



Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

The effect of subscapularis muscle contraction on coaptation of anteroinferior glenohumeral ligament–labrum complex after Bankart repair [☆]



Yoshiaki Itoigawa ^{a,1}, Alexander W. Hooke ^a, John W. Sperling ^b, Scott P. Steinmann ^b, Kristin D. Zhao ^c, Eiji Itoi ^d, Kai-Nan An ^a

^a Division of Orthopedic Research, Mayo Clinic, Rochester, MN, United States

^b Department of Orthopedic Surgery, Mayo Clinic, Rochester, MN, United States

^c Department of Physical Medicine and Rehabilitation, Mayo Clinic, Rochester, MN, United States

^d Department of Orthopaedic Surgery, Tohoku University School of Medicine, Sendai, Japan

ARTICLE INFO

Article history:

Accepted 10 January 2019

Keywords:

Bankart repair
Dislocation
Rehabilitation
Shoulder
Subscapularis

ABSTRACT

Facilitation of healing is important for the anteroinferior glenohumeral ligament–labrum complex (AIGHL-LC) after Bankart repair in shoulder dislocation. The purpose of this study was to investigate the effect of subscapularis muscle loading on contact area and contact pressure between the subscapularis and AIGHL-LC and between the glenoid bone and the AIGHL-LC following Bankart repair. Twenty-two fresh-frozen cadaveric shoulders were used. They were attached to a shoulder-positioning device to which a compression force was applied. Loads applied to the supraspinatus, infraspinatus, and teres minor tendons were held constant. The loads applied to the subscapularis tendon were set at 0, 10, 20, and 30 Newton (N). Contact pressure and area between the subscapularis and the AIGHL-LC were measured with the arm at 4 rotational positions: 60° and 30° internal, neutral, and 30° external. After the Bankart lesion was created, the contact area and pressure between the AIGHL-LC and glenoid bone were measured while Bankart repair was performed with or without loading of the subscapularis. The contact area and pressures with 10, 20, and 30 N of subscapularis loadings were significantly greater than with 0 N of subscapularis loading at 60° internal rotation and 30° external rotation ($P < .05$). After Bankart repair, contact area and pressure with subscapularis loading between the AIGHL-LC and glenoid bone were significantly greater than without subscapularis loading ($P < .01$). We conclude that isometric contraction exercises of the subscapularis might facilitate healing of the AIGHL-LC after Bankart repair.

© 2019 Elsevier Ltd. All rights reserved.

1. Introduction

Arthroscopic Bankart repair with suture anchors has become a standard treatment of recurrent anterior shoulder dislocation. Many authors have advocated specific surgical technical aspects, including repair of the labrum several millimeters onto the glenoid articular surface (Carreira et al., 2006; Kim et al., 2003a; Mazzocca et al., 2005; Rhee et al., 2006) or at the articular edge (Kim et al.,

2008; Magit et al., 2008) and double-row fixation (Iwaso et al., 2011; Lafosse et al., 2006). However, the best technique is unclear. Two studies biomechanically determined the footprints of double-row and single-row repairs using cadaveric shoulders and reported that the contact area of double-row repair was wider than single-row repair (Ahmad et al., 2009; Kim et al., 2011). Yet, in these studies, all muscles and tendons were removed. In vivo, the anterior labrum anatomically contacts the subscapularis (DeFranco and Cole, 2009). Therefore, muscle contraction of the subscapularis may affect the anterior labrum, including the repaired Bankart lesion. It may be involved in not only the surgical technique but also the rehabilitation after Bankart repair. This also has not been clarified.

The number of patients treated nonoperatively for recurrent anterior shoulder instability has increased in the past 3 decades

Abbreviations: AIGHL-LC, anteroinferior glenohumeral ligament–labrum complex; N, Newton.

[☆] Portions of this manuscript were presented in abstract form at the Orthopedic Research Society Meeting, New Orleans, Louisiana, March 15–18, 2014.

¹ Present address: Department of Orthopaedic Surgery, Juntendo University School of Medicine, Tokyo, Japan.

E-mail address: an.kainan@mayo.edu (K.-N. An)

<https://doi.org/10.1016/j.jbiomech.2019.01.023>

0021-9290/© 2019 Elsevier Ltd. All rights reserved.

(Hovelius et al., 1996, 1983; Tsai et al., 1991). Surgical treatment is effective (Bottoni et al., 2006), but nonoperative treatment is preferred. External rotation bracing is a new nonoperative method for treatment of anterior shoulder dislocations (Itoi et al., 2003, 2007, 1999, 2001). Itoi et al (2003, 2007) have suggested that immobilization in external rotation can substantially decrease recurrent instability after anterior shoulder dislocation. In a previous study, Itoi et al. (1999) removed all the rotator cuff muscles and observed the approximation and separation of the Bankart lesion on cadaveric shoulders. Moreover, they postulated that the labrum was returned to the glenoid rim in external rotation because of the tight anterior shoulder soft tissue, and this may reduce the risk of hematoma on the glenoid neck, as well as improve healing of the Bankart lesion, in clinical studies with magnetic resonance imaging (Itoi et al., 2001). That the anterior labrum be pressed by subscapularis tendon appears important, but this detail has not been clarified.

It is important to enhance healing of the labrum and glenoid bone for both the surgical and nonsurgical treatment. Some studies have reported investigations of contact pressure and footprint area to compare surgical techniques for rotator cuff repair (Park et al., 2005; Tuoheti et al., 2005). They have shown that maximization of the footprint's contact area and pressure exposes more of the tendon to the bone and improves the healing potential. A major complication of treatment of the anterior shoulder instability is a recurrence of instability, similar to rotator cuff repair. Therefore, it is clinically important to investigate the contact pressure and area around the Bankart lesion and the footprint after the Bankart repair. In addition, during conservative treatment, Miller et al (2004) reported that external rotation significantly increased the contact pressure between the anterior labrum and the glenoid bone. However, we still do not know whether this increase is caused by the subscapularis muscle tension or something else. We need to know the contact both between the labrum and the bone and between the labrum and the subscapularis muscle. The present study was designed to test the hypothesis that arm position and subscapularis muscle contraction affect the contact area and pressure between the subscapularis and the anteroinferior glenohumeral ligament–labrum complex (AIGHL-LC) and between the complex and the glenoid bone. On this basis, we investigated the effect of arm position and subscapularis muscle contraction on the anterior labrum by measuring contact area and pressure between the subscapularis and the AIGHL-LC. We then examined the effect of subscapularis loading on the contact area and contact

pressure between the AIGHL-LC and the glenoid following Bankart repair.

2. Materials and methods

2.1. Specimen Preparation

This study was approved by our institutional Biospecimen Committee. Twenty-two fresh-frozen shoulders were obtained from 19 cadavers (sex, 10 male and 9 female) (mean age of decedents, 68.9 years). Shoulders were screened for rotator cuff tears and radiologic evidence of moderate to severe glenohumeral osteoarthritis. The subcutaneous soft tissues were dissected away, except for the rotator cuff muscles. The subscapularis muscle and tendon were separated carefully from the anterior capsule and divided into superior and inferior portions (Fig. 1). A fiberglass rod was cemented into the medullary canal of the humeral shaft. The humeral rod and the scapula were secured in a custom-designed shoulder experimental device. Before the humerus was cut, a k-wire was passed through the midhumerus (proximal to where it was cut) parallel to the axis passing through the epicondyles. The intersections of this k-wire and the humerus were used as references for coordinate system definition. The device locked out all rotational and translational degrees of freedom during testing. The scapula was anteriorly protracted by 30° with reference to the coronal plane. Therefore, the neutral rotation was defined as the position at which the center of the bicipital groove was externally rotated 30° from the scapular plane (Carreira et al., 2006). We attached cables to the tendons of the superior subscapularis, inferior subscapularis, supraspinatus, infraspinatus, and teres minor muscles to load the rotator cuff muscles with a weight-and-pulley system (Muraki et al., 2010).

2.2. Measurement of contact area and pressure

2.2.1. Between subscapularis and AIGHL-LC while changing subscapularis rotation angle and loading

Measurement devices. Contact pressure and area were measured between the subscapularis and the AIGHL-LC with a pressure sensor (I-Scan System model 4000; Tekscan, Inc). According to the previous studies, the Tekscan resistive-based sensor system has been validated as adequate for determination of the pressure distribution under contact conditions with soft materials (Luo et al.,

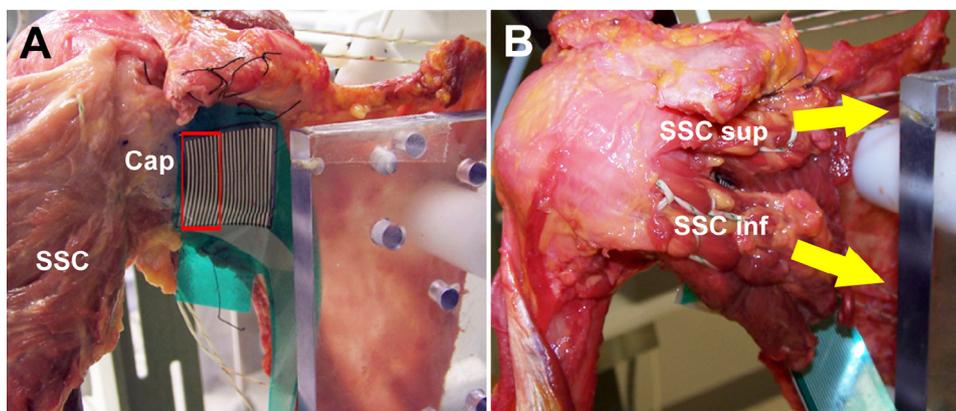


Fig. 1. Anterior View of a Right Shoulder. (A) The subscapularis (SSC) muscle and tendon were separated from the anterior capsule (cap), and the clear K-Scan sensor pad was placed between the SSC tendon and anterior cap on the glenoid. The region of interest was the anteroinferior glenohumeral ligament–labrum complex (red box). (B) The SSC muscle and tendon were divided into superior (sup) and inferior (inf) portions and loaded. The yellow arrows indicate the directions of loading for the subscapularis muscle and tendon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

1998). The model 4000 sensor also has been used previously to measure the pressure of a similar range in our shoulder study (Yamamoto et al., 2009). When the loads ranging from 0.1 to 20 N were applied in this experimental setup, the mean accuracy of this sensor was 3.94% and repeatability was 1.26% (Yamamoto et al., 2009). The anterior capsule including the glenohumeral ligament was attached to the anterior labrum, and the labrum was attached to the glenoid bone. The I-Scan sensor pad was placed carefully between the tendon of the subscapularis muscle and AIGHL-LC on the glenoid (Fig. 1A). The anterior capsule covered the anterior labrum from the anterior view of the shoulder specimen, and therefore the shape of the labrum was determined while it was touching the capsule. Pressure and contact area on the AIGHL-LC were recorded between the medial border of the anterior capsular attachment to the labrum and the labral attachment to the glenoid neck (Fig. 1A, red box). The sensor was fixed rigidly to the soft tissue on the glenoid bone with 4 sutures—2 superiorly and 2 inferiorly. The glenohumeral joint angle was monitored and measured with an electromagnetic tracking system (Liberty; Polhemus, Inc) and the MotionMonitor software (Innovative Sports Training, Inc). The electromagnetic Polhemus system has a static accuracy of 0.8 mm and an angular accuracy of 0.15°. This device can measure the 3-dimensional position and orientation of the sensors relative to the absolute coordinate system generated by the magnetic transmitter (Wu et al., 2005). The sampling frequency was 120 Hz. Data were analyzed with the MotionMonitor software and MATLAB (The MathWorks, Inc). Sensors were fixed solidly to the hard bones of the scapula and humerus.

Testing procedure. First, a compressive force of 22 Newton (N) was applied to the humeral head against the glenoid fossa through the cables attached to the superior subscapularis (5 N) and inferior subscapularis (5 N) (total force, 10 N), supraspinatus (4 N), infraspinatus (6 N), and teres minor (2 N) tendons with pulleys and weights to keep the humeral head centered in the glenoid fossa. The muscle loadings were selected on the basis of the relative size of muscle physiologic cross-sectional areas (Bassett et al., 1990). The resulting compressive loading of 22 N was indeed relatively low compared with what is experienced in vivo. However, this is the compromised loading that has been used extensively in the previous studies described in the literature (Limpisvasti et al., 2008; Omi et al., 2010; Warner et al., 1998) to capture the characteristics of the biomechanical behavior of the shoulder joint but without damage to the soft tissue during experiments. The cables were attached to the tendon with the Krackow double-stitch technique (Fitoussi and Bachy, 2015) (Fig. 1). Next, while the weights of the supraspinatus, infraspinatus, and teres minor tendons were held constant, the superior and inferior subscapularis tendons were equally set at 0, 10, 20, or 30 N. Contact pressure and area were measured during the following 4 arm rotation positions: 60° internal, 30° internal, neutral, and 30° external. When we measured the contact pressure and area, only the rotations were changed; the humerus was kept in 0° of abduction and 0° of flexion.

2.2.2. Between AIGHL-LC and glenoid after Bankart repair

Pressure-sensitive film preparation. With use of pressure-sensitive films (Fujifilm Prescale Ultra Super Low Pressure; Fuji Photo Film Co Ltd), the contact area and pressure between the AIGHL-LC and the attachment site of the glenoid bone were examined on the basis of previous studies (Kim et al., 2011). For measurement of the contact area and pressure on the footprint after Bankart repair, the sensor must be cut to a specific shape and have holes added to insert the suture anchors. However, the Tekscan sensors (used to measure it between subscapularis and AIGHL-LC while changing subscapularis rotation angle and loading) cannot be cut or have holes added to them. Therefore, we used Fujifilm

Prescale. The accuracy error of this sensor was less than 10%, and the pressure sensitivity range was 0.2–0.6 MPa. Measurement errors are reported to be in the range of approximately 10–15% (Hale and Brown, 1992).

The Prescale used in our study consisted of 2 sheets of A- and C-films. A template was prepared to facilitate standardized insertion of the suture anchors (Fig. 2A). The pressure-sensitive films and templates were cut to a size to match the AIGHL-LC footprint. The prepared template was placed between both film sheets so we could prepare uniform and symmetrical holes on both film sheets. After insertion of the suture anchors, the films and template were inserted between the AIGHL-LC and the glenoid surface. The sutures connecting the anterior capsulolabral complex to the glenoid bone were passed carefully through the prepared holes to allow the best possible panoramic view of the contact area and pressure. Before the knots were tied, templates were removed (Fig. 2B). The pressure-sensitive film was left in place for 2 min. Sutures were carefully cut, and the 2 opposing pieces of film were separated immediately after testing, thus minimizing inadvertent imprint colorization after testing. The films then were digitized for analysis with a scanner.

Bankart lesion model and repair technique. From the positions of 1 o'clock to 6 o'clock, the AIGHL-LC was dissected carefully from the glenoid bone to make a Bankart lesion model. For Bankart repair, Panalok anchors (DePuy Synthes) were used for all repairs and were placed on the glenoid rim at the positions of 2, 3, 4, and 5 o'clock (Fig. 2A). The sutures were passed through 1 cm of the capsulolabral complex. All knots were tied first with an arthroscopic sliding-knot technique (SMC knot) followed by 3 half-hitches on alternating posts. To standardize tension for the repair, we used 4 kg of tensile force, measured by a tensiometer attached to the strings, to secure each knot.

Testing protocol and pressure-sensitive analysis. For the experiment with the subscapularis loading, a 22-N force was applied to the humeral head against the glenoid fossa through the cables attached to the subscapularis (10-N force) (superior subscapularis, 5 N; inferior subscapularis, 5 N), supraspinatus (4-N force), infraspinatus (6-N force), and teres minor (2-N force) tendons with pulleys. For the experiment without the subscapularis loading, no force was applied to the subscapularis. All specimens were measured at 0° of abduction plus 60° of internal rotation. The testing fixtures were made entirely of nonferrous materials—primarily fiberglass and polycarbonate—to avoid errors caused by electromagnetic interference. All kinematics were determined with the electromagnetic track system. The contact pressure and area were measured with and without subscapularis loading under each condition (intact, Bankart created, and Bankart repaired). In odd-numbered specimens, measurements were done first with the subscapularis loaded and then without loading, whereas in even-numbered specimens, the order was reversed. Images imprinted on each pressure-sensitive film were scanned and stored with a Fuji Film Prescale Pressure Densitometer (FPD-8010E; Fuji Photo Film Co Ltd). Mean interface pressure and mean pressurized contact area were calculated for each group. The percentage value of the contact area was calculated on the basis of a native footprint area measured by ImageJ 1.42 software (US National Institutes of Health).

2.3. Statistical methods

Statistical analysis was performed with JMP version 10.0 software (SAS Institute Inc). For contact area and pressure between the subscapularis and the AIGHL-LC while changing the rotation angle and loading the subscapularis, repeated-measures analysis of variance, followed by the Tukey test as a post hoc analysis, was performed individually on the range of motion data for each

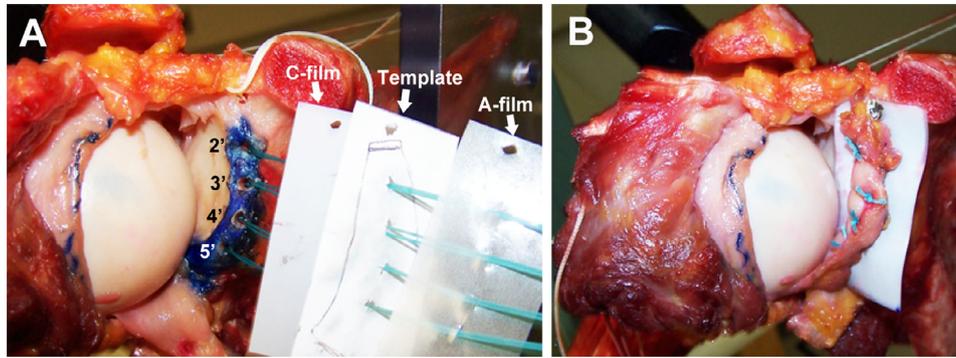


Fig. 2. A Right Shoulder. (A) After Panalok anchors were placed on the glenoid rim at the 2 (2'), 3 (3'), 4 (4'), and 5 (5') o'clock positions, sutures were passed through the prepared hole patterns of the C-film, template, and A-film. (B) After the template was removed, Bankart repair was performed.

arm position and on the force for the subscapularis. The independent variables were arm position and the subscapularis load; the dependent variables were contact pressure and area. The sphericity assumption was tested with use of the Mauchly sphericity test; if Mauchly test was significant, a Huynh-Feldt correction was used. For the arm positions showing a significant difference in subscapularis load between all conditions, a pairwise repeated-measures analysis was performed with proper corrections made to the α level. For all analyses, the α level for significance was set at 0.05. For contact area and pressure between the AIGHL-LC and glenoid after Bankart repair, unpaired *t* test was used to determine significant differences between with and without subscapularis load. A value of $P < .05$ was considered statistically significant.

3. Results

3.1. Contact area and pressure

3.1.1. Between subscapularis and AIGHL-LC while changing the subscapularis rotation angle and loading

Area. The contact area progressively increased with increases in subscapularis loading (Fig. 3A and B). The contact areas with 10-N, 20-N, and 30-N loadings were significantly greater than the matching 0-N loading conditions, regardless of arm position ($P < .05$). The contact area with 30-N loading was significantly greater than with 10-N loading at 30° internal rotation ($P < .05$). No significant differences were observed among arm positions.

Pressure. The average contact pressures with 10, 20, and 30 N of subscapularis loadings were significantly greater than those with 0-N subscapularis loading in the 60° internal rotation and 30° external rotation positions ($P < .05$) (Fig. 3C). The contact pressures in neutral rotation with 10-N and 20-N subscapularis loading were significantly greater than those with 0-N loading ($P < .05$). There were no significant differences among arm positions.

3.1.2. Between AIGHL-LC and glenoid fossa after Bankart repair

Area. Analysis of the contact area revealed spot welds around the insertion points of each suture anchor both with and without the subscapularis loading (Fig. 4A). The area around the insertion of each suture anchor was greater than in the space between the suture anchors, as represented by the color density in both with and without subscapularis loading. The area with subscapularis loading showed a wider area both on the articular surface of the glenoid and on the glenoid neck than the area without subscapularis loading. The contact area without subscapularis loading re-created a mean (SD) native surface area of 70.8% (10.0%); the contact area with subscapularis loading re-created 79.1% (11.8%). The

area with subscapularis loading was significantly wider than the area without subscapularis loading ($P < .01$) (Fig. 4B).

Pressure. The mean (SD) contact pressures were 0.48 (0.05) MPa in the pressure with subscapularis loading and 0.44 (0.05) MPa in the pressure without subscapularis loading. The pressure with subscapularis loading was significantly greater than the pressure without subscapularis loading ($P < .01$) (Fig. 4C).

4. Discussion

To our knowledge, this study is the first to show that loading of the subscapularis increases the contact area and pressure not only between the subscapularis and the AIGHL-LC but also between the AIGHL-LC and glenoid, after Bankart repair. Previous cadaveric studies on this topic measured the footprint of the repaired labrum on the glenoid with no rotator-cuff muscle loading present in the model, thereby disregarding any pressure contributions that the soft tissue may provide (Ahmad et al., 2009; Kim et al., 2011). In addition, these studies reported that the footprint of the repaired labrum using a double-row repair was from 78.4% to 90.4% of the anterior native labrum's footprint (Ahmad et al., 2009; Kim et al., 2011). Our findings suggest that this footprint size increased with the contraction of the subscapularis and was 79.1% of the native footprint using single-row repair.

With these findings taken into consideration, the double-row repair technique might not be needed because the footprint of a double-row repair measured by Kim et al. (2011) was similar to that of single-row repair with the contraction of the subscapularis, although we did not measure the footprint of the double-row repair. Yet, 20.9% of the native footprint was not re-created by Bankart repair and loading of the subscapularis in our study. The area around the insertion of each suture anchor was greater in the footprint and mostly equal among the positions of 2, 3, 4, and 5 o'clock in the present study. Itoigawa et al. (2012) described that the native footprint extending from 2 o'clock to 5 o'clock positions was not uniform but was widest at the 4 o'clock position. The re-created area at the 4 o'clock position in the single-row repair may be insufficient despite a contraction of the subscapularis. Further study will be needed.

Many surgeons generally immobilize the patient after Bankart repair, to permit time for healing of the repaired tissues. Rowe et al. (1978) suggested that early rehabilitation for range of motion was the key for better shoulder function and return to sports activities. Moreover, Kim et al. (2003b) compared 3 weeks of immobilization using conventional rehabilitation program (no isometric exercise) with a rehabilitation program started for isometric exercise from the immediate postoperative day. Their results were that the rehabilitation program with the isometric exercise recovers

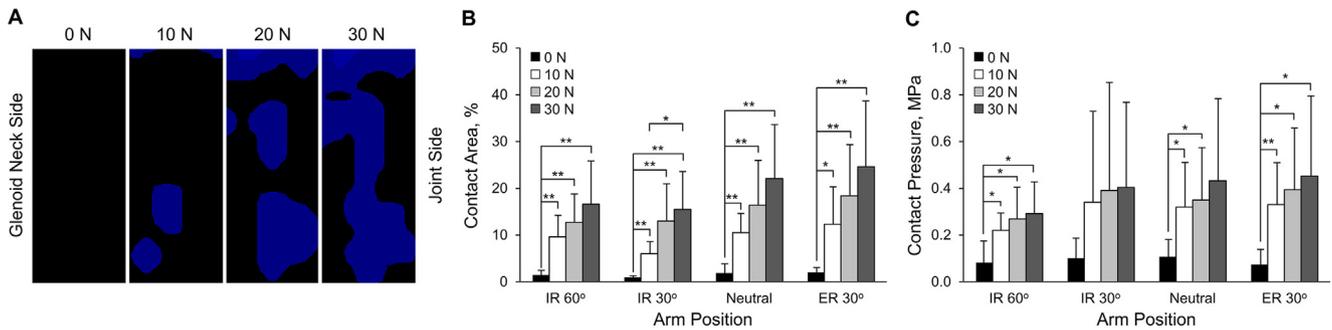


Fig. 3. Representation of the Contact Sites. (A) Schematic of contact sites of the anterior labrum with increase of subscapularis loading in the left shoulder. The contact sites increased with increasing force (from 0 Newtons [N] to 30 N) of subscapularis loading. Blue represents high pressure and black represents no pressure. (B) Average percentage of contact area at different subscapularis loading forces of all arm positions. (C) Average contact pressure at different subscapularis loading forces in all arm positions. Single asterisk indicates significance at $P < .05$; double asterisks, $P < .01$. Error bars indicate the standard deviation. ER indicates external rotation; IR, internal rotation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

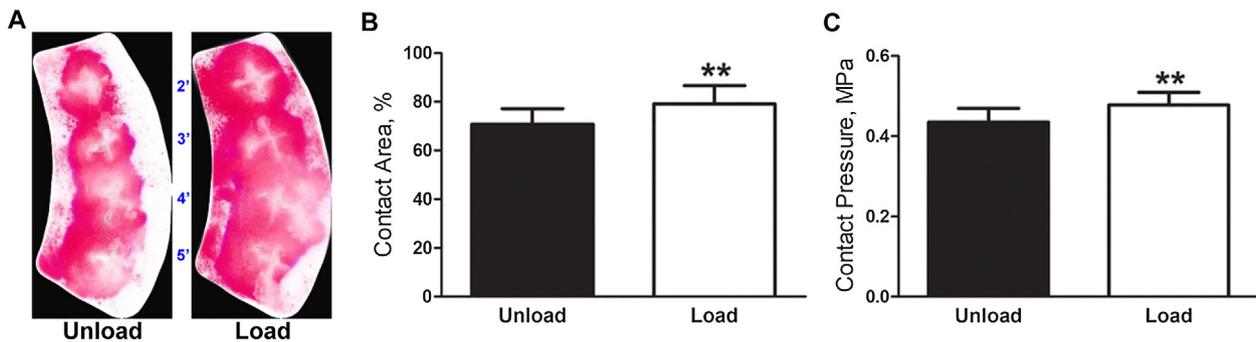


Fig. 4. Contact Area and Pressure for Bankart Repair. (A) Contact areas (red zone) without (unload) and with (load) subscapularis loading. White region indicates native surface area; 2', 3', 4' and 5' indicate 2 through 5 o'clock positions. The contact area was greatest around the anchor sites in both with and without the subscapularis loading situations. These contact areas were increased by the subscapularis loading, resulting in more footprint coverage. (B) Contact area was increased significantly by subscapularis loading. (C) Contact pressure was increased significantly by the subscapularis loading. Double asterisks indicate significance at $P < .01$. Error bars indicate the standard deviation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

shoulder function and decreases postoperative pain, and then they have patients return to activities early. In the present study, loading of the subscapularis increased the contact area and pressure between the AIGHL-LC and glenoid after Bankart repair. In consideration of these results and the previous reports that increased contact area and pressure improved the healing potential (Park et al., 2005; Tuoheti et al., 2005), isometric contraction exercises of the subscapularis might provide a better healing environment for the repaired tissues.

The subscapularis muscle is divided into the superior and inferior segments, which are innervated separately and have different lines of action (Kadaba et al., 1992). Wickham et al. (2014) reported that the inferior subscapularis might show its greater role as a humeral head depressor and anterior stabilizer. Yet, Rathi et al. (2017) demonstrated that the superior subscapularis muscle primarily acts as an agonist for internal rotation, and in contrast, inferior parts were active in external rotation. The superior subscapularis also functions as an abductor, whereas the inferior subscapularis functions as an adductor (Omi et al., 2010). In the present study, no significant differences were observed in the contact area and pressure on the AIGHL-LC between internal and external rotation, although both the superior and inferior subscapularis muscles were loaded. This result means that both the superior and inferior subscapularis muscles are equally important in producing the contact pressure. It also suggests that during rehabilitation after conservative treatment or surgical stabilization, both the superior and inferior portions of the subscapularis muscle must be strengthened equally for the healing of the soft tissue to the bone.

During a study of immobilization in external rotation after initial dislocation of the shoulder for the nonsurgical treatment, Itoi et al. (2001) speculated that the labrum was displaced medially on the glenoid neck with the arm in internal rotation but returned back to the glenoid rim in external rotation because of the tight subscapularis. This speculation was confirmed in a biomechanical study by Miller et al. (2004), who reported that external rotation significantly increased the contact pressure between the anterior labrum and the glenoid in a cadaveric model with a Bankart lesion created arthroscopically. However, Limpisvasti et al. (2008) reported that external rotation did not increase the contact pressure between the anterior labrum and the subscapularis, which was confirmed in the present study.

Clinically, a joint hematoma generally forms after a shoulder dislocation (Wintzell et al., 2000). Itoi et al. (2001) reported that the hematoma was located in the anterior joint cavity with the arm in internal rotation, whereas it was located in the posterior joint cavity with the arm in external rotation. They thought that this hematoma located anteriorly would stay between the soft tissue and the bone and would interfere with the reduction of the labrum. With use of cadaveric shoulders, this hematoma movement cannot be simulated, and thus the contact between the soft tissue and the bone cannot be re-created as well. This situation may explain the difference between the cadaver shoulders and the live shoulders.

According to our results, since the contracted subscapularis pushed the anterior capsule, it also pushed the hematoma in the anterior joint cavity, which might help to bring the detached capsulolabral structure back to the glenoid bone. In addition, maxi-

mization of the footprint contact area and pressure exposes more soft tissue to bone and improves the healing environment (Lo and Burkhart, 2003). If the AIGHL-LC is reduced by external rotation and contraction of the subscapularis improves the coaptation of the detached labrum to the glenoid, then immobilization in external rotation combined with isometric contraction exercises of the subscapularis might make this treatment more effective. This hypothesis needs to be proven in future studies.

The present study has several limitations. First, we had little information about the decedents regarding medical history or any shoulder symptoms. Thus, it is possible that the cadaveric shoulders in the study were not completely normal. Macroscopic and radiologic examinations, however, revealed no abnormalities. Second, although the subscapularis and the capsule are in contact with each other, an artificial space was created between them for placement of the pressure sensor. This might have affected our results. Third, the cadaveric model eliminates the dynamic influences. In addition, although our model created a Bankart lesion, the real Bankart lesion is accompanied with elongation of the capsule and labrum, which was not created in this experiment. Fourth, while it is not clear how much contact pressure between the tissues would facilitate healing, a certain base amount of contact pressure and area seems to be better than no force and no contact between the tissues for the healing process. Fifth, a shortcoming of the pressure-sensitive film is that it is effective only within a certain range of pressure. Pressures lower than the film range will not be detected, which will cause the actual contact area to be underestimated. Pressures that exceed the film range will saturate the film and will cause underestimation of the actual maximum pressure.

5. Conclusions

Loading of the subscapularis increases the contact area and pressure between the subscapularis and the AIGHL-LC and between the AIGHL-LC and the glenoid following Bankart repair. Isometric contraction exercises of the subscapularis might provide an improved healing environment for the repaired tissues and might make the treatment of anterior shoulder instability more effective.

Acknowledgments

This study was supported by the Alumni Scholarship Juntendo University School of Medicine.

Role of the funding source

The funders were the Division of Orthopedic Research, Mayo Clinic, and the Alumni Scholarship of Juntendo University School of Medicine. The funding sources had no role in the investigation or preparation of the manuscript.

Conflict of interest statement

The authors confirm that there is no potential conflict of interest, including employment, consultancies, stock ownership, honoraria, and paid expert testimony and patent applications, influencing this work.

References

Ahmad, C.S., Galano, G.J., Vorys, G.C., Covey, A.S., Gardner, T.R., Levine, W.N., 2009. Evaluation of glenoid capsulolabral complex insertional anatomy and restoration with single- and double-row capsulolabral repairs. *J. Shoulder Elbow Surg.* 18, 948–954.

Bassett, R.W., Browne, A.O., Morrey, B.F., An, K.N., 1990. Glenohumeral muscle force and moment mechanics in a position of shoulder instability. *J. Biomech.* 23, 405–415.

Bottoni, C.R., Smith, E.L., Berkowitz, M.J., Towle, R.B., Moore, J.H., 2006. Arthroscopic versus open shoulder stabilization for recurrent anterior instability: a prospective randomized clinical trial. *Am. J. Sports Med.* 34, 1730–1737.

Carreira, D.S., Mazzocca, A.D., Oryhon, J., Brown, F.M., Hayden, J.K., Romeo, A.A., 2006. A prospective outcome evaluation of arthroscopic Bankart repairs: minimum 2-year follow-up. *Am. J. Sports Med.* 34, 771–777.

DeFranco, M.J., Cole, B.J., 2009. Current perspectives on rotator cuff anatomy. *Arthroscopy* 25, 305–320.

Fitoussi, F., Bachy, M., 2015. Tendon lengthening and transfer. *Orthop. Traumatol. Surg. Res.* 101, S149–157.

Hale, J.E., Brown, T.D., 1992. Contact stress gradient detection limits of Pressensor film. *J. Biomech. Eng.* 114, 352–357.

Hovelius, L., Augustini, B.G., Fredin, H., Johansson, O., Norlin, R., Thorling, J., 1996. Primary anterior dislocation of the shoulder in young patients. A ten-year prospective study. *J. Bone Joint Surg. Am.* 78, 1677–1684.

Hovelius, L., Eriksson, K., Fredin, H., Hagberg, G., Husseini, A., Lind, B., Thorling, J., Weckstrom, J., 1983. Recurrences after initial dislocation of the shoulder. Results of a prospective study of treatment. *J. Bone Joint Surg. Am.* 65, 343–349.

Itoi, E., Hatakeyama, Y., Kido, T., Sato, T., Minagawa, H., Wakabayashi, I., Kobayashi, M., 2003. A new method of immobilization after traumatic anterior dislocation of the shoulder: a preliminary study. *J. Shoulder Elbow Surg.* 12, 413–415.

Itoi, E., Hatakeyama, Y., Sato, T., Kido, T., Minagawa, H., Yamamoto, N., Wakabayashi, I., Nozaka, K., 2007. Immobilization in external rotation after shoulder dislocation reduces the risk of recurrence. A randomized controlled trial. *J. Bone Joint Surg. Am.* 89, 2124–2131.

Itoi, E., Hatakeyama, Y., Urayama, M., Pradhan, R.L., Kido, T., Sato, K., 1999. Position of immobilization after dislocation of the shoulder. A cadaveric study. *J. Bone Joint Surg. Am.* 81, 385–390.

Itoi, E., Sashi, R., Minagawa, H., Shimizu, T., Wakabayashi, I., Sato, K., 2001. Position of immobilization after dislocation of the glenohumeral joint. A study with use of magnetic resonance imaging. *J. Bone Joint Surg. Am.* 83-A, 661–667.

Itoigawa, Y., Itoi, E., Sakoma, Y., Yamamoto, N., Sano, H., Kaneko, K., 2012. Attachment of the anteroinferior glenohumeral ligament-labrum complex to the glenoid: an anatomic study. *Arthroscopy* 28, 1628–1633.

Iwaso, H., Uchiyama, E., Sakakibara, S., Fukui, N., 2011. Modified double-row technique for arthroscopic Bankart repair: surgical technique and preliminary results. *Acta Orthop. Belg.* 77, 252–257.

Kadaba, M.P., Cole, A., Wootten, M.E., McCann, P., Reid, M., Mulford, G., April, E., Bigliani, L., 1992. Intramuscular wire electromyography of the subscapularis. *J. Orthop. Res.* 10, 394–397.

Kim, D.S., Yoon, Y.S., Chung, H.J., 2011. Single-row versus double-row capsulolabral repair: a comparative evaluation of contact pressure and surface area in the capsulolabral complex-glenoid bone interface. *Am. J. Sports Med.* 39, 1500–1506.

Kim, K.C., Rhee, K.J., Shin, H.D., Kim, Y.M., 2008. Arthroscopic separate labral repair and capsular plication with a suture anchor. *Arch. Orthop. Trauma Surg.* 128, 535–538.

Kim, S.H., Ha, K.I., Cho, Y.B., Ryu, B.D., Oh, I., 2003a. Arthroscopic anterior stabilization of the shoulder: two to six-year follow-up. *J. Bone Joint Surg. Am.* 85-A, 1511–1518.

Kim, S.H., Ha, K.I., Jung, M.W., Lim, M.S., Kim, Y.M., Park, J.H., 2003b. Accelerated rehabilitation after arthroscopic Bankart repair for selected cases: a prospective randomized clinical study. *Arthroscopy* 19, 722–731.

Lafosse, L., Baier, G.P., Jost, B., 2006. Footprint fixation for arthroscopic reconstruction in anterior shoulder instability: the Cassiopeia double-row technique. *Arthroscopy* 22, 231-e1.

Limpisvasti, O., Yang, B.Y., Hosseinzadeh, P., Leba, T.B., Tibone, J.E., Lee, T.Q., 2008. The effect of glenohumeral position on the shoulder after traumatic anterior dislocation. *Am. J. Sports Med.* 36, 775–780.

Lo, I.K., Burkhart, S.S., 2003. Double-row arthroscopic rotator cuff repair: re-establishing the footprint of the rotator cuff. *Arthroscopy* 19, 1035–1042.

Luo, Z.P., Berglund, L.J., An, K.N., 1998. Validation of F-Scan pressure sensor system: a technical note. *J. Rehabil. Res. Dev.* 35, 186–191.

Magit, D.P., Tibone, J.E., Lee, T.Q., 2008. In vivo comparison of changes in glenohumeral translation after arthroscopic capsulolabral reconstructions. *Am. J. Sports Med.* 36, 1389–1396.

Mazzocca, A.D., Brown Jr., F.M., Carreira, D.S., Hayden, J., Romeo, A.A., 2005. Arthroscopic anterior shoulder stabilization of collision and contact athletes. *Am. J. Sports Med.* 33, 52–60.

Miller, B.S., Sonnabend, D.H., Hatrick, C., O’Leary, S., Goldberg, J., Harper, W., Walsh, W.R., 2004. Should acute anterior dislocations of the shoulder be immobilized in external rotation? A cadaveric study. *J. Shoulder Elbow Surg.* 13, 589–592.

Muraki, T., Yamamoto, N., Zhao, K.D., Sperling, J.W., Steinmann, S.P., Cofield, R.H., An, K.N., 2010. Effect of posteroinferior capsule tightness on contact pressure and area beneath the coracoacromial arch during pitching motion. *Am. J. Sports Med.* 38, 600–607.

Omi, R., Sano, H., Ohnuma, M., Kishimoto, K.N., Watanuki, S., Tashiro, M., Itoi, E., 2010. Function of the shoulder muscles during arm elevation: an assessment using positron emission tomography. *J. Anat.* 216, 643–649.

Park, M.C., Cadet, E.R., Levine, W.N., Bigliani, L.U., Ahmad, C.S., 2005. Tendon-to-bone pressure distributions at a repaired rotator cuff footprint using transosseous suture and suture anchor fixation techniques. *Am. J. Sports Med.* 33, 1154–1159.

- Rathi, S., Taylor, N.F., Green, R.A., 2017. The upper and lower segments of subscapularis muscle have different roles in glenohumeral joint functioning. *J. Biomech.* 63, 92–97.
- Rhee, Y.G., Ha, J.H., Cho, N.S., 2006. Anterior shoulder stabilization in collision athletes: arthroscopic versus open Bankart repair. *Am. J. Sports Med.* 34, 979–985.
- Rowe, C.R., Patel, D., Southmayd, W.W., 1978. The Bankart procedure: a long-term end-result study. *J. Bone Joint Surg. Am.* 60, 1–16.
- Tsai, L., Wredmark, T., Johansson, C., Gibo, K., Engstrom, B., Tornqvist, H., 1991. Shoulder function in patients with unoperated anterior shoulder instability. *Am. J. Sports Med.* 19, 469–473.
- Tuoheti, Y., Itoi, E., Yamamoto, N., Seki, N., Abe, H., Minagawa, H., Okada, K., Shimada, Y., 2005. Contact area, contact pressure, and pressure patterns of the tendon-bone interface after rotator cuff repair. *Am. J. Sports Med.* 33, 1869–1874.
- Warner, J.J., Bowen, M.K., Deng, X.H., Hannafin, J.A., Arnoczky, S.P., Warren, R.F., 1998. Articular contact patterns of the normal glenohumeral joint. *J. Shoulder Elbow Surg.* 7, 381–388.
- Wickham, J., Pizzari, T., Balster, S., Ganderton, C., Watson, L., 2014. The variable roles of the upper and lower subscapularis during shoulder motion. *Clin. Biomech. (Bristol, Avon)* 29, 885–891.
- Wintzell, G., Hovelius, L., Wikblad, L., Saebo, M., Larsson, S., 2000. Arthroscopic lavage speeds reduction in effusion in the glenohumeral joint after primary anterior shoulder dislocation: a controlled randomized ultrasound study. *Knee Surg. Sports Traumatol. Arthrosc.* 8, 56–60.
- Wu, G., van der Helm, F.C., Veeger, H.E., Makhosou, M., Van Roy, P., Anglin, C., Nagels, J., Karduna, A.R., McQuade, K., Wang, X., Werner, F.W., Buchholz, B., International Society of B, 2005. ISB recommendation on definitions of joint coordinate systems of various joints for the reporting of human joint motion—Part II: shoulder, elbow, wrist and hand. *J. Biomech.* 38, 981–992.
- Yamamoto, N., Muraki, T., Sperling, J.W., Steinmann, S.P., Itoi, E., Cofield, R.H., An, K. N., 2009. Impingement mechanisms of the Neer and Hawkins signs. *J. Shoulder Elbow Surg.* 18, 942–947.