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Statistical shape analysis of clavicular cortical bone with applications to the development of mean and boundary shape models

Yuan-Chiao Lu, Costin D. Untaroiu*

Virginia Tech and Wake Forest University, School of Biomedical Engineering and Sciences, Blacksburg, VA, United States

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ABSTRACT

During car collisions, the shoulder belt exposes the occupant's clavicle to large loading conditions which often leads to a bone fracture. To better understand the geometric variability of clavicular cortical bone which may influence its injury tolerance, twenty human clavicles were evaluated using statistical shape analysis. The interior and exterior clavicular cortical bone surfaces were reconstructed from CT-scan images. Registration between one selected template and the remaining 19 clavicle models was conducted to remove translation and rotation differences. The correspondences of landmarks between the models were then established using coordinates and surface normals. Three registration methods were compared: the LM-ICP method; the global method; and the SHREC method. The LM-ICP registration method showed better performance than the global and SHREC registration methods, in terms of compactness, generalization, and specificity. The first four principal components obtained by using the LM-ICP registration method account for 61% and 67% of the overall anatomical variation for the exterior and interior cortical bone shapes, respectively. The length was found to be the most significant variation mode of the human clavicle. The mean and two boundary shape models were created using the four most significant principal components to investigate the size and shape variation of clavicular cortical bone. In the future, boundary shape models could be used to develop probabilistic finite element models which may help to better understand the variability in biomechanical responses and injuries to the clavicle.

Abbreviations: 2D, two-dimensional; 3D, three-dimensional; ATD, anthropomorphic test dummy; CDS, crashworthiness data system; CPU, central processing unit; CT, computed tomography; DetCov, determinant of the covariance matrix; FE, finite element; FOE, first order ellipsoid; GPA, generalized procrustes alignment; ICP, iterative closest point; LM-ICP, Levenberg–Marquardt iterative closest point; MDL, minimum description length; MSS, manually initialized subdivision surfaces; NASS, national automotive sampling system; PCA, principal component analysis; PMHS, post mortem human subject; SD, standard deviation; SHREC, SPHARM registration with ICP; SLIDE, iterative landmark sliding; SPHARM, spherical harmonics; SSA, statistical shape analysis.

* *Corresponding author*. Tel.: +1 540 231 8191; fax: +1 540 231 2953.
E-mail addresses: costin@vt.edu, costin.untaroiu@gmail.com (C.D. Untaroiu).

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1. Introduction

During car collisions, the occupant's shoulder belt subjects the clavicle to large loading, often causing injury. Based on the NASS CDS 2003 database [36], it was found that clavicle fractures occurred in over 9700 three-point belt restrained occupants each year. According to clinical studies, clavicle fractures usually take between 4 and 12 weeks to heal in adults [34], and in some cases non-union fractures may lead to a significant morbidity when treated non-operatively [47] Recently, the clavicle's biomechanical response and injury tolerance have been extensively investigated [21,36,62]; however, the results of previous studies were limited to the conditions and the characteristics of specimens tested, and the influence of the clavicle's shape on the biomechanical response was not considered.

The statistical shape analysis (SSA) is a common technique to evaluate the size and shape variations. Traditionally, the SSA begins with manual identification of anatomical landmarks on the training shapes, and follows with the model registration which removes translation, rotation, and/or scaling differences [20,23]. While the landmarks are also defined manually in some atlas-based segmentation schemes [7,42], the landmarking process is time-consuming and it is challenging when few homologous, well-defined anatomical features are available in complex two-dimensional (2D) and three-dimensional (3D) shapes [10,18,19,25,35,45,51], so in the recently SSA studies, semi-landmark approaches started to be employed. The semi-landmarks are the surface points utilized for the shape reconstruction of the object which are not required to be anatomic feature points [33]. In most semi-landmark approaches, the model registration, automatic landmark identification through correspondence process, and the principal component analysis (PCA) are included as major steps of the construction of 3D statistical shape models. The principal directions of variation, also called "modes of variation", could be represented by eigenvectors calculated from PCA [66]. Several studies had applied SSA on human internal organs [11,12,40,52], bones [3,9,26,44,66], and the entire human body [2]. Fripp et al. [26] and Bredbenner et al. [9] constructed the distal femur and proximal tibia models to investigate the shape variability of the knee joint. Giessen et al. [66] applied SSA on wrist bones and found the first five modes have the highest variations. Lorenz et al. [44] developed 3D lumbar vertebrae shape models and built corresponding finite element (FE) mesh models. Statistical shape models for human soft tissues have also been studied such as pancreas [52], liver [40], kidney and spleen [11,12] shape models. All of these recent studies utilized PCA to constructed statistical shape models and presented at least the first three significant shape modes.

While some studies have investigated the size and shape variations of human clavicle, they focused only on its exterior surface. Daruwalla et al. [15,16] constructed clavicle shape models based on the exterior surfaces of clavicles to design the clavicle fixation plates. However, the clavicular bone, as all human long bones, consists of two components (cortical and trabecular) with very different material properties; therefore, to develop statistical FE models of clavicles in addition to exterior surface, it is necessary to distinguish the separation surface (endosteal or interior surface) between the cortical and cancellous bones.

The registration process is an important operation allowing pairwise processing or group analysis across different surface models. The purpose of the registration is to minimize the translation, rotation, and/or scaling differences between a selected template shape and target shapes in a 3D Euclidean space [68]. The registration has extensive uses in many applications such as recognition, indexing and retrieval, and tracking. One of the most popular registration methods in SSA is the generalized procrustes alignment (GPA) [30,31]. While the standard procrustes match minimizes the mean squared distance between two shapes using an analytical approach, the GPA is an iterative process which tries to align a group of shapes to their unknown mean. Since the GPA method requires pre-determined landmarks before registration, establishing initial dense point correspondence between all 3D shapes is usually a challenging task. Davies et al. [19] proposed aligning all training shapes using the minimum description length (MDL) optimization. Nevertheless, the method involves extensive optimization process, resulting substantial computational time [59]. Another popular method is the iterative closest point (ICP) algorithm, first proposed by Besl et al. [6] and Zhang [74] and then applied in many studies [3,66,75]. ICP aligns two surfaces with potentially different number of vertices as input and delivers the optimal similarity transformation from one surface to the other as a result. On the other hand, global registration aligns all scans at the same time by distributing the registration error evenly over all overlapping views [39]. Fast convergence rate and high quality registrations of this algorithm can be observed. The spherical harmonics (SPHARM) registration method introduced by Brechbühler et al. [8] uses the first order ellipsoid (FOE) alignment, which was used extensively in medical imaging applications [28,29]. Even though a large amount of registration methods have been proposed, the best method for the clavicle shape model registration remains unknown.

The goal of this study is to develop statistical size and shape models of the clavicle, including both the exterior and the interior surface shapes of the cortical bone. The computer tomography (CT) scans of twenty left human clavicles were collected and segmented to build 3D models. Three registration methods were utilized and compared: (1) global registration, (2) Levenberg–Marquardt iterative closest point registration (LM-ICP), and (3) SPHARM registration with ICP strategy (SHREC). A dense correspondence map between each pair of surfaces was established using coordinates and surface normals [67]. PCA was then applied to develop statistical size and shape models of the clavicle such as the mean and boundary models.

2. Method

2.1. Sample collection and segmentation

Computed tomography (CT) scans of twenty intact left human clavicles (Table 1), which correspond to the driver's clavicle in the right-hand traffic countries, were collected *in vitro* for