torso shape asymmetry has been identified in adolescent patients affected by complex musculoskeletal deformations such as scoliosis [8]. For most of these applications, it is highly required to accurately identify the appropriate symmetry plane (or axis), and then to incorporate intrinsic anatomical features to measure the asymmetry between corresponding regions [4, 9]. The asymmetry may, however, be affected by the extrinsic deformations of non-rigid shapes that undergo different postures. Furthermore, when the shape is truncated or partially acquired, the efficient identification of the symmetry plane/axis becomes a major challenge [4]. In this paper, we focus on the asymmetry analysis of non-rigid incomplete shapes undergoing different postures.

The symmetry plane/axis of 3D rigid or non-rigid shape models (e.g. triangulated meshes) can be detected using functions, usually based on the Euclidean geometry, between the shape and its reflection [10, 9, 8]. When the Euclidean distance tends to zero, we say that the shape has, approximately, a reflective symmetry in the extrinsic sense. However, incomplete shapes (e.g., 3D human torsos with cropped arms and neck) cannot be extrinsically symmetric; the Euclidean geometry between the shape and its reflection is not perfectly symmetric. When changing their postures to bending, these shapes may neither be intrinsically symmetric; the geodesic distance is not preserved. A way to efficiently detect the symmetry plane or axis is to create an embedding through intrinsic representations such as Multi-Dimensional Scaling [11, 12, 13] or spectral transformation [14, 15]. The global symmetry can then be simply detected using the Euclidean geometry in the embedding space. The symmetry plane/axis partitions the shape approximately into two halves—one-half is considered to be a mirror of the other. Correspondence-based approaches (surveyed in [16]) would allow the computation of local features (e.g., surface contours, regions, landmarks) characterizing the asymmetry between reflective parts. Some of these methods were used in medical applications [8]; however, the correspondence does not account for the differences emerged from the imperfect reflections between shape parts, which are affected by posture changes and missing data.

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To establish a correct correspondence between partially reflective shape parts, we propose a new automatic method that computes the correspondence between partial geodesics with respect to the global symmetry of the shape. This paper will consider a specific medical application of human torsos affected by scoliosis—the surgery planning involves the examination of the trunk shape in neutral standing and lateral bending postures, but the asymmetry analysis relies on manual processing steps [17]. We show first how a spectral representation based on the graph Laplacian is used to detect the symmetry plane and the medial curve of the scoliotic torso in the different postures. A set of shape geodesics will result from the intersections of the plane of symmetry with the shape at different orientations around the medial axis. These intersections provide dense point representations of full geodesic curves. We then focus on the correspondence between the meaningful parts of the curves to extract a set of intrinsic features describing the shape. We report a preliminary study on scoliotic torso dataset with right thoracic spinal curves to show how the correspondence between a reflective pair of partial geodesic curves could help describing shape asymmetry. Our main contributions involve the detection of the global shape symmetry using Fiedler vector, and finding the 3D point correspondence between parts of reflective geodesic curves to analyze shape asymmetry.

2. DETECTION OF SYMMETRY PLANE AND MEDIAL CURVE

We begin by a brief review of the spectral shape representation based on the graph Laplacian [18] that we use to detect the global symmetry of the shape.

Let $G = \{V,E\}$ be a connected undirected graph representation of a 3D discrete shape (e.g., triangulated mesh) with a set of vertices $V$, having spatial positions $x_i \in \mathbb{R}^3$, and set of edges $E$, each connecting two neighbor vertices $(v_i, v_j)$. The Laplacian of the graph could be defined by some weighted adjacency matrix $W_{ij} = \exp(-||x_i - x_j||^2/4t)$ (t is a small coefficient) that accounts for the neighborhood structure of the graph, and a diagonal degree matrix $D_{ii} = \sum_j W_{ij}$, such that $L = D - W$. The spectral decomposition of $L$ provides a set of eigenvalues and eigenvectors. The eigenvector corresponding to the smallest non-zero eigenvalue, also called Fiedler vector, captures the natural vibration spanning the longitudinal direction of the shape, for instance, the craniocaudal direction of the torso shape (Fig.1(1)).

The Fiedler vector allows computing a line integral connecting the centroids of its level sets (Fig.1(1)). Since incomplete shape parts could lose their extrinsic/intrinsic symmetry under different postures, the level set analysis must be restricted to the complete portions of the shape (e.g., the main part of the truncated torso). In such case, the line integral can approximate the medial axis. We use the principal component analysis (PCA) to estimate the principal directions of the shape from the line integral; the first principal mode defines the medial axis; the second mode determines the lateral direction associated with the extrinsic deformations (e.g., bending of the shape). The symmetry plane is defined by the medial axis and the perpendicular line to the second mode, and the intersection of this plane with the shape provides the medial curve (Fig.1(4)).

3. DETECTION OF REFLECTIONAL GEODESIC CURVES

We need first to extract an arbitrary set of geodesic curves from the 3D non-rigid deformations of the shape with respect to its global symmetry. This can be done through intersecting the shape with a set of planes, each resulting from a rotational transformation (with rotation angle in $(0, 180^\circ)$) of the symmetry plane around its medial axis. The 3D planar intersections provide a subset $\{C_1, ..., C_f, C_I, ..., C_J\}$ of $I$ and $J$ geodesic curves at left and right sides of the shape, respectively, according to the medial plane. These curves are not perfect mirrors or reflections one of other due to the shape’s asymmetry. Our goal is therefore to find a pair of geodesic curves (one in each side) that are partially reflective for a given angular resolution and with respect to the reference symmetry indicated by the detected medial curve.

Let $C_m, C_r$ be the medial curve and an arbitrary curve selected from the right side of the shape, respectively. We use the nearest-neighbor search to establish a set of mappings (not necessarily bijective) $c^r, c_1^r, ..., c_j^r$ between the medial curve (the reference) and each of the geodesic curves in the subset $\{C^r, C_1^r, ..., C_J^r\}$. Each mapping $c$ searches for all the points of the medial curve their closest points on the left/right side
geodesic curves such that:
\[ c_k^l = \arg \min_{c_k^l} \| C^m - C_k^l \circ c_k^l \|^2 \] (1)
\[ c^r = \arg \min_{c^r} \| C^m - C^r \circ c^r \|^2 \]

The symmetry (reflection) of \( C^r \) is a left side geodesic curve \( C^l \) that minimizes the overall difference between the distance pairs medial-left (m-l) and medial-right (m-r) as follows:
\[ C^l = \arg \min_{\{c_1^l, ..., c_i^l, ..., c_j^l\}} \| d^{m-r} - d^{m-l} \|^2 \] (2)

where \( d^{m-r} = \| C^m - C^r \circ c^r \|^2 \) and \( d^{m-l} = \| C^m - C_k^l \circ c_k^l \|^2 \) are the Euclidean distances between the medial curve points and their closest points on the right (resp. left) curves. Figure 2(a) illustrates, on a right bending torso example, two reflective geodesic curves relative to the medial points of the shapes.

4. CORRESPONDENCE BETWEEN PARTIAL GEODESICS

According to (2), we obtain a pair of globally reflective closed curves, but we need to consider only parts\(^1\) of these geodesics and establish one-to-one / one-to-multiple correspondence.

Given two partial reflective curves \( PC^r \subset C^r \) and \( PC^l \subset C^l \) with \( N_1 \), \( N_2 \) vertices. We propose here a fast two-step pairwise alignment between the points of \( PC^r \) and \( PC^l \) using the Coherent Point Drift (CPD) algorithm [19]. The first step alignment functions as an initialization; it non-rigidly transfers the positions (3D point coordinates) between partial curves to find their corresponding endpoints (Fig. 2(c)). Here, we select the shortest curve as a template and match its endpoints to the longest curve.

The second step uses the nonrigid CPD alignment and involves intrinsic correspondence between the curves. This alignment incorporates a regularization term that enforces the closest points to have similar features with respect to the anatomy of the shape. The curvature-based features offer such an anatomical characterization of the shape [20]. In this context, we first compute the principal curvatures \( \kappa_1, \kappa_2 \) at each point of the mesh. Since the curves result from the intersection of the transformed symmetry plane with the mesh, there is no guarantee that the intersecting points lie exactly on the vertices. We, therefore, use the nearest neighbor search to assign each point on the curve with the principal curvatures of its closest vertex on the mesh. Accordingly, each point \( p_i \in PC^l \) (resp. \( p_j \in PC^r \)) is described by the feature vector \((\alpha\kappa_1, \beta\kappa_2)\) (resp. \((\alpha\kappa_1', \beta\kappa_2')\)), with
\[ f_i^l = (\kappa_1(x_i^l), \kappa_2(x_i^l))^T, \quad f_j^r = (\kappa_1(x_j^r), \kappa_2(x_j^r))^T \] (3)

are the shape curvature features at the points \( p_i \) and \( p_j \), \( x_i^l, x_j^r \) are the points positions, and \( \alpha, \beta \) are scaling factors used to normalize features. In our experiments, we scale the positions to be in the range of the principal curvature values. Finally, we compute the closest points between the aligned partial curves to define the correspondence map (see Fig. 2(d)).

5. RESULTS

5.1. Data

We apply our approach on a cohort of 15 scoliotic torso surfaces. These shapes are given in three different poses (7 in neutral standing, 8 left-right lateral bending). An imaging system of four optical digitizers (Capturor II LF, Creaform Inc.) at Sainte-Justine Hospital in Montreal is used to scan the body and reconstruct the 3D triangulated mesh. The surface meshes contain between 50k and 100k vertices and between 100k and 200k triangles, depending on the patient’s size. All meshes undergo a preprocessing to normalize the triangles, crop the trunk at its boundaries (at the arms, neck and pelvis), close the holes, and remove the noise.

5.2. Experiments

We describe the asymmetry of the scoliotic torsos by the multilevel axial rotation of a set of intrinsic shape contours, similar to the measures used in [17] (for the sake of comparison). This latter selects manually a set of anatomical landmarks on the surface of torso to construct "guiding curves" (two curves along the anterior part of torso and one along the back) that define the contour levels. We compute here each contour level by intersecting the shape with a plane defined through one pair of corresponding points between the reflectional curves and the mirror of their middle point on the back side. To extract the geodesic curves, we fix the angular rotation resolution to \( \delta \theta = 10^\circ \) for rotation angles \( \theta \in (0, 180^\circ) \) applied to the symmetry plane. We arbitrarily select one geodesic curve at \( \theta = \pm 45^\circ \) (sign chosen according to the bending direction) on the right-hand side of the torso and then detect its reflectional curve on the left-hand side. In order to define the partial curves, we filter out the points towards the neck and the pelvis by setting a threshold on the Fiedler vector (Fig.1(1)), and the posterior points with respect to the PCA plane (Fig.1(2)). In our experiments, we replace the multiple corresponding points between partial curves with their average point in order to convert the one-to-multiple correspondence into one-to-one, and then we interpolate the points to obtain uniform spacing between the contours. To evaluate our method, we use 20 contour levels and examine their global behavior compared to the manual method.

Figure 3 illustrates the contour levels computed using our proposed method on three examples of scoliotic torso shapes in neutral standing, right bending, and left bending postures.

\(^1\)For a human torso, it is the anterior shape that involves more anatomically intrinsic features.
Fig. 2. Illustration of a pair of reflectional geodesic curves and the correspondence between their parts. (a) A set of left-side geodesic curves (blue), medial curve (red), and a left-right \( (C_l-C_r) \) reflectional pair (green). (b) A pair of the partial left \( (PC_l) \) and right \( (PC_r) \) reflectional geodesics. (c) Detection of the partial curves limits. (d) Points correspondence (a small set of points are selected for visualization).

Fig. 3. Contour levels of three female torso shapes. Left to right: 20 cross-sections (surface contours) extracted using the corresponding points between partial curves in neutral standing, right-side bending, and left-side bending postures.

The resulting contours show that the one-to-one correspondence between the anterior parts of the reflective curves can describe the intrinsic asymmetry between the left and right sides of the shape in different postures. Figure 4 shows the dissimilarity angle (in average) between the major axes of the corresponding contours obtained through our method and the manual processing [17]. This preliminary comparison shows that the methods generally produce similar contour levels (10 out of 15 examples have dissimilarity angle less than 5°).

5.3. Discussion

We observe that the correspondence between the reflective curves may be incorrect in some examples, where the dissimilarity angle is greater than 5° (Fig.4). We could explain this by two facts: 1) the combination between the extrinsic and intrinsic asymmetries of the shape due to the bending posture and scoliosis pathology can affect the accuracy of the symmetry plane detection, i.e., the shape may lose its global symmetry, (see Fig.4(b)); 2) the partial geodesic curves may not have sufficient feature points when the shapes exhibit pronounced bending. Further improvements would thus incorporate another biometric features to allow better correspondence between reflective curve points. In addition, the existing baseline approach is limited to a very few set of anatomical landmarks; the contours are obtained by a simple interpolation of the points between landmarks. This could, in some cases, bias the dissimilarity angle to higher values. However, the preliminary results are the first step to efficiently analyze the asymmetry of non-rigid torso shapes through the matching between reflective geodesic curves.

6. CONCLUSION

We presented the first automatic method to analyze the asymmetry of 3D torso shapes in bending poses which explores the correspondence between parts of reflective curves. The experimental results show that the matching between partial shape geodesics captures the intrinsic asymmetry of shapes, adapts well to non-rigid shapes with bending postures, and computationally efficient. Future work will focus on more validations of the proposed method on general dataset including partial shapes with complex non-isometric deformations and under different poses. Moreover, our method could extrapolate the correspondence from partial curves to regions on the shape to capture more asymmetries. Further extensions might include its use in other medical applications such as maxillofacial surgery planning.
7. REFERENCES


