Statistical Shape Analysis for Development of a Probabilistic Finite Element Model of The Human Clavicle

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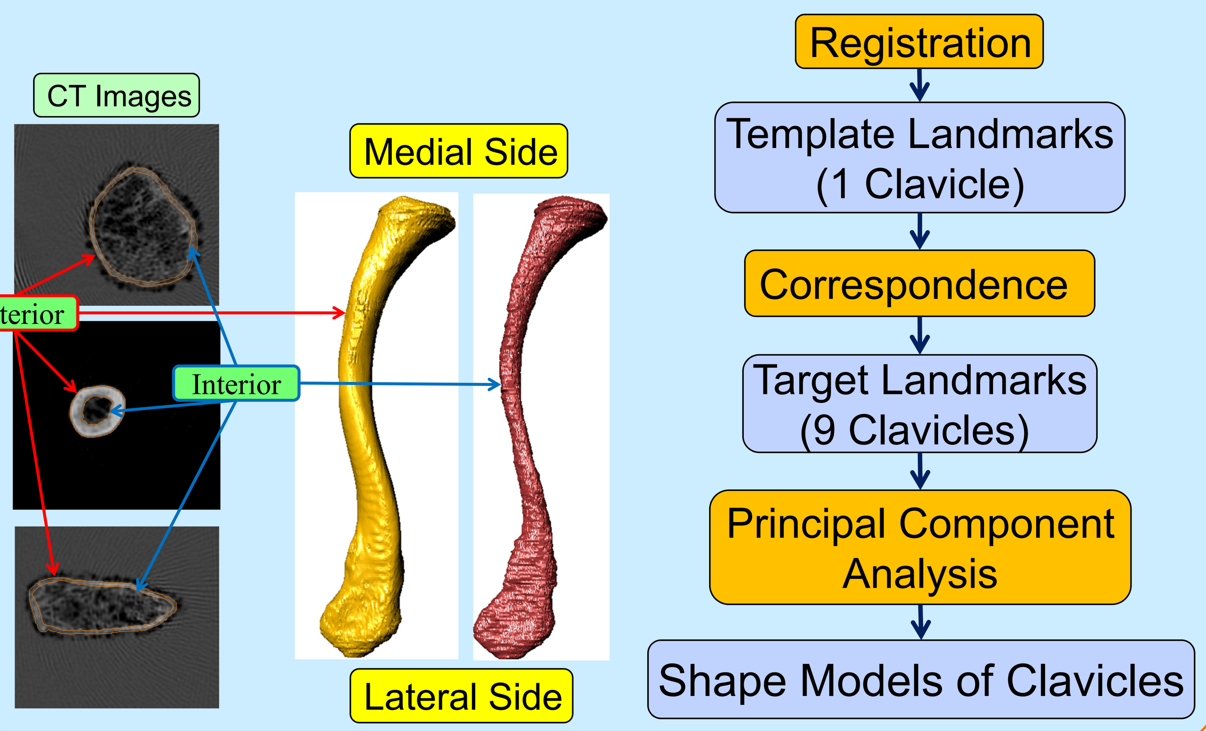
Introduction

Inherent variability exists in biological tissues in terms of geometrical shape and material properties. Statistical shape analysis has been shown to appropriately represent the geometric variability of bones, but it was limited to the applications of exterior bone surface and the human clavicle shape was investigated in only a few recent studies [1]. The main goal of this study is to enhance the knowledge regarding the shape of the human clavicle and distribution of cortical bone thickness along the shaft. In the future the statistical distributions of cortical bone thickness and material properties could be used in the development of a probabilistic finite element model of human clavicle.

Procedure



Methods

- The geometries of 10 clavicles were reconstructed from computerized tomography (CT) scans.
- The exterior and interior boundaries of cortical bone were obtained using Mimics 13 with different point densities for each clavicle.
- Registration
  - ➢ Align the clavicle models using translation, rotation and scaling transformations.
  - ➢ Remove the location and scaling differences by moving their centers of mass to the origin and normalizing their sizes to be the same.
  - ➢ Remove the rotations between samples by using the STL Registration function in Mimics 13.
- One shape instance was selected as the template U, then the template landmarks U_L were developed using the equal-size cubic grid method (Fig. 1) [2].
  - ➢ The 3D space was uniformly divided into equal-size cubic grid cells.
  - ➢ In each cell, the point closest to the center of the cell was picked from original point cloud as a landmark in U_L.

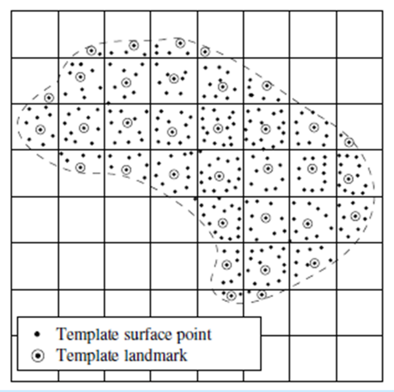


Figure 1. An illustration of constructing the template landmarks U_L from point clouds [2].

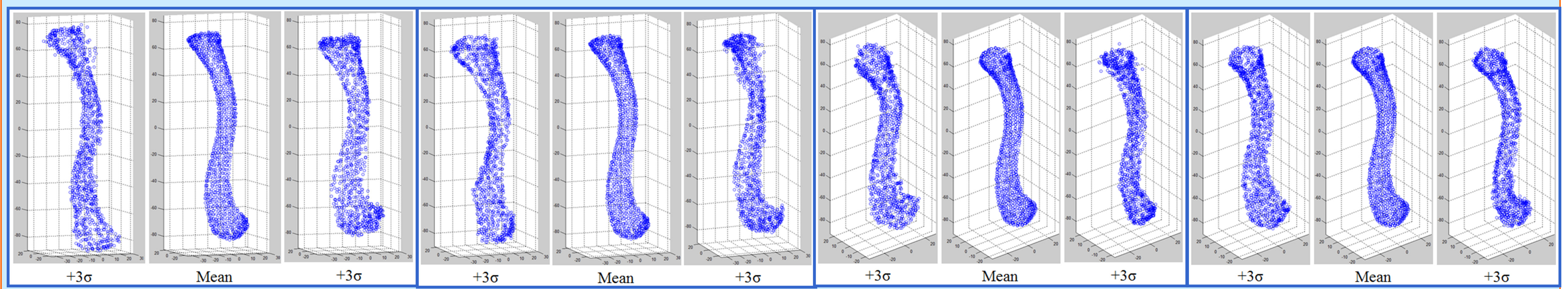
Statistical Shape Analysis

- Correspondence
  - ➢ A dense correspondence map between each pair of surfaces was established using coordinates as well as surface normals [3].
  - ➢ The correspondence between a point a_i on surface A and a point b_{ai} on surface B was defined by the minimum Euclidean distance in a six-dimensional space:

$$b_{ai} = \arg\min_{b_j} \| a_i - b_j \|$$

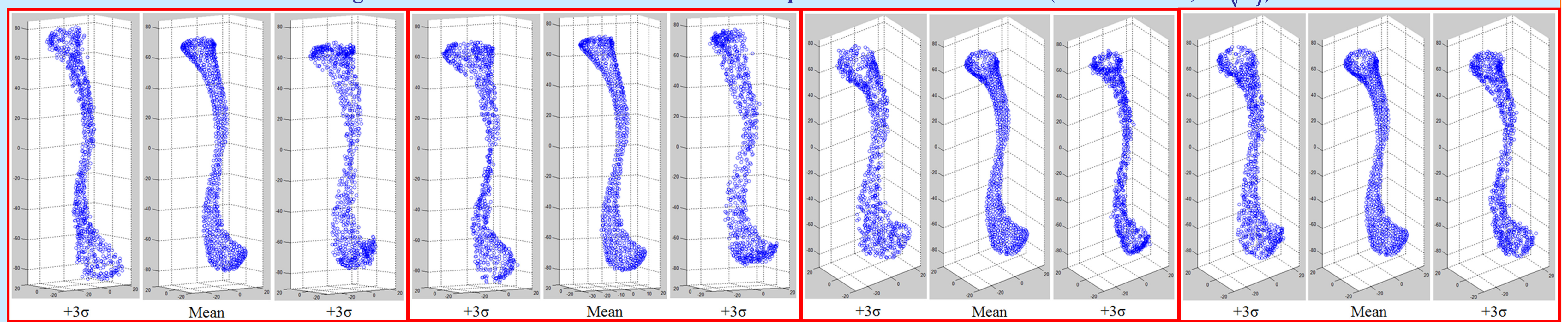
with $a_i = \begin{bmatrix} p_i \\ \lambda n_i \end{bmatrix}$ and $b_j = \begin{bmatrix} p_j \\ \lambda n_j \end{bmatrix}$, p_i and p_j the point coordinates and n_i, n_j the surface normals. The weight factor λ was chosen to be 1.
  - ➢ 11,360 corresponding points are on all cortical bone surfaces for each shape type (exterior and interior).
- Principal Component Analysis (PCA)
  - ➢ PCA consists of computing the covariance matrix D of landmarks and determining the eigenvalues λ_j and eigenvectors p_j [4].
  - ➢ The eigenvectors describe the directions of variation, called "modes of variation". The associated eigenvalue denotes the variance in the corresponding direction.
  - ➢ $\bar{x} = \frac{1}{n}\sum_1^n x_i$, where x_i are individual vectors for sample i
  - ➢ $D = \frac{1}{n-1}\sum_1^n (x_i - \bar{x}) \cdot (x_i - \bar{x})^T$; $D \cdot p_j = \lambda_j p_j$
  - ➢ Shape space: $\bar{x} - 3\sqrt{\lambda_j} p_j$, $\bar{x}$, and $\bar{x} + 3\sqrt{\lambda_j} p_j$ for mode j
- Evaluation Criteria
  - ➢ (1) *Percentage of variability*-the contribution of each mode to the overall variation [4].
  - ➢ (2) *Compactness*-the ability to use a minimal set of modes [5]. $C(M) = \sum_{j=1}^{M} \lambda_j$ where M: modes, λ_j: eigenvalues.

Results



(a) 1st Mode (b) 2nd Mode (c) 3rd Mode (d) 4th Mode

Figure 2. Modes of variation of the exterior shape of clavicle cortical bone (axis unit: mm; σ: $\sqrt{\lambda_j}$).



(a) 1st Mode (b) 2nd Mode (c) 3rd Mode (d) 4th Mode

Figure 3. Modes of variation of the interior shape of clavicle cortical bone (axis unit: mm; σ: $\sqrt{\lambda_j}$).

- The length of the clavicle is shown to be the most significant shape mode (Fig. 2a and 3a) for both exterior and interior cortical bone surfaces.
- The curvature variation and the size of the medial end of the clavicle shapes are described by the 2nd mode (Fig. 2b and 3b).
- The size of the lateral end of clavicles is described by the 3rd and 4th modes (Fig. 2c and 3c).
- Width variation of clavicles can be found in the first four modes (Fig. 2 and 3).

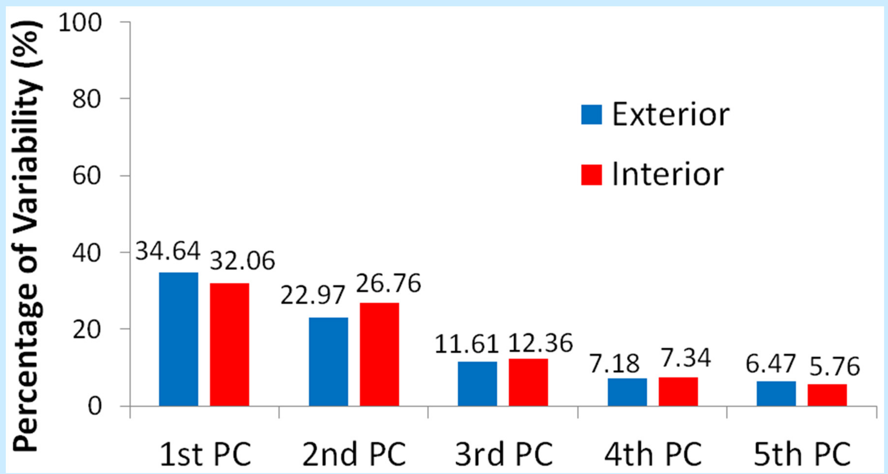


Figure 4. Percentage of variability of modes

- Fig. 4 presents the percentages of variation of the exterior and interior surfaces of clavicle cortical bone.
- In both cases, the first modes account for 32-35% of variance while the 2nd, 3rd and 4th modes account for 7-27% of anatomical variation.

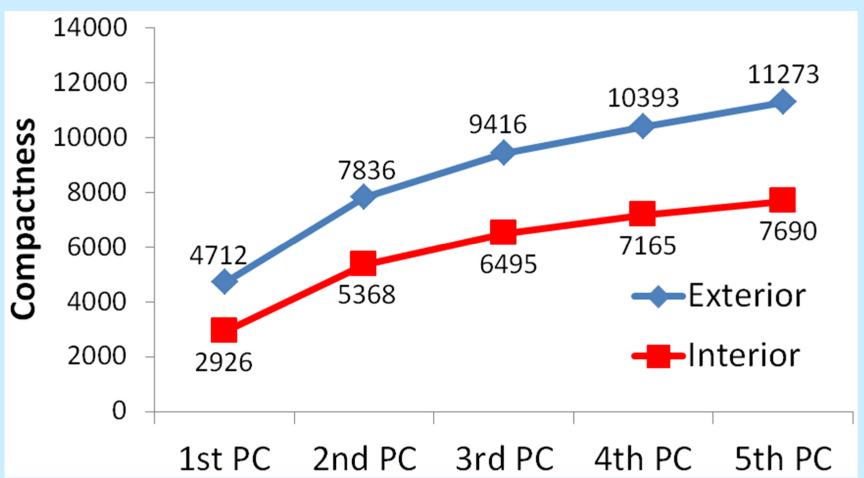


Figure 5. The compactness evaluation of the statistical shape model of the human clavicle.

- The compactness evaluation shows that the exterior part exhibits higher variability in each mode than the interior part while in both cases the first five modes would be essential to describe the overall shape variation (Fig. 5).

Discussion

- The shape variability of clavicle cortical bone was investigated in this study.
- The length of the clavicle is shown to be the most significant shape mode for both exterior and interior bone surfaces.
- The first five modes would be sufficient to describe the overall shape variation, where the first five modes account for approximately 84% of anatomical variation.
- The noise of CT scanning and random point sampling influences the higher modes.
- When comparing the exterior with interior cortical bone shapes, the compactness evaluation shows that the interior shape models are more compact than the exterior shape models.

Future Work

- A statistical shape approach will help to better understand variability observed in biomechanical and injury response of clavicle under bending and axial loading [6]. The force-displacement test corridor obtained from [6] is expected to be included in the corresponding corridor from finite element shape model simulation.

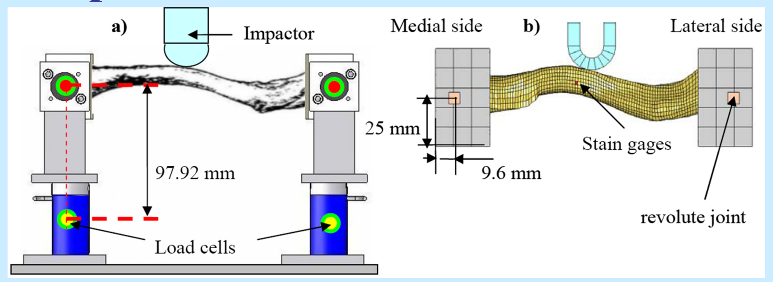


Figure 6. Schematic of a) physical test setup used to apply bending loading to the clavicle specimens and of b) finite element setup and clavicle model used in FE simulation [6].

- The statistical shape models could better represent 5%, 50% and 95% human finite models used in the automotive research compared to those obtained by scaling techniques [7].
- The shape models could be further combined with property distributions of cortical bone to develop probabilistic finite element models of clavicle.
- The shape models could also be applied for the development of prosthetics [1].

Reference

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