PASSIVE AND ACTIVE CONTRIBUTIONS TO GLENOHUMERAL STABILITY

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Abstract- **Fresh-frozen shoulder specimens were used to evaluate restraining forces provided by capsuloligaments and muscles crossing the glenohumeral (GH) joint to better understand various factors contributing to GH stability. The humeral head was translated in the posterior-anterior (Post-Ant), inferior-superior (Inf-Sup), and medial-lateral (Med-Lat) directions, and rotated about the humeral long axis relative to the glenoid from the neutral position, and restraining forces and moments acting on the humeral head by passive and active structures were recorded. Results showed that the GH capsuloligaments generated considerable resistance forces to passive displacements, which varied systematically in amplitude and direction. The restraining force increased more quickly with Post-Ant displacement than with Inf-Sup displacement. Furthermore, GH stiffness was higher in the anterior direction than in the posterior direction and stiffness in the superior direction was higher than that in the inferior direction. Loading muscles across the GH-joint made the joint considerably more stable and humeral axial rotation laxity was reduced markedly when the muscles were loaded moderately at ~2% maximal muscle force. Contributions of the rotator cuff were found to be especially important in preventing excessive inferior humeral translations.**

I. INTRODUCTION

The GH-joint is the most mobile joint of the human body with the humeral head supported partially by the relatively small concave glenoid. Passive structures, including the joint capsule, ligaments, labrum, and articular surfaces, work together with muscles to maintain stability of the GH-joint. Articular joint conformity and contraction of the rotator cuff and biceps are major stabilizing factors for this joint [1-6]. Besides, the capsuloligamentous structures function to guide the humeral head during motions and limit translations and rotations [1, 6-10]. Also, local sub-atmospheric pressure inside the capsule is one of the main stabilizers of the joint [11], and may provide a restraint to pathologic translations. It is not very clear how different portions of the capsuloligamentous system contribute to GH stability. GH instabilities occur frequently in various shoulder injuries, manifested as excessive GH translations and rotations. Improved understanding of the aetiology behind these problems can be obtained through better understanding of the restraining forces provided by various structures in the GH joint.

In existing computer models of the shoulder complex, GH translations are usually neglected and the joint is assumed to have only three rotational DOFs (a ball-socket joint). Maintained by its surrounding muscles, all joint movements are restricted not only by passive structures, but also by the force-deformation properties of the muscle-tendon complex. While the deformation of the bone structures under the influence of normal stresses may be neglected, this is not so for the soft tissue. The joint capsule, ligaments, labrum and muscle-tendon complexes generally deform under stress. The passive structures act against rotations and translations when they are deformed and taut [12].

The objectives of this study were to evaluate the passive restraining forces provided by the capsuloligamentous system and active forces provided by muscles crossing the GH joint under systematically varied humeral head translations and rotations relative to the glenoid at different loading conditions to better understand various factors contributing to GH stability.

II. METHODS

Specimen

Six fresh-frozen shoulder specimens with no sign of injury were used for the study. All donors were male and 58 ± 9 years old at death. Skin and subcutaneous tissues were peeled off. In order to test the biomechanical properties of the capsuloligamentous structure of the GH-joint with less bony restraints, the posterolateral corner of the acromion was chopped off to the lateral edge of acromio-clavicular joint capsule.

Wires were sutured to individual muscle through fiberglass mesh wrapped around it. These muscles were anterior, medial, and posterior portion of the deltoid (Delt-a, Delt-m, and Delt-p), supraspinatus (Supras), upper, middle, and lower portions of the subscapularis and infraspinatus (Sub-u, Sub-m, and Sub-l, Inf-u, Inf-m, Inf-l), the long head of biceps (Bic-l) and teres minor (Teres-mi). Multiple wires were sutured onto each portion and passed through eye-

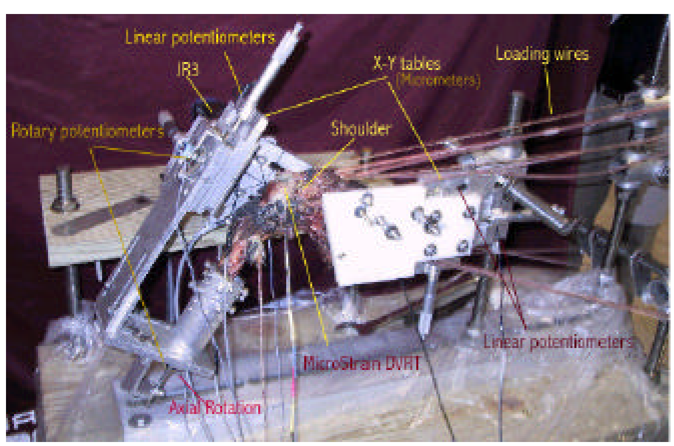

Fig. 1. Experimental setup for evaluating GH stability.

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Abstract

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screws fixed on bony structure to maintain the anatomical line of action [13].

Experimental setup.

The specimen was mounted on the customer designed testing device, which allowed 3-D rotation (abduction-adduction, flexion-extension, and internal-external rotation (IR, ER)) and translation (Post-Ant, Inf-Sup, and Med-Lat) of the GH-joint. The scapula was mounted rigidly onto a Teflon plate with 4 screws and the glenoid surface was oriented vertically (Fig. 1). The humerus was fixed into an aluminum tubing by sharp tip screws and the shaft of humerus was aligned with the centerline of the tubing. A beam attached parallel to the humeral shaft was mounted to an X-Y table which moved the humerus relative to the glenoid in the Post-Ant and proximal-distal directions, by two micrometers. The scapular plate can be translated in the Med-Lat and Inf-Sup directions by another X-Y table. The displacements of the two X-Y tables were measured by four linear potentiometers as well as by the micrometers built into the X-Y tables. The humeral abduction, flexion, and axial rotation were measured by three precision rotary

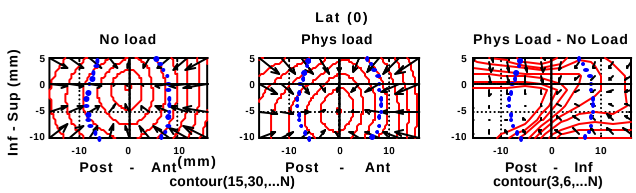

Fig. 2. Restraining force acting on the humeral head as a function of Post-Ant and Inf-Sup translations for the 'No Load' and 'Phys Load' conditions; and differences of the restraining force fields between 'Phys. load' and 'No load' conditions at zero Med-Lat translations.

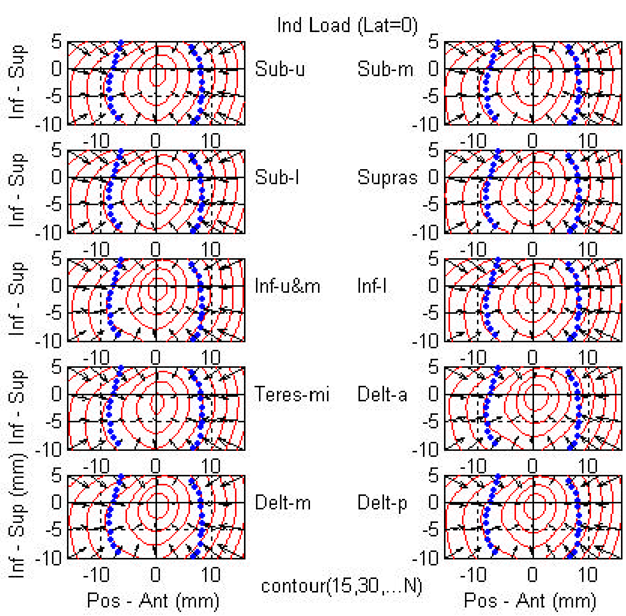

Fig. 3. Restraining force acting on the humeral head as a function of Post-Ant and Inf-Sup translations for the 'Ind Load' condition at zero Med-Lat translation.

potentiometers. A six-axis force sensor (JR3 Inc.. USA) was mounted with its vertical axis aligned to the GH-joint center. This force sensor was used to measure the restraining forces and moments exerted onto the humerus caused by the translations and axial rotations of the humerus relative to the glenoid. A pulley system was used to load muscles or different portions of large muscles.

Protocol

Before dissection of the muscles, the neutral rotation of the humerus was measured by digitizing landmarks on the humerus and the scapula using a digitizer (MicroScribe-3D, Immersion Corp., USA), when the arm was positioned at 60° abduction (corresponding to 90° arm abduction) in the scapular plane. After dissection, the center of the humeral head was aligned with the center of glenoid by following steps: First, press the humeral head into the glenoid fossa in order to ensure concentric reduction of the humeral head in the socket [14]; Second, find the neutral axial rotation of the humerus by using Bic-l groove, which should be 45° externally rotated relative to the scapular plane. Third, use the digitized data to define the position of neutral rotation for the shoulder and to confirm that found in second step.

Passive restraining forces provided by the GH capsuloligamentous structure were measured statically when the humerus was translated relative to the glenoid in the Post-Ant (-16 to 16 mm), Inf-Sup (-10 to 5 mm), and Med-Lat (-2.5 to 5 mm) directions, at the increment of 4, 2.5 and 2.5mm, respectively. A minimum of sixty-three data points was collected to cover translation in a Post-Ant/Inf-Sup plane at each fixed Med-Lat position.

At neutral position (no translation), data was also collected when the humerus was axially rotated from neutral rotation to maximal ER and IR.

In order to quantify the passive properties of the GH capsuloligamentous structure and the contribution to the joint stability of each relative muscle, the procedure was repeated at the following 12 loading conditions: no muscle load (No Load); 2% maximum muscle force, representing the physiological muscle contraction during free arm suspension and proportional to muscle physiological cross-sectional area [15] (Phys Load); ditto plus an extra 8% load individually on each of the muscle, i.e. Supras, Inf-u&m, Inf-l, Sub-u, Sub-m, Sub-l, Teres-mi, Delt-a, Delt-m, and Delt-p, one muscle at a time (Ind Load). Measurement under different loading conditions was used to investigate the influence of muscle tone, i.e. small amount of muscle contraction around GH-joint.

Stiffness of the GH capsuloligamentous structure, which is the ratio of the force required to stretch the capsule by a small translation (dF/dT), was calculated for each direction of translations (Post, Ant, Inf, and Sup) at the neutral position.

III. Results

The restraining force applied to the humeral head by the GH capsuloligamentous structures varies systematically with the Post-Ant and Inf-Sup translations (Figs. 2 and 3). The concept of force vector field is used in order to show both direction and magnitude of the forces. At each mapping position, force measured is depicted as small arrow with the length and direction corresponding to the force magnitude and direction, respectively. Force magnitude distribution over the rectangular area, where the humeral head was translated, is also given by contours with values at every 15 N (15, 30, 45, …). Force field difference between 'No load' and 'Phys. load' at zero Med-Lat is also given in Fig. 2.

The GH capsuloligaments generated considerable resistance forces to the passive displacements, which varied systematically in amplitude and direction (Fig. 2 and Fig. 3). The origin in the field corresponded to the neutral position where the glenoid and the humeral head were aligned with each other (no translation). The dots demonstrate the glenoid surface.

The restraining force increased more quickly with the Inf-Sup displacement than with the Post-Ant displacement at zero Med-Lat displacement, as shown by the contour lines. Furthermore, the resistance force of the capsuloligaments increased considerably inferiorly for all Post-Ant translations when the capsuloligaments was stretched laterally. This remarkable force increase may come from the sub-atmospheric pressure in the capsule, suction effect of labrum and the capsuloligamentous structures.

Physiologically loading the muscles generated larger restraining forces than those of the 'No Load' condition for the same humeral head translations, as indicated by the shrinkage of the contour curves and the faster rise of the restraining forces with the passive displacements. Results for the individual muscles loading (Fig. 3) showed that the additional muscle loading provided even more restraining force against inferior translation for all Post-Ant translations.

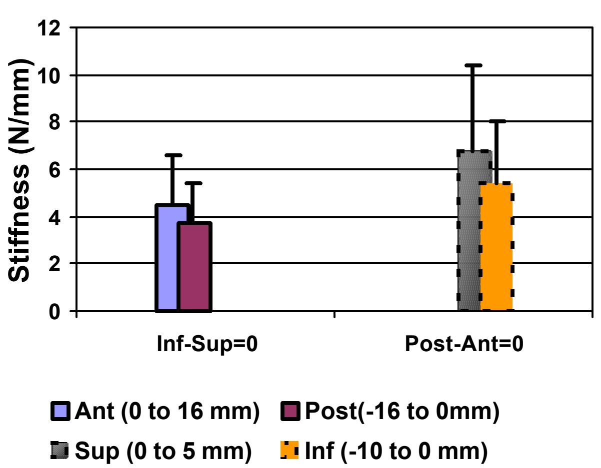

Fig. 4. Left: Post-Ant stiffness of the GH capsuloligamentous structure (mean ± S.D over 5 specimens) at neutral Inf-Sup position (Inf-Sup=0); Right: Inf-Sup stiffness at neutral Post-Ant position (Post-Ant=0). Both were under 'No Load' condition and zero Med-Lat translation.

Generally, the resistance force increased approximately linearly with Post-Ant displacement, indicating that the stiffness (the slope of force-displacement curve) is constant across the Post-Ant translation at each level of Inf-Sup translation, as well as for the Inf-Sup translation at each level of Post-Ant translation. Fig. 4 shows the stiffness (mean ± S.D) values from five shoulder specimens across the Post-Ant and the Inf-Sup translation. The superior stiffness is higher than the inferior stiffness and the anterior stiffness is higher than the posterior stiffness at the neutral rotation.

Humeral axial rotation laxity in ER and IR was reduced markedly when muscles crossing the GH joint were loaded moderately at 2% maximal muscle force (i.e., under the 'Phys Load' condition). The rotation laxity was further decreased for the IR by loading Bic-l, Sub-m, or Teres-mi by 10% of maximal force (i.e. 'Ind Load' condition). Loading the Sub-u, Sub-m, Sub-l, Supras, Bic-, or Teres-mi resulted in less axial torque for ER compared with 'Phys Load' condition, and loading Delt-a, or Inf-l resulted in less axial torque for the IR.

IV. DISCUSSION

The study provides us quantitative information on the restraining force provided by the GH-capsuloligamentous structures as the humerus is displaced relative to the glenoid in the Post-Ant, Inf-Sup, and Med-Lat directions. The helps us understand the roles of the capsuloligaments in GH stability, analyze glenohumeral injury and instability, develop mathematical models of the GH-joint, and gain insight into pathological changes in the glenohumeral joint.

The measured restraining force in our study shows that there is always larger resistance force acting on the humeral head on the anterior direction than that for posterior side under comparable translations. Also the calculated stiffness for capsuloligamentous structure is higher in anterior part than that in posterior side. Considering that there are four GH ligaments (superior GH ligaments, middle GH ligaments, anterior, and superior portions of inferior GH ligament) and coracohumeral ligament that insert to the anterior part of the humeral head together with the capsule, while only one such ligament (posterior portion of inferior GH ligament) inserts to the posterior inferior capsule, our results do suggest the idea that the shoulder joint has higher anterior stability than that of posterior direction for 90° arm abduction.

We also found that the capsuloligamentous structure generated a large restraining force against the humeral head lateral translation relative to the glenoid, and this force is larger than those in glenoid plane for comparable translation. Because the capsule and the GH ligaments are loose at the side where translation is directed to, only the part opposite to the translation direction is stretched and provides resistance to the translations in glenoid plane. But when the humeral head is translated laterally to some extent, the whole capsule and all the GH ligaments are stretched to give reaction forces. Moreover, the suction effect of the glenoid labrum may also prevent lateral translation of the humeral head. Therefore, stronger lateral resistance is usually found.

Contributions of the rotator cuff were found to be very important under inferior humeral translations. Our results are consistent with Soslowsky [4] in that the supraspinatus was important active stabilizer in inferior stability. Our results also suggested that low-level muscle activity (2% of maximum muscle contraction), representing physiological muscle tone contraction, is important and effective in stabilizing the GH-joint [16].

Also the biomechanical role of individual muscle for shoulder axial rotation stability is confirmed by our founding that maximal ER and IR were markedly reduced at Ind Load condition.

It is also worthy of mention that the capsule stiffness calculated here is about the material property of the joint capsule and GH ligaments. It may contribute to some degree to the joint stiffness. While the capsule and ligaments around GH-joint is complicated—the linear increase of restraining force with displacement indicates that the stiffness is constant within the measured range of displacement. Furthermore, this study shows that the stiffness is different in Post-Ant and Inf-Sup at comparable displacement, suggesting the anisotropic nature of the GH capsuloligamentous structure. Further work should be carried out to characterize those properties.

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