Am J Transl Res 2023;15(3):1953-1963
www.ajtr.org /ISSN:1943-8141/AJTR0147456

*Original Article*

# Effect of glenohumeral ligaments on posterior shoulder stabilization: a biomechanical study

Min Yi[1], Fan Yang[2], Jingjing An[3], Fuguo Huang[1]

*[1]Trauma Center, West China Hospital, Sichuan University, Chengdu 610041, Sichuan, China; [2]Department of Orthopedics, West China Hospital, Sichuan University, Chengdu 610041, Sichuan, China; [3]Department of Operating Room, West China Hospital/West China School of Nursing, Sichuan University, Chengdu 610041, Sichuan, China*

Received November 2, 2022; Accepted December 11, 2022; Epub March 15, 2023; Published March 30, 2023

**Abstract:** Objectives: To theoretically confirm that the glenohumeral ligament (GHL), specifically the inferior glenohumeral ligament (IGHL), plays an important role in posterior shoulder stability in different postures, and to provide reference for clinical diagnosis and treatment of posterior shoulder instability (PSI). Materials and Methods: In this retrospective study, bone-ligament-bone models were established in 15 fresh adult shoulder joint specimens and selective cutting was performed for analysis. The humeral head was loaded posteriorly at a central pressure of 22N using the INSTRON8874 biomechanical testing system and the load-displacement curve was plotted. The posterior displacement of the humeral head was measured after continuous cutting of the following structures: (1) complete; (2) superior glenohumeral ligament (SGHL); (3) SGHL + middle glenohumeral ligament (MGHL); (4) SGHL + MGHL + IGHL; (5) MGHL; (6) MGHL + IGHL; (7) anterior-bundle IGHL (IGHL-AB); (8) posterior-bundle IGHL (IGHL-PB); (9) IGHL. The results obtained were analyzed using the SPSS10.0 statistical software. Results: Favorable posterior stability of the complete bone-ligament-bone model was observed, with an average displacement of 11.32±3.89 mm. The displacement of SGHL and SGHL + MGHL groups was not significantly increased compared with that in the complete group ($P>0.05$). After cutting of SGHL + MGHL + IGHL, the posterior displacement of all angles increased ($P<0.05$), resulting in PSI that was manifested in dislocation or subluxation. There was no obvious increase in posterior displacement after cutting the IGHL-AB ($P>0.05$). Significantly increased posterior displacement was observed at 45° abduction after cutting the IGHL-PB compared with the complete group, but not at the 90° abduction. The posterior displacement increased obviously at both 45° and 90° abduction when the IGHL was completely cut off ($P<0.05$). Conclusions: Repairing the IGHL plays a certain role in rebuilding the posterior stability of the shoulder joint. Detecting the function of the IGHL in the abduction and external rotation positions of the shoulder joint has certain significance for diagnosing PSI.

**Keywords:** Glenohumeral ligament (GHL), superior glenohumeral ligament (SGHL), middle glenohumeral ligament (MGHL), inferior glenohumeral ligament (IGHL), anterior-bundle inferior glenohumeral ligament (IGHL-AB), posterior-bundle inferior glenohumeral ligament (IGHL-PB), load-displacement curve, glenohumeral joint, posterior shoulder instability (PSI)

## Introduction

The shoulder joint, or the glenohumeral joint, is the most flexible ball-and-socket joint of the whole body, with its joint surface covering only 1/3-1/4 of the humeral head and loose joint capsule and strong muscle groups surrounding it, all of which make the shoulder joint move in a large range that allow for movements such as flexion, extension, retraction, protraction, internal rotation, external rotation, and circumduction. Correspondingly, the humeral head is prone to dislocation or subluxation from the glenoid cavity, known as shoulder instability. The humeral head can be dislocated in all directions, with anterior and inferior dislocations more commonly seen and a relatively low incidence of posterior dislocations, accounting for only 4% of acute shoulder dislocations. Cooper first described posterior shoulder instability (PSI) as early as in 1839, and Malgaigne first reported it in bulk in 1855.

To accommodate the characteristics of shoulder motion, a number of mechanisms have played a role in constraining the posterior displacement of the humeral head. Generally speaking, the stable structures of the shoulder joint can be classified into two types: static and dynamic stability structures. The former mainly refers to the morphology of the joint capsule, ligaments, intra-articular negative pressure and glenoid cavity, while the latter refers to the muscles and tendons, especially the four muscles that make up the rotator cuff. Existing research shows that in the normal range of motion, the dynamic structure plays the main stabilizing role, while the static structure only plays a role in the limit position. Shoulder joint movement is the result of multiple mechanisms. The humeral head is prone to posterior instability and even dislocation and subluxation when the statically stable structure is diseased or defective. Therefore, it is of great significance to study the static stability structure of the shoulder joint for clinical diagnosis and treatment of patients with shoulder joint-associated diseases.

According to shoulder anatomy, the ligaments around the shoulder joint mainly consist of the glenohumeral ligament (GHL), coracohumeral ligament (CHL) and coracoacromial ligament (CAL). Of them, the CHL is the thickened part of the shoulder capsule. The GHL, which arises from the lower anterior part of the anatomical neck of the humerus and ends up inward at the supraglenoid tuberosity and glenoid lip of the glenoid, can be further divided into superior (SGHL), middle (MGHL) and inferior glenohumeral ligament (IGHL). The SGHL is thin and parallel to the long head tendon of the biceps brachii, with the upper part attached to the superior glenoid and the root of the coracoid process. The MGHL originates from the glenoid lip and scapular neck and is attached to the tubercle, with great variation. While the IGHL is triangular with its tip attached to the glenoid lip and its base mixed with the joint capsule between the subscapularis muscle and triceps brachii muscle, thickening the lower part of the shoulder joint capsule. Histological examinations reveal that the IGHL can be further classified as anterior-bundle IGHL (IGHL-AB), posterior-bundle IGHL (IGHL-PB), and Axillary Pouch. The IGHL is attached to the glenoid lip, with the IGHL-AB located in the direction of 2-4 o'clock, IGHL-PB in the direction of 7-9 o'clock, and the Axillary Pouch in between [1]. Shoulder joint stability owes to the result of multiple factors and mechanisms. There are complex interactions between dynamic and static stability structures, with the tension of the static stability structure varying from position to position. How to accurately determine the effect of a single factor without the interference from other factors is a difficulty in shoulder biomechanics research. However, PSI is a rare condition, with no research reporting the biomechanics of posterior instability in China. Accordingly, this study investigated the static effect of GHL on maintaining posterior shoulder stability by selective ligament cutting, so as to provide theoretical basis for clinical diagnosis and treatment of PSI.

## Materials and methods

### *Specimen preparation*

In this retrospective study, fresh upper extremity specimens were collected from 15 adult male corpses (age: 20-40 years, mean age: 28 years) with no shoulder injury or medical history, and no bone and soft tissue diseases as confirmed by X-ray examinations. Specimens were stored in the refrigerator at -20°C and removed 24 h before the formal experiment. We cut approximately 1/3 of the upper arm humerus with a bone saw, dissected the shoulder joint, and removed the muscles around the shoulder joint, including the superficial triceps brachii, deltoid, pectoralis major, pectoralis minor, platysma and biceps brachii (the long tendon of biceps to join the joint capsule was retained), the deep subscapularis, teres minor, supraspinatus and infraspinatus (retaining the four tendons that feed into the joint capsule), so as to establish a bone-ligament-bone model (**Figure 1A** and **1B**). This study was approved by the Ethics Committee of West China Hospital, Sichuan University.

Immediately after dissection, all specimens were refrigerated in a freezer at about 2°C. A rubber strip and a 2-kg weight (**Figure 1C**) were used to apply about 22N pressure to the center of the humeral head to the glenoid cavity, a pressure that has been shown to allow mild displacement of the humeral head without dislocation under a certain load [2].

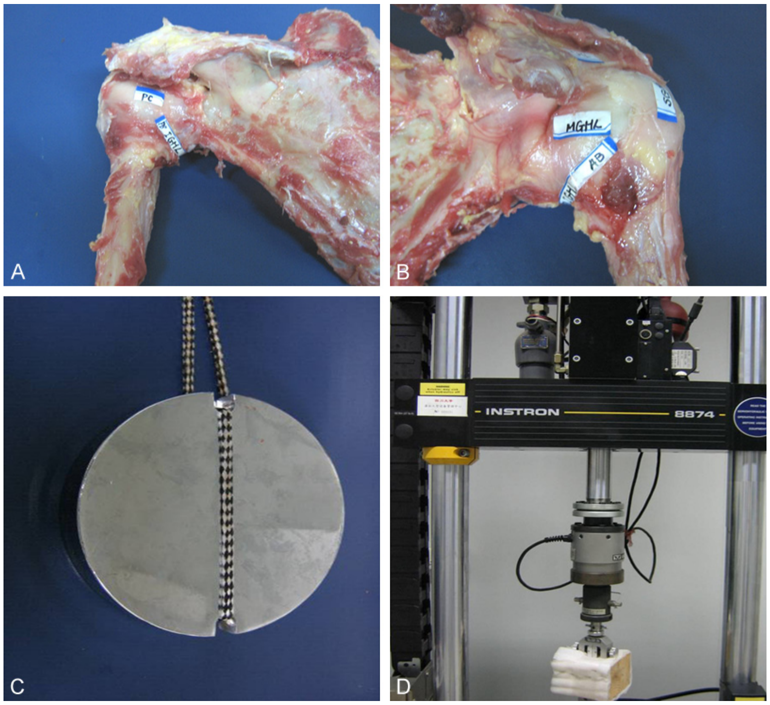



**Figure 1.** Research models and equipment. A: Posterior view of the bone-ligament-bone model. B: Anterior view of the bone-ligament-bone model. C: A 2.24-kg weight maintains a center load of 22N on the humerus head. D: INSTRON8874 Biomechanical Testing System.

*Fixation of specimens*

Four screws were used to approximately fix the scapula horizontally on a homemade scaffold, ensuring that the distal humerus was movable. The humerus was fixed to the scaffold by screws with a protractor when the humerus was 0°, 45°, and 90° from the horizontal line. A single screw was then fixed 3 cm under the greater tuberosity of the humerus and a 2.24 kg traction weight was connected with a thick wire to maintain the central load of 22N for the whole device.

*Measuring tool*

A hydraulic servo-material mechanics testing machine (INSTRON8874 Biomechanical Testing System) (**Figure 1D**) was used to carry out uniaxial tensile, compression and rotation tests; it can slowly increase the load to an ideal value within a set period of time while measuring the displacement caused by the load and drawing the load-displacement curve to evaluate the tensile resistance of the test object. The uniaxial compression test was carried out with a loading speed of 10.0 mm/min at normal temperature and pressure. A 10KN sensor was used, and the loading was stopped when the load reached 50N, an ideal load for the pretest and similar tests to allow mild displacement of the humeral head without subluxation or dislocation [3].

*Test methods and outcome measures*

1) The 15 specimens were randomized to 5 groups with 3 specimens in each group (Supplementary Table 1).

2) The shoulder with an abduction of 0°, 45° and 90° was measured for each specimen.

3) Each position was pressed from front to back with INSTRON8874. To ensure reproducibility and to eliminate other influencing factors, each force point was located at the same position of the humeral head. The lateral displacement of the humeral head was recorded, and a load-displacement curve was plotted.

4) A ligament was cut off. In case of an anatomical gap or the absence of ligaments at this site, the corresponding joint capsule documented in the literature was cut off [1]. Then Step 3 was repeated.

5) Step 3 was repeated after sequentially excising the next ligament.

*Statistical methods*

Step 1 of all specimens was unified into one group, and the other steps were grouped independently, with 9 groups of data in total. First, the SPSS10.0 statistical software was used to analyze the test data. Analysis of variance (ANOVA) was applied for the comparison between groups among three abducent angles, followed by the LSD method to perform pairwise comparisons if statistical significance ($P<0.05$) was present in the former test.

**Table 1.** Between- and within-group ANOVA for the abducent angle at 0°, 45° and 90°

| | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| Between Groups | 0° | 31.495 | 8 | 3.937 | 0.326 | 0.950 |
| | 45° | 457.622 | 8 | 57.203 | 3.915 | 0.003 |
| | 90° | 453.621 | 8 | 56.703 | 2.454 | 0.036 |
| Within Groups | 0° | 362.818 | 30 | 12.094 | | |
| | 45° | 438.315 | 30 | 14.610 | | |
| | 90° | 693.183 | 30 | 23.106 | 693.183 | 30 |
| Total | 0° | 394.313 | 38 | | | |
| | 45° | 895.937 | 38 | | | |
| | 90° | 1146.804 | 38 | | | |

**Table 2.** Original test results of group 1 specimens (unit: mm)

| | Abducent angle | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|
| Complete | 0° | 13.15 | 13.15 | 10.80 |
| | 45° | 11.32 | 11.32 | 9.16 |
| | 90° | 9.82 | 9.49 | 6.99 |
| After cutting off SGHL | 0° | 17.64 | 13.32 | 12.48 |
| | 45° | 12.32 | 12.65 | 14.65 |
| | 90° | 8.49 | 8.82 | 9.32 |
| After cutting off SGHL + MGHL | 0° | 13.15 | 13.49 | 10.32 |
| | 45° | 12.82 | 13.15 | 10.66 |
| | 90° | 10.32 | 10.15 | 8.65 |
| After cutting off SGHL + MGHL + IGHL | 0° | 14.15 | 12.15 | 12.32 |
| | 45° | 11.15 | 7.81 | 10.16 |
| | 90° | 19.64 | 17.81 | 22.64 |

SGHL: Superior Glenohumeral Ligament, MGHL: Middle Glenohumeral Ligament, IGHL: Inferior Glenohumeral Ligament.

## Results

*Comparison between- and within-groups by ANOVA*

The outcome of ANOVA between and within groups for the three abducent angles (0°, 45° and 90°) is as follows.

The *P* value of ANOVA between groups was greater than 0.05 for 0° abduction (**Table 1**), indicating no significant difference between the procedures at 0° abduction, which may be due to the fact that all parts of the GHL were in a relaxed state at 0° abduction with no posterior stabilizing effect. The *P* values of the other two angles were both less than 0.05 (**Table 1**), suggesting the presence of significant differences between the groups. Therefore, within-group ANOVA (LCD method) was performed only on 45° and 90° groups.

*Group 1 specimens*

*Step 1:* The complete bone-ligament-bone model had good posterior stability, with no posterior dislocation or subluxation under the afterload of 50N. The average displacements at 45° and 90° were 10.99±3.26 mm and 10.01±4.76 mm, respectively, with a mean of 11.32±3.89 mm (**Tables 2** and **3**).

Significant tension of the inferior articular capsule was observed at 45°-90° of shoulder abduction (**Figure 2A**).

*Step 2:* SGHL was cut off in front of the biceps tendon of the three specimens (**Figure 2B**). After loading, the average displacements at 45° and 90° abductions were 13.21±1.26 mm and 8.86±0.41 mm, respectively, with a mean of 12.18±2.97 mm (**Table 3**). Compared with the complete group, the *P* values of 45°

**Table 3.** Test results of group 1 specimens after sorting (unit: mm)

| Neutral abduction of shoulder joint (NR*) | 0° | 45° | 90° | Mean |
|---|---|---|---|---|
| 1. Complete | 12.98±3.05 | 10.99±3.26 | 10.01±4.76 | 11.32±3.89 |
| 2. After cutting off SGHL | 14.48±2.77 | 13.21±1.26 | 8.86±0.41 | 12.18±2.97 |
| 3. After cutting off SGHL + SGHL | 12.32±1.74 | 12.21±1.35 | 9.71±0.92 | 11.41±1.75 |
| 4. After cutting off SGHL + MGHL + IGHL | 12.87±1.11 | 9.71±1.72 | 20.03±2.44 | 14.20±4.84 |

*: NR, neutral rotation.


**Figure 2.** Stability test on group 1 specimens. A: P-direction stability test for the complete shoulder joint. B: A-direction stability test for SGHL damage at 0° abduction. C: A-direction stability test for SGHL + MGHL damage at 90° abduction. D: Posterior bundle of the inferior glenohumeral ligament. E: P-direction dislocation after GHL was completely severed. SGHL: Superior Glenohumeral Ligament.

and 90° displacement groups were 0.367 and 0.712, respectively (**Tables 4** and **5**), both of which were greater than 0.05 without statistical significance, indicating that SGHL had little relationship with posterior stability in the above positions.

*Step 3:* The MGHL was cut off at the 1-3 o'clock position above the glenoid lip, with the IGHL retained (**Figure 2C**). After loading the load backward, the average displacements at 45° and 90° abductions were 12.21±1.35 mm and 9.71±0.92 mm, respectively, with a mean of 11.41±1.75 mm (**Table 3**), which differed insignificantly compared with the complete group (**Tables 4** and **5**). It shows that the combined action of SGHL and MGHL does not contribute much to posterior stability in the above positions.

*Step 4:* Similarly, the three parts of the IGHL, i.e., IGHL-AB, IGHL-PB, and Axillary Pouch, were continued to be removed from the first group of specimens, leaving only the posterior part of the joint capsule. In this experiment, it was found in anatomy that the posterior capsule wall was thickened in the direction of 7-9 o'clock of the glenoid cavity, with its elasticity and texture obviously different from those of the surrounding capsule tissue (**Figure 2D**).

After the resection of all three parts of the GHL, it was found that the posterior stability was extremely poor, with subluxation found in specimen 3 (**Figure 2E**); the displacements at 45° and 90° abduction were 9.71±1.72 mm and 20.03±2.44 mm, respectively (mean: 14.20±4.84 mm), with the presence of a significant difference at 90° abduction (P = 0.003, **Table 5**). In addition, it was observed that the IGHL-PB was significantly strained at 90° abduction, indicating that the IGHL-PB played an important role in posterior stability at 45°-90° abduction.

*Group 2 specimens*

*Step 1:* Same results as group 1 were obtained.

*Step 2:* In the second group of specimens, MGHL was cut off at the position of 1-3 o'clock above the anterior glenoid lip (Supplementary Figure 1). The average displacements at 45° and 90° abductions were measured as

**Table 4.** Pairwise comparison (LSD method) results after variance analysis among 9 test groups at the 45° abduction angle

| (I) g | (J) g | Mean Difference (I-J) | Std. Error | Sig. |
|---|---|---|---|---|
| 1.00 | 2.00 | -2.2120 | 2.41748 | 0.367 |
| | 3.00 | -1.2153 | 2.41748 | 0.619 |
| | 4.00 | 1.2880 | 2.41748 | 0.598 |
| | 5.00 | -.5987 | 2.41748 | 0.806 |
| | 6.00 | -1.7687 | 2.41748 | 0.470 |
| | 7.00 | 2.4547 | 2.41748 | 0.318 |
| | 8.00 | -12.3120 (*) | 2.41748 | 0.000 |
| | 9.00 | -2.0087 | 2.41748 | 0.413 |
| 2.00 | 3.00 | .9967 | 3.12095 | 0.752 |
| | 4.00 | 3.5000 | 3.12095 | 0.271 |
| | 5.00 | 1.6133 | 3.12095 | 0.609 |
| | 6.00 | .4433 | 3.12095 | 0.888 |
| | 7.00 | 4.6667 | 3.12095 | 0.145 |
| | 8.00 | -10.1000 (*) | 3.12095 | 0.003 |
| | 9.00 | .2033 | 3.12095 | 0.948 |
| 3.00 | 4.00 | 2.5033 | 3.12095 | 0.429 |
| | 5.00 | .6167 | 3.12095 | 0.845 |
| | 6.00 | -.5533 | 3.12095 | 0.860 |
| | 7.00 | 3.6700 | 3.12095 | 0.249 |
| | 8.00 | -11.0967 (*) | 3.12095 | 0.001 |
| | 9.00 | -.7933 | 3.12095 | 0.801 |
| 4.00 | 5.00 | -1.8867 | 3.12095 | 0.550 |
| | 6.00 | -3.0567 | 3.12095 | 0.335 |
| | 7.00 | 1.1667 | 3.12095 | 0.711 |
| | 8.00 | -13.6000 (*) | 3.12095 | 0.000 |
| | 9.00 | -3.2967 | 3.12095 | 0.299 |
| 5.00 | 6.00 | -1.1700 | 3.12095 | 0.710 |
| | 7.00 | 3.0533 | 3.12095 | 0.336 |
| | 8.00 | -11.7133 (*) | 3.12095 | 0.001 |
| | 9.00 | -1.4100 | 3.12095 | 0.655 |
| 6.00 | 7.00 | 4.2233 | 3.12095 | 0.186 |
| | 8.00 | -10.5433 (*) | 3.12095 | 0.002 |
| | 9.00 | -.2400 | 3.12095 | 0.939 |
| 7.00 | 8.00 | -14.7667 (*) | 3.12095 | 0.000 |
| | 9.00 | -4.4633 | 3.12095 | 0.163 |
| 8.00 | 9.00 | 10.3033 (*) | 3.12095 | 0.002 |

*The mean difference is significant at the 0.05 level.

**Table 5.** Pairwise comparison (LSD method) results after variance analysis among 9 test groups at the 90° abduction angle

| (I) g | (J) g | Mean Difference (I-J) | Std. Error | Sig. |
|---|---|---|---|---|
| 1.00 | 2.00 | 1.1313 | 3.04014 | 0.712 |
| | 3.00 | .3013 | 3.04014 | 0.922 |
| | 4.00 | -10.0220(*) | 3.04014 | 0.003 |
| | 5.00 | 2.8480 | 3.04014 | 0.356 |
| | 6.00 | -6.6453 (*) | 3.04014 | 0.037 |
| | 7.00 | 2.0280 | 3.04014 | 0.510 |
| | 8.00 | -1.4220 | 3.04014 | 0.643 |
| | 9.00 | -2.6453 | 3.04014 | 0.391 |
| 2.00 | 3.00 | -.8300 | 3.92480 | 0.834 |
| | 4.00 | -11.1533 (*) | 3.92480 | 0.008 |
| | 5.00 | 1.7167 | 3.92480 | 0.665 |
| | 6.00 | -7.7767 | 3.92480 | 0.057 |
| | 7.00 | .8967 | 3.92480 | 0.821 |
| | 8.00 | -2.5533 | 3.92480 | 0.520 |
| | 9.00 | -3.7767 | 3.92480 | 0.344 |
| 3.00 | 4.00 | -10.3233 (*) | 3.92480 | 0.013 |
| | 5.00 | 2.5467 | 3.92480 | 0.521 |
| | 6.00 | -6.9467 | 3.92480 | 0.087 |
| | 7.00 | 1.7267 | 3.92480 | 0.663 |
| | 8.00 | -1.7233 | 3.92480 | 0.664 |
| | 9.00 | -2.9467 | 3.92480 | 0.459 |
| 4.00 | 5.00 | 12.8700 (*) | 3.92480 | 0.003 |
| | 6.00 | 3.3767 | 3.92480 | 0.396 |
| | 7.00 | 12.0500 (*) | 3.92480 | 0.005 |
| | 8.00 | 8.6000 (*) | 3.92480 | 0.036 |
| | 9.00 | 7.3767 | 3.92480 | 0.070 |
| 5.00 | 6.00 | -9.4933 (*) | 3.92480 | 0.022 |
| | 7.00 | -.8200 | 3.92480 | 0.836 |
| | 8.00 | -4.2700 | 3.92480 | 0.285 |
| | 9.00 | -5.4933 | 3.92480 | 0.172 |
| 6.00 | 7.00 | 8.6733 (*) | 3.92480 | 0.035 |
| | 8.00 | 5.2233 | 3.92480 | 0.193 |
| | 9.00 | 4.0000 | 3.92480 | 0.316 |
| 7.00 | 8.00 | -3.4500 | 3.92480 | 0.386 |
| | 9.00 | -4.6733 | 3.92480 | 0.243 |
| 8.00 | 9.00 | -1.2233 | 3.92480 | 0.757 |

*The mean difference is significant at the 0.05 level.

11.59±3.09 mm and 7.16±0.92 mm, respectively, with a mean of 10.76±3.69 mm (Supplementary Tables 2 and 3), which was not statistically different from that of the complete group (**Tables 4** and **5**) (P>0.05), indicating that MGHL in the above positions has little relationship with posterior stability.

*Step 3:* Similarly, the IGHL was cut off completely in the second group of specimens (Supplementary Figure 2). After loading, the posterior shoulder stability decreased significantly, and subluxation and dislocation gradually appeared when the abduction was greater than 45°. The shoulder posterior displacements at 45° and 90° abductions were 12.76±5.27 mm and 16.65±10.38 mm, respectively (mean: 13.84±6.89 mm); the displacement was not significantly different from that of the complete group at 45° (P>0.05), but a significant difference was present at 90° abduction compared with the complete group (P<0.05) and at 90° compared with the previous step (**Tables 4** and **5**), indicating that IGHL also has a posterior stabilizing effect at 90°. The above results indicate that IGHL plays an important role in stabilizing the posterior shoulder joint when the abduction is 45°-90°.

*Group 3 specimens (simple cutting-off of the IGHL-AB)*

*Step 1:* Same results as group 1 were obtained.

*Step 2:* In the third group of large specimens, only IGHL-AB was cut off (Supplementary Figure 3); the average displacements at 45° and 90° abductions after loading were 8.54±0.86 mm and 7.98±0.74 mm, respectively, with a mean of 10.74±5.17 mm (Supplementary Tables 4 and 5), showing no evident differences compared with the complete group at both 45° and 90° (P>0.05). It confirms that the IGHL-AB has no posterior stabilizing effect in the above positions.

*Group 4 specimens (simple cutting-off of the IGHL-AB)*

The abduction displacements at 0°, 45° and 90° abductions were 12.81±2.52 mm, 23.30±6.92 mm, and 11.43±5.29 mm, respectively (mean: 15.85±7.23 mm) (Supplementary Tables 6 and 7), when only the IGHL-PB was cut off (Supplementary Figure 4). Compared with the complete group, the difference was significant at 45° abduction (P< 0.05, **Table 4**) but non-significant at 90° abduction (P>0.05, **Table 5**). It is suggested that the IGHL-PB plays an important role in posterior stability at 45° abduction, but it has no marked effect on posterior stability at 90° abduction, which is different from the expected results.

*Group 5 specimens (simple cutting-off of the IGHL)*

*Step 1:* Same results as group 1 were obtained.

*Step 2:* For this group of specimens, the average 45° and 90° abduction displacements after cutting-off all the 3 parts of the IGHL (IGHL-AB, IGHL-PB, and Axillary Pouch) and loading (Supplementary Figure 5) were 13.00±7.21 mm and 12.65±5.74 mm, respectively (mean: 12.91±4.66 mm, Supplementary Tables 8 and 9), which has no statistical difference compared with the complete group (**Tables 4** and **5**). However, it is significantly different from the average value of the complete displacement of the three specimens in this group, which may be due to individual differences and anatomical variation. The above data partially indicate that the IGHL-PB has a stabilizing effect on the posterior shoulder joint when the shoulder abduction is greater than 45°.

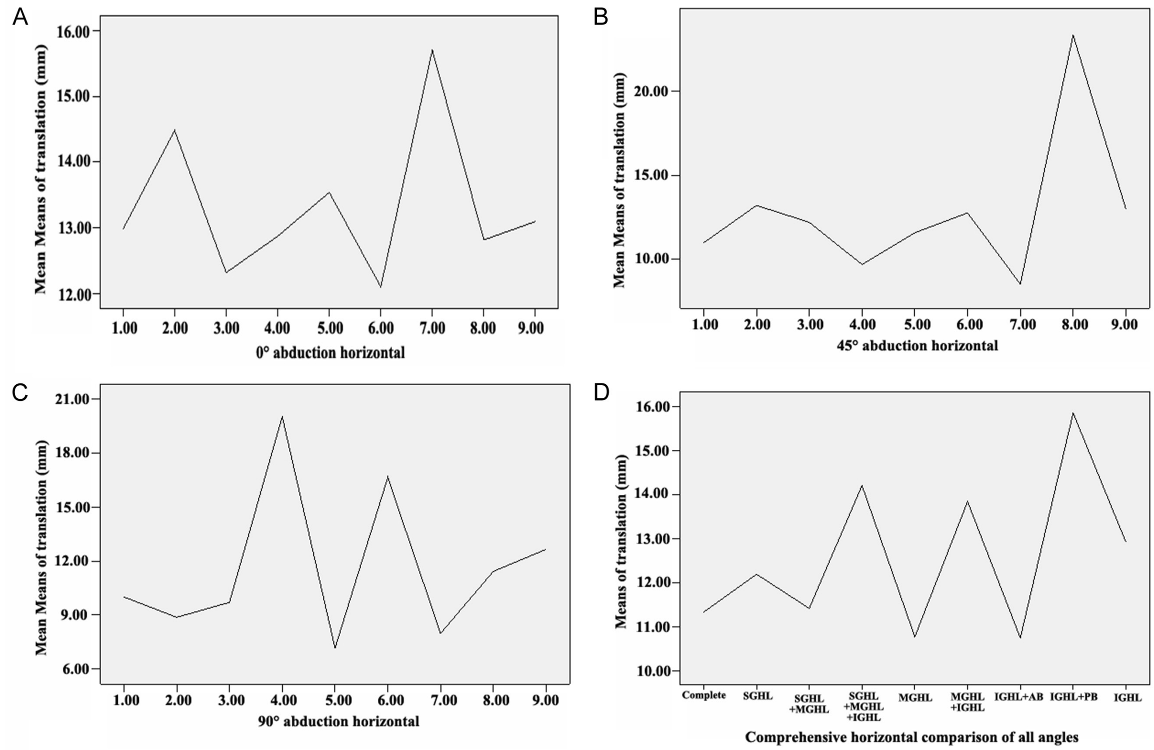
*Horizontal comparison*

The horizontal comparison of all groups showed that at 45° abduction, the posterior displacement of the IGHL-PB group was the largest, reaching 23.30±6.92 mm (**Figure 3A** and **3B**); while at 90° abduction, the SGHL + MGHL + IGHL group had the largest posterior displacement, reaching 20.03±2.44 mm (**Figure 3C**), followed by MGHL + IGHL group (16.65± 10.38 mm). The displacement after the cutting off of the IGHL-PB was the largest in all groups (**Figure 3D** and **3E**), which also indicates the important role of the LGHL-PB in posterior shoulder stability.

## Discussion

*Biomechanical research on shoulder joint stability*

Selective cutting is an important method to study static structures. The principle of this method is to selectively cut off a certain structure, impose a certain load to the humeral head in a fixed direction before and after cutting off, and measure the displacement of the humeral head caused by the load, so as to judge whether the structure has the function of limiting the humeral head displacement [4]. By removing the muscles and tendons around the joint capsule, eliminating other confounding factors, and selecting suitable test instruments and fixation methods, the stress of shoulder joint in extreme position can be truly simulated. The purpose of this method is to determine the stabilizing effect of a single static structure without interference of other factors, and to explain the clinical mechanism of multidirectional shoulder instability. Our experimental



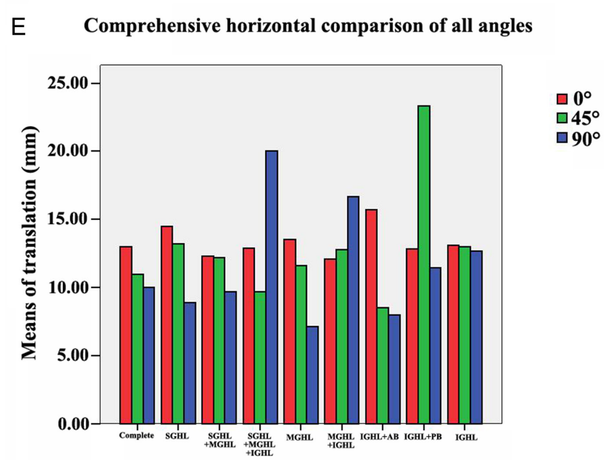




**Figure 3.** Abduction horizontal comparison results. A: 0° abduction horizontal comparison results. B: 45° abduction horizontal comparison results. C: 90° abduction horizontal comparison results. D: Comprehensive horizontal comparison of all angles. E: Comprehensive horizontal comparison of all angles.

results show that this method is effective in evaluating the stabilization effect of a static structure on shoulder joint when other interfering factors are excluded as much as possible. Compared with the previous research methods of measuring structural damage after violent impact, this test can more intuitively simulate the clinical situation of shoulder instability, which is an effective static biomechanical research method.

*Role of SGHL in posterior shoulder stability*

The SGHL is the most common of the three GHLs, originating from the anterior upper portion of the glenoid lip, which is oriented obliquely downward and parallel to the long head tendon of the biceps brachii. Depalma [4] found that the starting points of SGHL in 73 of the 96 specimens were initially attached to the MGHL, biceps tendon and glenoid lip, while 20 were attached to the biceps tendon and glenoid lip, 2 to the MGHL, IGHL and glenoid lip, and 2 were missing. Most of the stops are located in the small tubercle that is closely related to the CHL; this ligament runs from the outside to the inside of the joint, like the femoral head ligament, resulting in the fact that the ligament is not visible in the joint capsule.

This research showed that the SGHL had no obvious effect on the posterior stability at all abduction angles in the rotationally neutral position, nor was there any obvious tension of the SGHL during the experiment. However, since INSTRON8874 can only provide two-dimensional plane load instead of multi-dimensional shoulder joint movement positions, it remains to be defined whether the SGHL has a posterior stabilizing effect in other positions. In experiments similar to ours, O'Connell [5] measured the A-direction pressure, strain and stress of the GHL and CHL in a three-angle, external rotation position using the TTC Instron Universal three-dimensional testing device, an instrument that can provide a fixed torque to the humeral head. It is concluded that SGHL and MGHL provide the maximum anterior support at 0° abduction. Warner et al. [6] also validated that the SGHL was the most important factor to maintain the stability of the lower shoulder joint at 0° abduction, whilst the tension of this ligament can be observed. The superior articular capsule ligament and the CHL play a major role in maintaining posterior stability during shoulder adduction, whereas if the SGHL is absent or dysplastic, the CHL takes over. Bowen et al. [7] suggested that when the upper limb was in the anteflexion position, the upper joint capsule and rotator cuff were responsible for PSI.

*Role of MGHL in PSI*

The MGHL starts from the glenoid lip and scapular neck, runs below the SGHL, and attaches to the tubercle, with a close relationship with the subscapular tendon and the position, attachment point, width and thickness varying the most among the three parts of the GHL. Depalma [4] reported that among the 96 cases, the MGHL was obviously present in 68 cases, not obviously present in 16 cases, and absent in 12 cases. Snyder et al. [8] reported a hammock-like MGHL that was attached to the biceps tendon instead of the anterior and superior glenoid lip.

This trial showed that simple damage to the MGHL did not cause a significant increase in the posterior displacement of the humeral head at all shoulder abduction angles, suggesting that the MGHL cannot stabilize the posterior part in a rotationally neutral position.

The MGHL has been suggested to be most important for the anterior stability of the shoulder joint, because it is located in the lower anterior part of the joint capsule with many variations. When thickened, it becomes the most important stabilizing structure to compensate for the partial functions of the SGHL and IGHL. Turkel et al. [9] believed that the MGHL and the IGHL-AB were the main stabilizing structures in front of the shoulder joint when the abduction was less than 45 degrees. Ovesen et al. [10] demonstrated that the MGHL played an anterior stabilizing role when the shoulder abduction was 70°-90°. As described above, O'Connell et al. [5] argued that 0° abduction contributed to the important role of the MGHL. Ovesen et al. [10] also believed that when shoulder abduction was 0°-40°, the anterior rotator cuff and the anterior joint capsule (part of the MGHL) also contribute to the posterior instability, suggesting that the joint capsule as a whole and its parts could compensate for each other's stability.

*Role of IGHL in posterior shoulder stability*

Recent studies have shown that the IGHL, which runs from the glenoid and glenoid lip to the anatomical neck of the humerus, is not a complete structure but a complex. O'brien et al. [1] divided the IGHL into three parts: IGHL-BD, IGHL-PB, and Axillary Pouch in the middle. The three parts were composed of painless fiber bundles as observed by histology and anatomic microscopy. The attachment point of the IGHL in the humeral neck varies widely. Part of the semicircular collar of the IGHL is attached below the attachment point of the humeral joint capsule (slightly below the surgical neck of the humerus), and the other part is attached in a "V" shape, with the Axillary Pouch at the apex of the V. Internal or external rotation is easily observed during shoulder abduction. The attachment points of the IGHL on the glenoid lip are located at 2-4 o'clock in the anterior part and 7-9 o'clock in the posterior part, with the Axillary Pouch, a hammock-like structure, lying between them. In this study, significant thickening at 6-8 o'clock-direction was also observed in the posterior part of the shoulder capsule, which increased with the abduction tension of the shoulder joint. However, it was absent in 3 (20%) of the 15 specimens. For specimens without significant anatomical variation, the lower third of the posterior articular capsule was cut off. McGlynn et al. [11] found that glenoid labrum tear without IGHL injury would not cause anterior dislocation, but simple inferior ligament tear can.

This study showed that the IGHL was in a relaxed state at 0° abduction, with the tension increased as the abduction increased. At 90° abduction, the anterior, posterior bundle and Axillary Pouch of the IGHL were obviously stretched and tense. After selective cutting of the IGHL-PB, the posterior displacement was obviously increased, even with the appearance of posterior subluxations and dislocations. This suggests that the IGHL-PB plays a very important role that is greater than MGHL in the posterior stability when the abduction of the shoulder joint is more than 45°.

*Influence of other static structures*

In addition to ligaments, other structures also have static effects. There is a glenoid lip around the glenoid to increase the glenoid fossa depth; the glenoid is slightly backward, and the line perpendicular to the glenoid fossa is the glenoid centerline [12, 13], which forms an angle of 10° with the scapular axis under normal circumstances. This study also found that the cutting off of all the GHLs can easily lead to anterior dislocations, while it had little influence on posterior dislocations, which may be related to this angle. In addition, the glenohumeral joint is not the only important joint structure between the scapula and the humerus [14, 15]. The coracoacromial arch, sternoclavicular joint, acromioclavicular joint, scapular-chest wall connection, and subacromial mechanism all have stabilizing effects on shoulder joint. All of the above factors may influence the test results to a certain extent.

Moreover, there are some shortcomings in the study. First of all, the sample size of this study is small, so more cadaver samples and different degrees of central pressure are needed for further research. In addition, all the included specimens had no shoulder injuries or medical history, nor bone and soft tissue diseases confirmed by X-rays. While actually, ligament injury itself will have a certain impact on the stability of the shoulder joint. Thus, we will include more specimens with different conditions for comparison in subsequent studies.

## Conclusion

In conclusion, the IGHL is the main static structure that maintains the posterior stability of the shoulder joint in extreme positions. The SGHL and MGHL do not limit the posterior displacement of the humeral head in the rotationally neutral position of the shoulder joint. The IGHL-PB is the most important static structure in shoulder rotationally neutral position at 45°-90° abduction. Clinically, IGHL function examination can reveal the posterior instability of the shoulder joint, and reconstruction of IGHL function is of great significance for the clinical treatment of PSI.

## Disclosure of conflict of interest

None.

**Address correspondence to:** Fuguo Huang, Trauma Center, West China Hospital, Sichuan University, Chengdu 610041, Sichuan, China. Tel: +86-028-85422114; E-mail: huang-f-g@163.com

## References

[1] O'Brien SJ, Neves MC, Arnoczky SP, Rozbruck SR, Dicarlo EF, Warren RF, Schwartz R and Wickiewicz TL. The anatomy and histology of the inferior glenohumeral ligament complex of the shoulder. Am J Sports Med 1990; 18: 449-456.
[2] Speer KP, Deng X, Borrero S, Torzilli PA, Altchek DA and Warren RF. Biomechanical evaluation of a simulated Bankart lesion. J Bone Joint Surg Am 1994; 76: 1819-1826.
[3] Curl LA and Warren RF. Glenohumeral joint stability: selective cutting studies on the static capsular restraints. Clin Orthop Relat Res 1996; 54-65.
[4] DePalma AF. Surgery of the shoulder. Surg the shoulder. 1950. p. xix, 437.
[5] O'Connell PW, Nuber GW, Mileski RA and Lautenschlager E. The contribution of the glenohumeral ligaments to anterior stability of the shoulder joint. Am J Sports Med 1990; 18: 579-584.
[6] Warner JJ, Deng XH, Warren RF and Torzilli PA. Static capsuloligamentous restraints to superior-inferior translation of the glenohumeral joint. Am J Sports Med 1992; 20: 675-685.
[7] Bowen MK and Warren RF. Ligamentous control of shoulder stability based on selective cutting and static translation experiments. Clin Sports Med 1991; 10: 757-782.

[8] Snyder SJ, Karzel RP, Del Pizzo W, Ferkel RD and Friedman MJ. SLAP lesions of the shoulder. Arthroscopy 1990; 6: 274-279.

[9] Turkel SJ, Panio M, Marshall J and Girgis FG. Stabilizing mechanisms preventing anterior dislocation of the glenohumeral joint. J Bone Joint Surg Am 1981; 63: 1208-1217.

[10] Ovesen J and Nielsen S. Anterior and posterior shoulder instability: a cadaver study. Acta Orthop Scand 1986; 57: 324-327.

[11] McGlynn FJ and Caspari RB. Arthroscopic findings in the subluxating shoulder. Clin Orthop Relat Res 1984; 173-178.

[12] Harryman DT 2nd, Sidles JA, Clark JM, McQuade KJ, Gibb TD and Matsen FA 3rd. Translation of the humeral head on the glenoid with passive glenohumeral motion. J Bone Joint Surg Am 1990; 72: 1334-1343.

[13] Blasier RB, Soslowsky LJ, Malicky DM and Palmer ML. Posterior glenohumeral subluxation: active and passive stabilization in a biomechanical model. J Bone Joint Surg Am 1997; 79: 433-440.

[14] Pagnani MJ, Warren RF, Altchek DW, Wickiewicz TL and Anderson AF. Arthroscopic shoulder stabilization using transglenoid sutures: a four-year minimum followup. Am J Sports Med 1996; 24: 459-467.

[15] Ovesen J and Nielsen S. Posterior instability of the shoulder: a cadaver study. Acta Orthop Scand 1986; 57: 436-439.

**Supplementary Table 1.** Specimen grouping and operation procedures

| Groups | Specimen No. | Operating procedures |
|---|---|---|
| 1 | 1-3 | Step 1: complete model loading and after-loading |
| | | Step 2: loading and after-loading following cutting off SGHL |
| | | Step 3: loading and after-loading following cutting off SGHL + MGHL |
| | | Step 4: loading and after-loading following cutting off SGHL + MGHL + IGHL |
| 2 | 4-6 | Step 1: complete model loading and after-loading |
| | | Step 2: loading and after-loading following cutting off MGHL |
| | | Step 3: loading and after-loading following cutting off MGHL + IGHL |
| 3 | 7-9 | Step 1: complete model loading and after-loading |
| | | Step 2: loading and after-loading following cutting off IGHL-AB |
| 4 | 10-12 | Step 1: complete model loading and after-loading |
| | | Step 2: loading and after-loading following cutting off IGHL-PB |
| 5 | 13-15 | Step 1: complete model loading and after-loading |
| | | Step 2: loading and after-loading following cutting off IGHL |

**Supplementary Figure 1.** P-direction stability test for MGHL damage at 45° abduction.

**Supplementary Table 2.** Original test results of group 2 specimens (unit: mm)

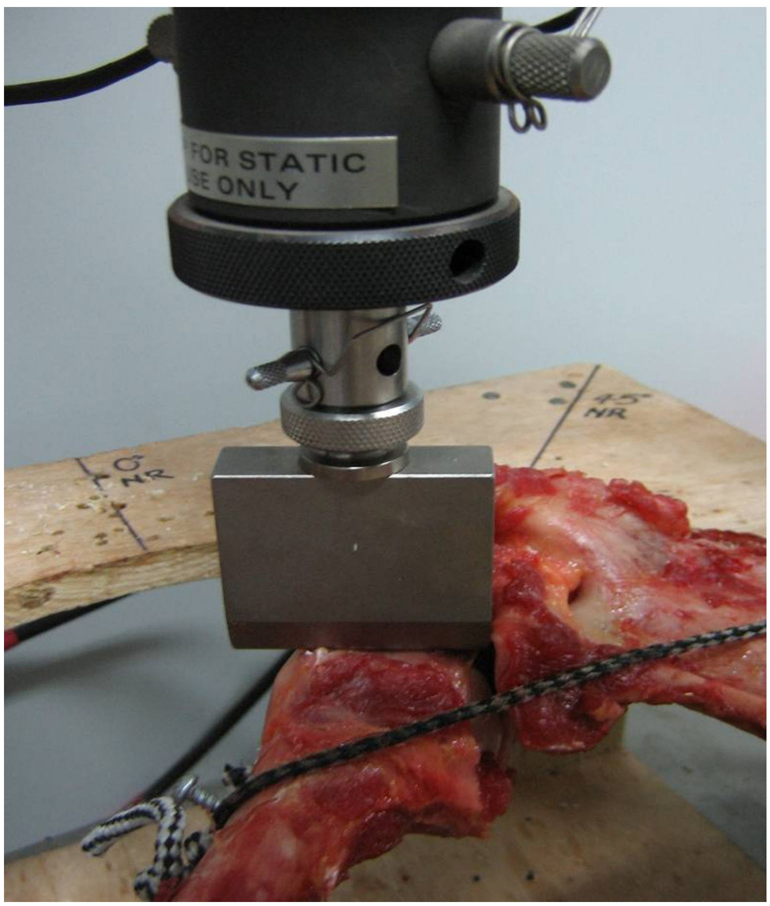
| | Abducent angle | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|
| Complete | 0° | 11.64 | 12.98 | 13.32 |
| | 45° | 9.65 | 13.31 | 8.98 |
| | 90° | 18.64 | 5.66 | 5.66 |
| After cutting off MGHL | 0° | 14.31 | 12.32 | 13.99 |
| | 45° | 11.98 | 14.48 | 8.32 |
| | 90° | 10.82 | 6.66 | 4.00 |
| After cutting off MGHL + IGHL | 0° | 15.32 | 15.82 | 5.17 |
| | 45° | 12.15 | 18.32 | 7.82 |
| | 90° | 10.66 | 28.64 | 10.66 |

**Supplementary Table 3.** Test results of group 2 specimens after sorting (unit: mm)

| Neutral abduction of shoulder joint (NR*) | 0° | 45° | 90° | Mean |
|---|---|---|---|---|
| 1. Complete | 12.98±3.05 | 10.99±3.26 | 10.01±4.76 | 11.32±3.89 |
| 2. After cutting off MGHL | 13.54±1.07 | 11.59±3.09 | 7.16±0.92 | 10.76±3.69 |
| 3. After cutting off MGHL + IGHL | 12.10±6.01 | 12.76±5.27 | 16.65±10.38 | 13.84±6.89 |

*: NR, neutral rotation.

**Supplementary Figure 2.** Joint cutting of MGHL + IGHL.




**Supplementary Figure 3.** Posterior stability test of simple IGHL-AB injury at 45° abduction.

**Supplementary Table 4.** Original test results of group 3 specimens (unit: mm)

| | Abducent angle | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|
| Complete | 0° | 9.48 | 13.82 | 14.98 |
| | 45° | 12.82 | 9.79 | 10.65 |
| | 90° | 18.64 | 7.99 | 7.82 |
| After cutting off IGHL-AB | 0° | 23.80 | 12.49 | 10.82 |
| | 45° | 7.82 | 9.49 | 8.31 |
| | 90° | 7.45 | 7.66 | 8.83 |

**Supplementary Table 5.** Test results of group 3 specimens after sorting (unit: mm)

| Neutral abduction of shoulder joint (NR*) | 0° | 45° | 90° | Mean |
|---|---|---|---|---|
| 1. Complete | 12.98±3.05 | 10.99±3.26 | 10.01±4.76 | 11.32±3.89 |
| 2. After cutting off IGHL-AB | 15.70±7.06 | 8.54±0.86 | 7.98±0.74 | 10.74±5.17 |

*: NR, neutral rotation.

**Supplementary Table 6.** Original test results of group 4 specimens (unit: mm)

| | Abducent angle | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|
| Complete | 0° | 17.48 | 16.81 | 14.98 |
| | 45° | 19.48 | 10.31 | 14.15 |
| | 90° | 10.49 | 18.98 | 5.49 |
| After cutting off IGHL-PB | 0° | 15.65 | 11.98 | 10.82 |
| | 45° | 25.14 | 29.13 | 15.65 |
| | 90° | 15.65 | 13.15 | 5.49 |

**Supplementary Table 7.** Test results of group 4 specimens after sorting (unit: mm)

| Neutral abduction of shoulder joint (NR*) | 0° | 45° | 90° | Mean |
|---|---|---|---|---|
| 1. Complete | 12.98±3.05 | 10.99±3.26 | 10.01±4.76 | 11.32±3.89 |
| 2. After cutting off IGHL-PB | 12.81±2.52 | 23.30±6.92 | 11.43±5.29 | 15.85±7.23 |

*: NR, neutral rotation.


**Supplementary Figure 4.** Anterior stability test of simple IGHL-PB injury at 45° abduction.


**Supplementary Figure 5.** Anterior stability test of IGHL at 90° abduction.

**Supplementary Table 8.** Original test results of group 5 specimens (unit: mm)

| | Abducent angle | Specimen 1 | Specimen 2 | Specimen 3 |
|---|---|---|---|---|
| Complete | 0° | 5.49 | 15.65 | 10.98 |
| | 45° | 7.16 | 11.49 | 5.33 |
| | 90° | 8.49 | 7.64 | 8.32 |
| After cutting off IGHL | 0° | 9.66 | 13.32 | 16.31 |
| | 45° | 5.88 | 20.31 | 12.82 |
| | 90° | 6.83 | 18.31 | 12.82 |

**Supplementary Table 9.** Test results of group 5 specimens after sorting (unit: mm)

| Neutral abduction of shoulder joint (NR*) | 0° | 45° | 90° | Mean |
|---|---|---|---|---|
| 1. Complete | 12.98±3.05 | 10.99±3.26 | 10.01±4.76 | 11.32±3.89 |
| 9. After cutting off IGHL | 13.09±3.33 | 13.00±7.21 | 12.65±5.74 | 12.91±4.66 |

*: NR, neutral rotation.