Synthesizing Possible Variations of Finger Structure Using Principal Component Analysis for Non-Rigid Volume Registration Results

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Abstract
In order to synthesize possible variations of finger structure, we analyzed individual differences in anatomical geometry of soft tissue, distal phalanx and middle phalanx using principal component analysis (PCA). Non-rigid volume registration technique was employed to quantify individual differences in finger structure from MR images of 49 male subjects aging from 21 to 39. The result of PCA demonstrated that the top three principal components corresponded to individual difference in dimension, torsion and wapage of finger geometry, respectively. We can synthesize possible finger geometries by computing a weighted sum of the obtained principal components.

Introduction

Anatomical geometry of human body plays an important functional role in daily life, especially in physical interaction with environment. In order to simulate possible situations in such interactions, varieties of geometric models of human anatomy are necessary. There have been many human models for numerical simulation such as total human model for safety [1] and realistic high-resolution whole-body voxel model [2]. However, most of all have made for an averaged subject only, since geometric modelling is time consuming work requiring manual segmentation for medical volume data.

Tada et al. [3] have proposed shape warping approach to create subject specific geometric model of human anatomy. This method creates a geometric model of the target subject by warping a reference model according to a displacement field computed by non-rigid volume registration for MR images of target and reference subjects. This enables us to obtain subject specific geometric model rapidly and automatically, while the obtained geometric model is limited to that of existing subject.

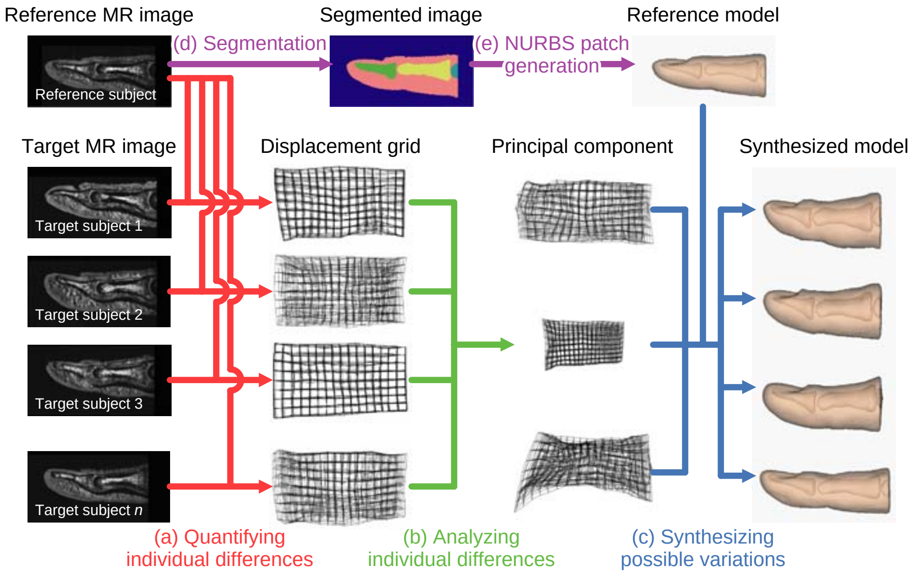
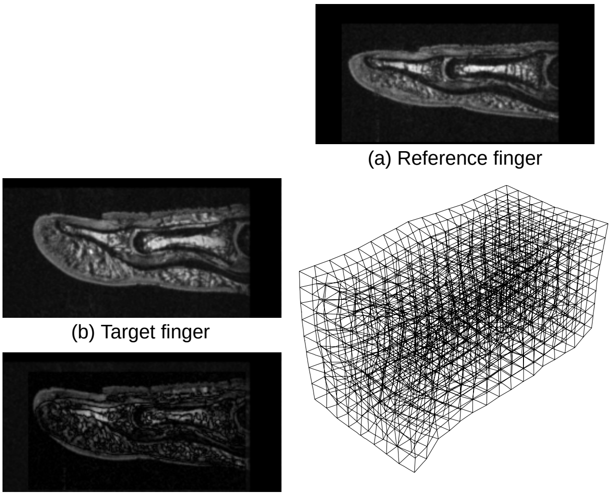


Figure 1. Overview of the proposed method

In this paper, we propose a method to synthesize possible variations of human anatomy by computing principal axes of individual differences, displacement field computed by non-rigid volume registration for volumetric data of MRI, using principal component analysis (PCA).

Methods

We synthesize possible geometric structure of human finger, since it plays fundamental role in manipulation that we intend to simulate. Figure 1 shows the overview of the proposed method. It involves three procedures. (1) Quantifying individual differences (Figure 1-(a)): we employed non-rigid volume registration technique [3] so that we can quantify individual differences as a displacement field; spatial mapping that transforms reference geometry into target geometry. (2) Analysing individual differences statistically (Figure 1-(b)): we employed PCA for the statistical analysis. This method reveals principal axes of individual differences. (3) Synthesizing possible variations of finger structure (Figure 1-(c)): once the principal axes are obtained, we can compute displacement field that transform reference geometry into possible finger geometry by computing weighted sum of the principal components. We can thus synthesize variations of finger structure just transforming a manually created reference model according to the synthesized displacement field.



(a) Reference finger (b) Target finger (c) Registered finger (d) Initial error (e) Displacement grid (f) Final error

Figure 2. Result of the non-rigid volume registration

Quantifying Individual Differences

We imaged an index finger of 50 male subjects aging from 21 to 39 using 4.7 T experimental MRI (Unity Inova: Varian, Inc.). We used three-dimensional gradient echo sequence (GE3D) with TR/TE of 20/10 msec, field of view (FOV) of 120x30x30 mm and volume size of 512x128x128 voxel. The resolution of the obtained volume data was thus 234 um/voxel.

The following four pre-processes were applied to all the obtained data. (1) Trimming the volume data from the end of a middle phalanx, (2) Resizing the trimmed volume data to 256x128x128 so that the finger region is positioned at the center, (3) Applying the Gaussian filter with kernel size of 3x3x3 to the resized volume data, and (4) Scaling the smoothed volume data so that the intensity value is scaled into the range of 0.0 to 1.0.

We quantified individual differences in finger structure using non-rigid volume registration technique [3]. In this algorithm, sum of squared differences (SSD) was employed for similarity measure between two volume data. Displacement is computed at every control vertex assigned in the volume data so that the target volume is volumetrically registered into the reference volume using constraint of optical flow [4]. The control vertices are distributed at regular intervals, 16 voxel in each axial direction in this paper. The non-rigid transformation model of this registration has total 1377 control vertices and 4131 DOF, since the volume data has the voxel size of 256x128x128.

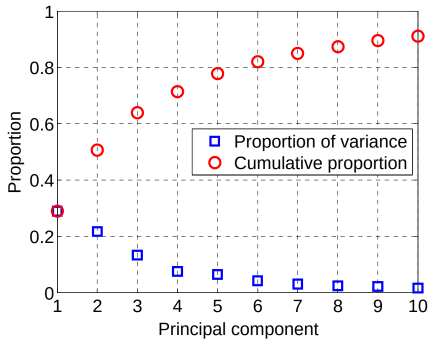


Figure 3. Proportion of variance and cumulative proportion

Figure 2 shows the result of the non-rigid volume registration. By applying this technique, the target finger in Figure 2-(b) was registered into the reference finger in Figure 2-(a), and finally transformed into the registered finger in Figure 2-(c). Figure 2-(d) and (f) show successful decrease in the intensity error. Figure 2-(e) shows the computed displacement field. Let us call this field as displacement grid henceforth in this paper. It should be noticed that the displacement grid quantifies individual differences in finger structure, including geometry of soft tissue, phalanxes and tendons. Since we need one reference subject, we registered total 49 data sets.

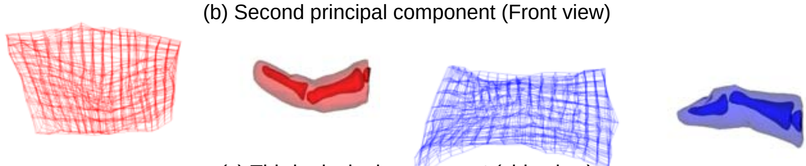
Analyzing Individual Differences Using PCA

In order to compute principal axes of individual difference, displacement grids were analyzed by PCA. Let us define the computed displacement grid between the reference and *j*-th target subject as $d_j = (x_1, y_1, z_1, \cdots x_m, y_m, z_m)$, where (x_i, y_i, z_i) is the computed displacement at *i*-th control vertex and m is the number of control vertices. Next, we define a matrix $D = (d_1^T, \cdots d_n^T)^T$ that has d_i in *i*-th row, where n is the number of computed displacement grids. This matrix was analyzed by PCA; i.e. we computed covariance of the matrix D and then applied singular value decomposition (SVD) to the covariance matrix. Figure 3 shows the result of PCA, proportion of variance and cumulative proportion for the top ten principal components.

In order to visualize principal components as displacement grids, *k*-th principal component p_k was computed as $p_k = a + w_k c_k$, where a is the average displacement grid; $a = \sum_{i=1}^{n} d_i / n$, w_k is the weight for this component, and c_k is the *k*-th eigen vector computed by SVD. Figure 4 shows the visualized top three principal components when w_k takes both positive (red) and negative (blue) value. It also shows the manually created reference model transformed by each principal

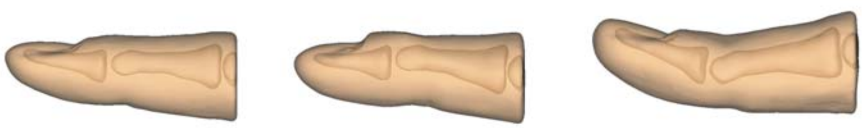
(a) First principal component (side view)

(b) Second principal component (Front view)



(c) Third principal component (side view)

Figure 4. Principal components and corresponding geometric feature of a finger



(a) Average finger (b) Small and downswept finger (c) Large and upswept finger

Figure 5. Synthesized possible finger geometry

component. Please refer to next section for the detail of the reference model creation. These figures clearly show the geometric feature of each principal axis; first, second and third principal component corresponds to individual difference in dimension, torsion and warpage of finger geometry, respectively.

Synthesizing Possible Variation of Finger Structure

Creation of the reference model requires segmentation of the reference volume data into three regions. The Sobel filter was applied to axial slices of the volume data in order to enhance the boundaries of these three regions. Each axial image was then manually segmented into soft tissue, distal phalanx and middle phalanx referring to the extracted edges. Next, we create a polygon model of each region using marching-cube algorithm [5]. The resultant polygon models were imported to geometric modelling software (Geomagic Studio 8: Geomagic, Inc.) to perform smoothing and NURBS patch generation. These procedures are schematically shown in Figure 1-(d) and (e). It took about 1200 minutes to create the reference model.

We obtain a displacement grid d that transforms the reference geometry into possible finger geometry just computing a weighted sum of principal components as $d = a + \sum_{i=1}^{n} w_i c_i$. Here, possible range of the weight w_i is obtained by computing the range of *i*-th row of a matrix W in the following equation.

$$W = \begin{pmatrix} c_1 \\ \vdots \\ c_{n-1} \end{pmatrix} \begin{pmatrix} d_1 - a \\ \vdots \\ d_n - a \end{pmatrix}^T$$

Figure 6 shows possible finger geometry synthesized from the top three principal components. This method enables us to synthesize various geometric models rapidly and automatically, once the reference model is manually created.

Conclusion

In order to synthesize possible variations of finger structure, we analyzed individual differences in anatomical geometry of soft tissue, distal phalanx and middle phalanx using PCA. Non-rigid volume registration technique was employed to quantify individual differences in finger structure from MR images of 49 male subjects. The result of PCA demonstrated that the top three principal components corresponded to individual difference in dimension, torsion and warpage of finger geometry. We can synthesize possible finger geometries by computing weighted sum of the obtained principal components. This method enables us to synthesize various geometric models rapidly and automatically, and is expected to be promising method in the numerical simulation of human function.

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