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In vivo three-dimensional evaluation of the functional length of glenohumeral ligaments

Chen Yang [a], Akira Goto [b,*], Wataru Sahara [b], Hideki Yoshikawa [b], Kazuomi Sugamoto [c]

[a] *Department of Orthopaedic Surgery, First Hospital of Jilin University, Changchun, China*
[b] *Department of Orthopaedic Surgery, Osaka University Graduate School of Medicine, Osaka, Japan*
[c] *Department of Orthopaedic Biomaterial Science, Osaka University Graduate School of Medicine, Osaka, Japan*

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ABSTRACT

Background: Glenohumeral ligaments play an important role in stabilizing the shoulder. However, it is impossible to know how they function *in vivo* during shoulder motion. To help elucidate this stabilizing role, we studied the *in vivo* three-dimensional kinematics of the normal shoulder joint using a markerless bone-registration technique.

Methods: Our technique utilized image registration to determine corresponding relations between several image volumes represented at different coordinates. Magnetic resonance images of 14 shoulder joints of seven healthy volunteers were acquired for seven isometric abduction orientations between 0° and 180°. We then calculated three-dimensional shortest path between the origin and insertion of each ligament based on anatomical study in each abduction orientation.

Findings: At 0° of abduction, the posterior band of the coracohumeral ligament displayed the maximum length. At 30° of abduction, the superior glenohumeral ligament displayed the maximum length. At 60° of abduction, the anterior band of the coracohumeral ligament and the middle glenohumeral ligament displayed the maximum length. At 120° of abduction, the anterior band of the inferior glenohumeral ligament displayed the maximum length.

Interpretation: Based on progressive abduction of the arm, each ligament had different pattern in change of length. At different arm orientation of abduction, each ligament displayed the maximum length. We think that each ligament might play an important role in stabilizing the shoulder at different arm orientation.

1. Introduction

The shoulder is the most commonly dislocated joint of the human body (Hovelius, 1982; Kazár and Relovszky, 1969) and glenohumeral ligaments play an important role in stabilizing it. Their main contribution is to maintain anterior stability and restrict superior–inferior translation. A lesion in one of these ligaments may result in disability, instability, and dislocation of the shoulder. The different functions performed by the various ligaments depend on both arm orientation and direction of the load. Therefore, numerous studies have attempted to determine the relative contributions of superior, middle, and inferior glenohumeral ligaments and the coracohumeral ligament to glenohumeral stability (Boardman et al., 1996; Ferrari, 1990; Moore et al., 2005; Ovesen and Nielsen, 1985; Turkel et al., 1981; Warner et al., 1992). Several authors have provided biomechanical accounts of selective sectioning observations (Ovesen and Nielsen, 1985; Turkel et al., 1981; Warner et al., 1992) and examined the material or tensile properties of these ligaments (Boardman et al., 1996; Moore et al., 2005). More recently, a three-dimensional (3D) finite element technique has been used to analyze strains and forces in ligaments (Debski et al., 2005; Ellis et al., 2007). All these studies have improved our understanding of ligament function. However, an obvious shortcoming of the previous studies is that their conclusions were derived from cadaveric modeling *in vitro* and thus cannot reflect the actual events that happened in the living body because of muscle removal or scapular fixation (Kelkar et al., 2001). The purpose of this study is to characterize the functional lengths of the coracohumeral ligament (CHL), the superior glenohumeral ligament (SGHL), the middle glenohumeral ligament (MGHL), and the anterior band of the inferior glenohumeral ligament (AIGHL) during active abduction of the shoulder using *in vivo* 3D movement patterns.

* Corresponding author. Address: Department of Orthopaedic Surgery, Osaka University Graduate School of Medicine, 2-2, Yamada-oka, Suita, Osaka 565-0871, Japan.

E-mail addresses: yangchen1115@yahoo.com.cn (C. Yang), goto-akira@umin.ac.jp (A. Goto), sugamoto@ort.med.osaka-u.ac.jp (K. Sugamoto).

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2. Methods

The method applied in this study comprised of two steps. In the first step, we obtained 3D attachment points of the ligaments by investigating cadaveric specimens. We dissected formalin-embalmed cadaveric shoulders and exposed the ligaments. Then, we inserted marker pins in the centroid of each ligament and scanned the ligaments by 3D computed tomography (3D CT). Using a marching cubes algorithm (Lorensen and Cline, 1987), 3D bone models showing the marker pins were generated. We performed 3D measurements to specify the attachments of each ligament.

In the second step, 14 shoulder joints of seven healthy volunteers were studied *in vivo* during arm abduction using a noninvasive 3D motion-analysis system. Based on anatomical study data and motion analysis, we calculated the change in length between insertion and origin *in vivo* during arm abduction. Three-dimensional (3D) lengths were based on the shortest calculated paths between each origin and insertion in 3D space along the 3D bone surface for each abduction orientation (Marai et al., 2004). These steps are explained in detail below.

2.1. Anatomical study

Ten formalin-embalmed cadaveric shoulders of five cadavers were investigated (two men and three women, 60–96 years; average age, 83.4 years). None of them exhibited abnormal evidence on gross examination. All skin, subcutaneous tissue, and musculature were removed except for the glenohumeral joint capsule. The capsule was opened using a posterior approach and the structures of CHL, SGHL, MGHL, and AIGHL were characterized. We inserted metal pins ($\varnothing$ 0.3 mm) to mark the centroid of the attachment area of each ligament. Then, all the specimens were scanned using CT (Somatom Spirit; Siemens, Munich, Germany; scan time 60 s, scan pitch 2 mm, 80 mA s, 120 kV, slice thickness 0.5 mm).

2.1.1. Creating 3D bone surface model and template for virtual measurement of ligaments

The scanned data were uploaded into a graphics workstation, and regions of individual bones were semi-automatically constructed from 3D CT images using a software (Virtual Place-M®; AZE, Tokyo, Japan). The 3D surface bone models were produced using a Marching Cubes algorithm (Lorensen and Cline, 1987). Geometric models for each shoulder were visualized using the original program based on the Visualization Toolkit (Kitware, Clifton Park, New York). We used only models of the right shoulder. Images from left shoulders were converted to mirror-image models using this program to make virtual measurement templates for shoulder ligaments. There were variations in bone size among individuals. To normalize bone sizes, we measured the anteroposterior and superoinferior diameters of the humeral head and the height and width of the glenoid. Then, we scaled the bone models up or down from these measurements using a computer to normalize all subjects to the same bone size. Finally, all subjects were spatially registered using the iterative closest point algorithm (Besl and Mackay, 1992). This algorithm is one of the most well-developed methods for surface-based registration. In this method, a 3D surface model and a set of 3D points are registered starting from initial transformation parameters and eventually finding the best parameters while minimizing the sum of the distance from each 3D point to the surface. The accuracy of this method has been determined to be 0.04 ± 0.01 mm in translation and $0.82 \pm 0.38°$ in rotation (Goto et al., 2004). In this way, all centroid coordinates with respect to the global coordinate system were plotted in one model. We obtained the mean 3D coordinates of the centroids of the ligamentous attachments (Fig. 1) and defined this humerus and glenoid model along with the mean ligamentous attachments as the template for calculating virtual measurements of the ligaments.

2.2. Kinematics and calculation of the functional length

In this analysis, image acquisition, segmentation, and registration were conducted. A mathematical description of the motion of individual bones and their relative motion was derived by computing the rigid transformation required to match the volume data of the images.

2.2.1. Image acquisition

Fourteen shoulders of seven healthy male volunteers (19–30 years; average age, 23.6 years) were examined. None of them had shoulder dysfunction and all gave informed consent to participate in this study. Magnetic resonance (MR) images were obtained using an MR scanner with a vertically open configuration (Signa SP/i 2, 0.5 T, GE Medical Systems, Milwaukee, WI, USA; section thickness 1 mm, field of view 240×240 mm^2). Each subject was examined in an upright seated position between two gantries of the vertically open MRI system. Positions of the sternum and sacrum were fixed by the original stand and the posterior gantry, and the subject grasped an antimagnetic movable knob in order to minimize motion artifacts. Seven isometric abduction orientations of the arm in the coronal plane were investigated (0°, 30°, 60°, 90°, 120°, 150°, and 180°).

2.2.2. Segmentation and volume-based registration

Contours of the humerus and scapula at 0° of abduction were semi-automatically extracted from the MR images in a process known as "segmentation". A 3D model was constructed from the extracted area of the MR images using the marching cubes algorithm (Lorensen and Cline, 1987). Voxel-based registration technique was used to identify transformation from the coordinate system of one image to another, by comparing the intensity between two images that were arbitrarily superimposed (Hill et al., 2001). Using this method, a segmented bone at 0° of abduction was superimposed on the same bone in images of other orientations. Transformation matrices from 0° of abduction to other orientations were calculated for each bone in the MR scanner coordinate system. The accuracy of voxel-based registration has been determined to be less than 0.52 mm in translation and 0.43° in rotation, based on our previous report (Ishii et al., 2004).

2.2.3. Calculating in vivo functional length

Three-dimensional lengths between the insertion and origin of ligaments were calculated as the shortest paths in 3D space along the 3D surface of the bone models (Marai et al., 2004). In this algorithm, information on ligament attachments was obtained from anatomical studies. We used templates marked with the mean ligamentous attachments by normalizing their size to completely match them with the *in vivo* 3D models (0° abduction). To register the templates over the *in vivo* 3D models, we first measured the sizes of the humeral head and glenoid in the *in vivo* 3D models. Then, to normalize the *in vivo* 3D models and templates, we scaled the templates up or down from these measurements using the program Visualization Toolkit on a computer. The templates and the *in vivo* 3D models were spatially registered (Besl and Mackay, 1992) using the iterative closest point algorithm. We obtained the mean coordinates of attachment for the glenohumeral ligaments in the *in vivo* 3D models. Using software developed in our laboratory based on Visualization Toolkit (Kitware, Clifton Park, New York), the change in length and path were represented by curved lines in the 3D bone models to express the ligament paths from origin to insertion, as shown in Fig. 2.