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Different fixation methods for artificial femoral head replacement: A biomechanical comparison of joint stability*

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Abstract

BACKGROUND: Artificial humeral head replacement is an effective method for the treatment of complex proximal humeral fractures, which has received good results in relieving pain. However, the final functional recovery is unpredictable.
OBJECTIVE: To compare biomechanical stability between anatomical and overlapping reconstruction of the greater tuberosity in cadaveric humeral head replacement models.
METHODS: Eight pairs of fresh-frozen shoulder cadavers (16 shoulder joints) were match-paired into two groups. Standardized humeral head replacement procedure was performed in all specimens, and anatomical and overlapping reconstruction of the greater tuberosity was adopted in each group respectively. For overlapping group, the greater tuberosity was reattached to the proximal humeral shaft in an overlapping style, which was achieved by an additional 5 mm bone osteotomized from the medial cortex of the humeral diaphysis. Custom mounting apparatus and fixation jigs were designed for designated shoulder motion.
RESULTS AND CONCLUSION: When the shoulder was external rotated to neutral position, the mean displacement of greater tuberosity in the anatomical reconstruction group was smaller than that of the overlapping reconstruction group ($P < 0.05$). When the gleno-humeral joint was elevated to 30° and 60° forward flexion (accounting for 45° and 90° shoulder forward flexion), there was no significant difference of greater tuberosity displacement between the anatomical group and overlapping group. The findings demonstrated that, although overlapping reconstruction can increase the bone healing area between the greater tuberosity and the humeral diaphysis, there may be some loss in mechanical stability as the trade-off. Even though we strictly follow the standardized postoperative rehabilitation protocol after humeral head replacement, prominent displacement between the greater tuberosity relative to the humeral diaphysis was detected. Accordingly, postponing of the postoperative rehabilitation program after humeral head replacement for a decent period may improve tuberosity healing.

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INTRODUCTION

Humeral head replacement is an effective method for the treatment of complex proximal humeral fractures. Although the pain relief is often satisfactory, the function outcome is unpredictable[1-3]. The most common complications are related to the reduction and healing of tuberosities[4-7]. Nonunion or malunion of the greater tuberosity is common. According to our own series of patients, we found that almost 80% of the patients with a compromised postoperative shoulder function have healing problems with the greater tuberosity. In addition, some authors suggested that the greater tuberosity should be reconstructed in an overlapping manner to increase the contact area between the fragment and the humeral diaphysis to improve the healing of the tuberosity[8] (Figure 1).


a: An anatomical reconstruction


b: An overlapping reconstruction

Figure 1　X-ray films for different types of tuberosity reconstruction

However, there are few reports concerning the effects of overlapping reconstruction on biomechanical stability of greater tuberosity. Thus, this study attempted to compare the biomechanical stability of the fixation of the greater tuberosity between an anatomical and an overlapping reconstruction in the humeral head replacement.

MATERIALS AND METHODS

Design
A biomechanical observation of samples.

Time and setting
The experiment was performed at the Biomechanical Laboratory in Tsinghua University from January 2005 to June 2005.

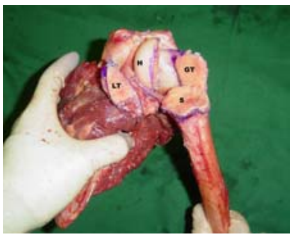
Materials
Eight pairs of fresh frozen human shoulder specimens were provided by tissue bank of Beijing Jishuitan Hospital, and the procedure was accordance with related ethic standards. Every specimen was checked before being included to make sure there was not any deformity of skeletal structure or defect of rotator cuff tendon. Bigliani-Flatow shoulder prostheses and bone cement were purchased from Zimmer. The Ethibond suture line (Ethicon) was produced by Johnson & Johnson.

Methods
Preparation of specimens
The study included eight pairs of fresh frozen shoulder specimens from individual cadavers,

average aged 72 years (46−77 years). Every specimen was checked before being included to make sure there was not any deformity of skeletal structure or defect of rotator cuff tendon. They were divided into two groups: an anatomical group and an overlapping group. Each side of every pair of the specimens was put into the anatomical group or the overlapping group randomly, and they were matched with each other to reduce the error caused by individual differences. The specimens were coded from A1−A8 or O1− O8; the different letters represented the different groups. Both sides of each pair were coded with the same number but different letters. The specimens were thawed in room temperature for 36 hours before the study began. Each specimen originally consisted of an entire scapula, a glenohumeral joint with a capsule and rotator cuff, an intact coraco-acromial arch, a humerus, an entire elbow joint, both bones of the forearm, an interosseous membrane, and a distal radioulnar joint. All other soft tissues were removed.

Preparation of four-part proximal humerus fracture models

The subscapularis muscle was elevated from its origin at the scapular blade and reflected laterally with its humeral insertion kept intact. Careful dissection was made during the separation the cuff tendon from the capsule adjacent to the humeral insertion[9]. The rotator interval was identified and divided. The anterior capsule was then inferiorly opened from the rotator interval level to the level of the IGHL anterior band. The glenohumeral joint was exposed by an external rotation of the humeral head. The long head of the biceps tendon was incised from its anchor on the supraglenoid tuberosity. The osteotomy of the humeral head was performed along the rim of the articular surface of the humeral head using an oscillating saw. Special attention was paid to preserve the integrity of the rotator cuff insertion. Then the greater and lesser tuberosities and the diaphysis were further divided by osteotomy along the bicipital groove and the surgical neck. For the specimens in the overlapping group, an extra 5 mm of the medial cortex of the humeral neck was osteotomized that allowing for the further subsidence of the prosthesis (Figure 2).

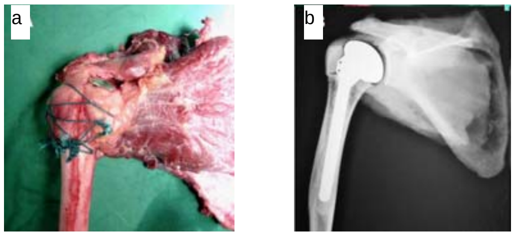


LT: lesser tuberosity; H: humeral head; GT: greater tuberosity; S: surgical neck

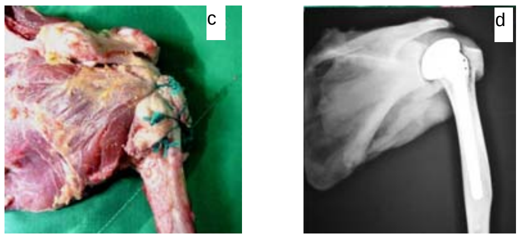
Figure 2 Four-part fracture models

Humeral head replacement and reconstruction of the greater and lesser tuberosities

Bigliani-Flatow shoulder prostheses were used in this study. The humeral head replacements were applied with standard surgical procedure. The size of the stem used in each cadaver was decided after the medullary cavity of the specimen was reamed. The stem diameter 1 size smaller than the largest reamer was chosen. All prostheses were cemented at a 30° of retroversion with the medial collar of the prostheses in closely contact with the medial cortex of the diaphysis[10]. Nine number 5 Ethibond sutures were used to fix the greater and lesser tuberosities in each specimen. Four of them were used to bind the greater tuberosity with the diaphysis, two for the lesser tuberosity and diaphysis, and the other three sutures were used to bind the greater and lesser tuberosity (Figures 3a−b). In the anatomical reconstruction group the tuberosities were reduced anatomically, while in the overlapping group, the distal cortex of the greater tuberosity was overlapped with the lateral cortex of the diaphysis to achieve the anatomical relationship between the head and the tuberosity (Figures 3c−d). All surgical procedures were performed by the senior surgeon to reduce bias.



a−b: Fixation of greater and lesser tuberosities using Ethibond suture lines



c−d: Greater tuberosity was overlapped with the lateral cortex of the diaphysis

Figure 3 Preparation of anatomical reconstruction and the overlapping reconstruction models

Afterwards, the forearm was amputated from the level of the elbow joint and the whole length of the humerus was preserved for a later mounting test. All cuff muscles were dissected from their scapular origin. The muscular belly was excised leaving only the tendinous part in place. The remnant tendon was tagged with a number 5 Ethibond suture in a modified Mason-Allen manner. These sutures were reserved as the traction suture for weight loading as to the simulate rotator cuff muscle force[11].

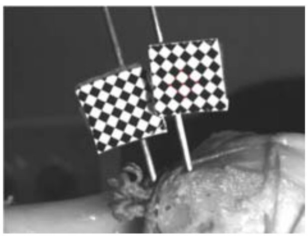
Mounting apparatus and measurement methods

A custom mounting apparatus and a fixation jig were designed to simulate the postoperative passive range of motion exercise. The passive motion we addressed included the external rotation at the side and forward elevation. Movement between the greater tuberosity and the humeral diaphysis was measured by a binocular 3-D computer vision metrical method[12].

mounting apparatus: two holes were drilled on the scapular body. Then, the scapula was fixed on a frame by two bolts. According to the direction of the contraction of each muscle, sutures that had been originally incorporated into the tendons were pulled through corresponding pulleys fixed on the frame. A weight was attached to the freely hanging end of each cord to simulate residual tension in the rotator cuff. The rotator cuff tendons were loaded proportionally to the respective cross-sectional areas of their muscles. The magnitude of loading was 4 N for the supraspinatus, 6 N for the infraspinatus, 2 N for the teres minor, and 6 N for the subscapularis. The corresponding literatures on the biomechanical study of shoulder joint were reviewed and no consensus was found with regard to how much weight should be applied to simulate the tension of rotator cuff muscles. Some of them used the same load in different rotator cuff muscle. The others used different load proportionally to the respective cross-sectional areas of each muscle.

The main part of the loading device was a rocker, which could freely spin on a plexiglass dial disk. The angle the rocker went through could be read from the scale on the disk. During the external rotation test, the humerus was mounted perpendicularly to the dial disk. A Steinmann pin was drilled through the distal part of the humerus with its direction perpendicular to the diaphysis. This pin was only allowed to go through the long axis of humeral shaft. It was fixed in the jigs around the axle of the rocker so that when the rocker was spinning the shoulder joint could be rotated passively. While in the forward elevation test, the humerus was mounted parallel to the rocker and the center of the forward elevation of the shoulder joint was positioned on the axial of the rocker. The distal pin was inserted in a slot in the distal part of the rocker. Thus, when the rocker was spinning, the humerus was elevated passively.

Optical measurement of the displacement: a Binocular 3-D computer vision metrical method was used to measure the displacement. The stereo visual system consisted of two position-fixed CCD cameras. Two markers were carefully fixed on the greater tuberosity and the diaphysis respectively. The cameras were used to collect real time images of the markers when the specimens moved to different positions. The displacement between the greater tuberosity and the humeral diaphysis was calculated by analyzing these images (Figure 4).



Red marks: corresponding points marked by CCD cameras

Figure 4 Markers were fixed on the greater tuberosity and the diaphysis

The study was divided into two parts, the external rotation part and the forward flexion part. The initial position of the shoulder joint of the specimen was internally rotated to 40° with the arm beside the body, which mimicked the position of the arm in a sling after the humeral head replacement. The joint was externally rotated passively by rotating the rocker. The pictures of the markers were shot when the shoulder joint was placed at 0°, 10° and 20° of external rotation.

In the forward flexion part of the study, the initial position of the specimen was set at 0° of forward flexion. Then, the humerus was forward flexed passively in the scapular plane by rotating the rocker. Pictures of the markers were shot when the glenohumeral joint was placed at 30° and 60° of forward flexion (accounting for 45° and 90° shoulder forward flexion considering the scapulothoracic movement).

Every shoulder movement was designated, degrees measured 3 times, and the average value of these results was used as the final result.

Main outcome measures

The displacements of greater tuberosity in two groups were measured.

Design, enforcement and evaluation

All authors performed experimental procedures. No blind method was used for the evaluation.

Statistical analysis

The Wilcoxon signed rank test from a SPSS 11.0 software package was used to analyze the results by the first author. A value of P < 0.05 was considered statistically significant.

RESULTS

Results of external rotation and forward elevation tests were described (Tables 1−2).

Table 1 Displacement of the greater tuberosity when the shoulder joint was in different degrees of external rotation ($\bar{x}\pm s$, n=8, mm)

Group	External rotated to 0°	External rotated to 10°	External rotated to 20°
Anatomical reconstruction	1.81±1.75	2.27±2.23	2.46±2.43
Overlapping reconstruction	3.23±2.91	3.21±3.17	3.44±3.66
Z	−2.100	−1.820	−1.680
P	0.036	0.069	0.093

Table 2 Displacement of the greater tuberosity when the shoulder joint was in different degrees of forward elevation ($\bar{x}\pm s$, n=8, mm)

Group	Forward elevation 30°	Forward elevation 60°
Anatomical reconstruction	4.01±5.00	5.99±6.97
Overlapping reconstruction	3.02±5.27	6.97±7.00
Z	−1.120	−0.280
P	0.236	0.779

DISCUSSION

Problems in humeral fractures replacement

Complex proximal humeral fractures are still challenging problems to orthopedics surgeons. It is difficult to achieve a satisfactory reduction and an effective fixation for those with severe osteoporosis or significantly comminuted fragments. A humeral head replacement can be a reasonable choice in these situations; however, results are often unpredictable[13-14]. Many authors believed that the nonunion or malunion of the greater tuberosity maybe the most common complications after the prosthetic reconstruction of complex proximal humeral fracture[15-16]. From February 2002 to December 2005, 91 patients with a complex proximal humerus fracture were treated with the humeral head replacement at Department of Sports Medicine, Beijing Jishuitan hospital were analyzed. The overall satisfactory rate was 81%. For patients with a compromised postoperative function, over 80% of them had problems with reconstruction of tuberosities. The reason why the greater tuberosity was not visible on the anterior posterior view of the X-ray film was proved to be the nonunion and posterior migration of the greater tuberosity[17]. Our experiences also suggested that the healing of greater tuberosity in an appropriate position is critical to patients' functional recovery.

Clinical application significance

The inadequate height of the prosthesis definitely impacts the postoperative function. Thus, theoretically, an overlapping manner of tuberosity reconstruction would benefit the healing process of the tuberosity due to the increased bony contact area between the tuberosity and the humeral diaphysis. However, Boileau[18] suggested that shortening the humerus to no more than 10 mm would not influence the postoperative shoulder function. By reviewing the literatures, we were not able to find any report that compared the biomechanical characteristics between the anatomical and the overlapping reconstruction of the tuberosity. Our hypothesis is that if there is no significant difference in the biomechanical stability between the two methods, then the overlapping reconstruction should be recommended because of the increased bony contact area.

A passive range of motion exercises began from the first postoperative day. For the first two weeks, the range of motion was limited within 90° of forward elevation and 0° to 10° of external rotation. A specifically designed mounting apparatus and loading system was used in our study to simulate this passive forward elevation and external rotation exercise. Our result indicated that no significant difference was found between the two groups when the glenohumeral joint was in the positions of 30° and 60° of forward elevation (accounting for 45° and 90° of forward elevation of shoulder joint). However, a significant difference could be found regarding the greater tuberosity displacement when the shoulder was externally rotated from 40° of internal rotation to 0°. The biomechanical stability was better in the anatomical reconstruction group than in the overlapping group. This suggested that by gaining the increased bony contact area between the greater tuberosity and the diaphysis, the anti-torsion stability of the fixation might also decrease. We could not conclude whether this compromised stability could be compensated by the increment of the bony contact area. The overall effect of the overlapping reconstruction on the healing process could not be solely determined from the information provided by an *in vitro* cadaveric study. We concluded that the hypothesis prompted previously had not been proved according to our study. Further prospective clinical research is needed to prove that the overlapping reconstruction of the greater tuberosity is better than the anatomical reconstruction regarding the healing process of the tuberosity.

Moreover, a prominent displacement of the greater tuberosity during a passive forward elevation or external rotation could be found with either reconstruction methods. A better fixation of the greater tuberosity should not be expected in a real operation due to the possibly worse conditions of exposure and more complex fractures. To reduce the negative impact of the intro-fragment movement to the healing process of the greater tuberosity, we are considering a change in our postoperative protocol. Postponing the rehabilitation for a period of time to allow partial healing of the surrounding tissue may be helpful to keeping the stability of the greater tuberosity, and therefore increase the chance of a bone union. Now in our clinical practice, the passive range of motion exercise was postponed 2 weeks after the replacement. However, it should be noted that this delay will increase the risk of postoperative stiffness so the overall effect needs to be investigated through further clinical study.

Design of mounting apparatus and measurement of greater tuberosity displacement

As a natural organ, there is neither a definite rotation center in humeral head joints nor a central axis in humeral diaphysis, all of these result in difficulty for humeral loading. Previous studies concerning loading devices neglected unregularity of humerus, which influence the precise of experiment[19]. Here, a special load device was designed to simulate the postoperative passive range of motion exercise. And passive motion we addressed included the external rotation and forward elevation.

Mercury strain gage was used by Frankle[20] in measuring displacement. But, the obtained results were smaller because of the influence of pretensioning tensile. De *et al*[21] utilized an opto-electronic device to record the measurements, but the precise is unsatisfactory. Authors in this paper applying binocular CCD cameras to obtain two-dimensional images, and to perform three-dimensional reconstruction using related algorithm.

Limitation of this study

The standard deviation within each group is relatively high due to the limited number of specimens used in this study. Although the rotator cuff muscle tension was simulated by hanging weights on corresponding pulleys, the exact *in vivo* biomechanical situation could not be exactly reproduced. The biomechanics of the shoulder joint was the result of the cooperation of many shoulder girdle muscles. The effects of many of these muscles could not be simulated during our study. However, the main subject of our study is to evaluate the greater tuberosity displacement happening in the early postoperative period when just a passive range of motion exercises was adopted without any involvement of active muscle traction.

In summary, our study demonstrated that the anatomical reconstruction of the greater tuberosity has a better mechanical stability than the overlapping reconstruction during a passive external rotation to neutral position. This result suggests that although an overlapping reconstruction can increase the bone healing area between the greater tuberosity and the humeral diaphysis, there may be some loss in mechanical stability as the trade-off. According to our data, even though we strictly follow the standardized postoperative rehabilitation protocol, a prominent displacement between the greater tuberosity and the humeral diaphysis was detected. Postponing the rehabilitation for a period of time to allow partial healing of the surrounding tissue may be helpful to keeping the stability of the greater tuberosity, therefore, increase the chance of a bone union.

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不同固定方法置换人工股骨头后关节稳定性的生物力学比较*

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摘要
背景：人工肱骨头置换是治疗复杂的肱骨近端骨折的有效手段之一，对疼痛的缓解效果也较好，但最终的功能恢复结果却难以预料。
目的：对比人工肱骨头置换中以解剖方式和以重叠方式对大结节进行固定后的生物力学稳定性。
方法：取材8对16个肩关节尸体标本，按左右侧配对分为解剖重建组和重叠重建组。解剖重建组标本中的大、小结节按解剖位置复位固定；重叠重建组在保证大、小结节与肱骨头假体相对位置正常的前提下将大小结节与肱骨干进行重叠方式固定(重叠5 mm)。两组标本均使用相同的缝合线和相同的固定方式进行固定。
结果与结论：当肱骨干外旋至中立位时，解剖重建组标本的平均位移低于重叠重建组($P < 0.05$)。当肱骨干前屈至30°和60°(相当于肩关节前屈45°和90°)时，解剖重建组的位移与重叠重建组无显著差异。结果提示，在采用重叠方式对大结节进行固定，虽然增加了骨-骨之间的接触面积，但在抗外旋稳定性上可能出现损失。即便按照术后标准康复程序进行被动活动，大结节相对于肱骨干的位移还是比较显著。因此在应用人工肱骨头置换治疗肱骨近端骨折时应适当推迟术后开始被动功能锻炼的时间。

关键词：人工肱骨头；肩关节；关节置换；生物力学；大结节
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