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Effect of biceps rerouting technique to restore glenohumeral joint stability for large irreparable rotator cuff tears: a cadaveric biomechanical study

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Background: The concept of stabilizing the humerus has taken on an important role in the treatment of irreparable cuff tears, and the biceps rerouting (BR) method is considered one of the most effective treatments in this field. The study aimed to evaluate the biomechanical effects of BR for large irreparable rotator cuff tears (LICTs).

Methods: A total of 8 cadaveric shoulders were used for testing under 5 conditions: intact shoulder, LICT, partial repair (PR), BR, and biceps rerouting with side-to-side repair (BRSS). Total rotational range of motion was measured at 40°, then 20°, and finally 0° of glenohumeral (GH) abduction. Superior humeral translation and subacromial contact pressure were measured at 0°, 30°, 60°, and 90° of external rotation at each abduction angle. Repeated-measures analyses of variance with Tukey post hoc tests were used for statistical comparisons.

Results: Superior humeral translation was significantly decreased in the BR and BRSS conditions compared with the LICT and PR conditions at 0° and 20° of GH abduction ($P < .001$). BR and BRSS significantly reduced subacromial contact pressure compared with LICT and PR at 0° of GH abduction ($P < .001$). There was no significant decrease in total rotational range of motion after BR at any abduction angle.

Conclusion: BR biomechanically restored shoulder stability without overconstraining range of motion in an LICT model.

The Institutional Review Board of Seoul St. Mary's Hospital, The Catholic University of Korea, approved this study (no. KC17DESI0798).

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Several surgical options have been developed for the treatment of chronic rotator cuff tears. However, for large to massive cuff tears, the results are often unpredictable or less favorable compared with small- to medium-sized tears owing to tendon retraction,[4,25] muscle atrophy,[4,9,18,19,24] or fatty infiltration.[9,18,19,25]

Recently, the role of the superior capsule in stabilization of the humeral head within the glenohumeral joint has gained attention in the treatment of massive irreparable cuff tears.[12] Superior migration of the humeral head in massive rotator cuff tears results in altered glenohumeral joint mechanics, leading to shoulder dysfunction and other long-term sequelae of rotator cuff arthropathy, including glenohumeral arthritis and acetabularization of the acromion. Studies of superior capsular reconstruction have shown that depression of the humeral head back to the pre-tear position restores joint biomechanics and improves clinical outcomes.[20,21] This technique was first introduced by Mihata et al[20,21] under the concept of superior capsule reconstruction (SCR) with the tensor fasciae latae (TFL). Several clinical and biomechanical studies of SCR with TFL have achieved promising results, and the treatment is considered an option for irreparable cuff tears.[20,21] However, this treatment has some drawbacks, such as the creation of an additional wound at the donor site, risk of muscle herniation or hematoma formation, and prolongation of operation time.[7,22]

To overcome these drawbacks, we developed a technique that involves using the long head of the biceps, which is adjacent to the humeral head, as a resistant to superior migration of the humeral head and as a support fixture for stabilization. Although the role of the long head of the biceps tendon (LHBT) inside the glenohumeral joint is controversial, it is known to help stabilize the humeral head in situ.[3,13,14] In a previous cadaveric study of the role of the LHBT at the glenohumeral joint, loading of the biceps tendon in a deficient rotator cuff tear reduced glenohumeral translation by up to 53% and contributed to joint stability.[14,30]

A few recent studies have attempted to use the LHBT for augmentation or reconstruction of the superior capsule to support massive rotator cuff repair.[6,8,11,16,23,28,29,32] Recently, biomechanical studies using the LHBT for SCR have been carried out owing to interest in the important role of the superior capsule in the treatment of massive rotator cuff tears.[8,11,16,27] In cadaveric biomechanical studies, SCR[8,11,16] and anterior capsule reconstruction[27] using the LHBT for the treatment of massive rotator cuff tears have succeeded in restoring glenohumeral joint stability. The concern is that the LHBT used for reconstruction of the superior capsule is tenotomized distally,[8,11,16,27] so patients may be at risk of the disadvantage of an unexpected biceps tenotomy. In contrast, Kim et al[15] proposed a new technique called ‘‘biceps rerouting’’ (BR) for the treatment of massive rotator cuff tears that maintains the original continuity of the LHBT. With the BR technique,[15] the LHBT is rerouted from the original bicipital groove to a new groove made at the footprint of the rotator cuff without tenotomizing it distally. This technique is advantageous because it maintains the LHBT itself with less risk of biceps tenotomy. Two separate suture anchors are used solely for the biceps tendon, so some tenodesis may occur from the securely fixed LHBT. A separate suture anchor is used for coverage of the partially reparable posterior cuff to avoid any unnecessary tension.

Through this biomechanical study, we evaluated the biomechanical effects of a rerouted LHBT for the treatment of large irreparable rotator cuff tears (LICTs). We hypothesized that this stabilization method using the LHBT would have a positive effect on resisting superior translation of the humeral head.

Material and methods

Specimen preparation and muscle loading conditions

A total of 8 fresh-frozen shoulders from 5 female and 3 male donors (mean age, 65 years; age range, 56-69 years) were tested in this study. Each specimen was thawed and dissected free of all skin and subcutaneous fat. The clavicle, serratus anterior, pectoralis minor, coracobrachialis, short head of the biceps, trapezius, triceps, and brachialis muscles were completely removed, along with all neurovascular structures. The deltoid was reflected off of its acromial and clavicular origins to expose the rotator cuff. The remaining muscles, including the subscapularis, supraspinatus, infraspinatus, teres minor, teres major, latissimus dorsi, and pectoralis major, were reflected from their origins and prepared for loading. The LHBT was left intact. No. 2 FiberWire (Arthrex, Naples, FL, USA) was used to place Krackow sutures in all tendinous insertions for loading. The humeral shaft was cut 2 cm distal to the deltoid tuberosity. The coracoacromial ligament, coracohumeral ligament, and shoulder capsule were left intact. The rotator cuff was carefully inspected for pre-existing tears. If any tear or capsulotomy was identified, the specimen was excluded from the study. A total of 10 shoulders were dissected. Two specimens were found to have pre-existing rotator cuff tears and were excluded.

The infraspinatus fossa was mounted to a steel plate, which was then mounted to a custom shoulder-testing jig at 0° of scapular abduction and 20° of anterior scapular tilt to mimic the anatomic position of the scapulothoracic articulation (Fig. 1). The humeral shaft was mounted to an intramedullary rod within a custom humeral cylinder and fixed distally using 6 opposing screws. The intramedullary rod was attached to an abduction arc that facilitated humeral abduction in the scapular plane. A SmartTool digital level (M-D Building Products, Oklahoma City, OK, USA) was used to identify 0°, 20°, and 40° of glenohumeral abduction along this arc. With the assumption of a 2:1 ratio of glenohumeral-to-scapulothoracic abduction, these glenohumeral abduction angles equated to 0°, 30°, and 60° of total shoulder abduction, respectively. A goniometer was fixed to the intramedullary rod to measure internal and external humeral rotation. The humerus was externally rotated until the bicipital groove was in line with the anterior edge of the acromion at 40° of abduction, and the goniometer was calibrated to 90° of external rotation at this point. Physiological muscle loading based on data of the cross-sectional area of each muscle[1,31] during testing was simulated using braided low-stretch fishing line (Izorline, Paramount, CA, USA) tied to the Krackow sutures at the musculotendinous junction. The fishing lines were fed through adjustable pulleys and loading plates to approximate physiological muscle force vectors, with the desired forces applied using weights. Movement of the humeral head for each testing condition was assessed under 2 different loading conditions (balanced and unbalanced load). As in a previous study, tendons were loaded as follows in the balanced state: upper subscapularis (5 N), lower subscapularis (5 N), anterior supraspinatus (5 N), posterior supraspinatus (5 N), superior infraspinatus (2.5 N), inferior infraspinatus (2.5 N), teres minor (5 N), teres major (10 N), latissimus dorsi (10 N), biceps tendon (5 N), upper pectoralis major (10 N), lower pectoralis major (10 N), anterior deltoid (13 N), middle deltoid (13 N), and posterior deltoid (13 N).[21,27] For unbalanced loading, a superior-directed load was applied by removing loads from the pectoralis major, latissimus dorsi, and teres major, and an additional 13 N was added to each of the 3 deltoid lines (anterior, middle, and posterior).[21,27] The remaining loads were left unchanged. This effectively removed inferior force vectors applied by the pectoralis major, latissimus dorsi, and teres major and doubled the superior force vectors of the deltoid.

Figure 1 Anterolateral view of custom shoulder-testing system with right shoulder mounted in 0° of glenohumeral abduction.

Test conditions

A total of 5 conditions were tested sequentially as follows: intact shoulder, LICT, partial repair (PR), BR, and biceps rerouting with side-to-side repair (BRSS). Each condition is presented in Figure 2. The intact state served as the internal control for each specimen. No alterations were made to the native shoulder for this condition. For the second condition (LICT), a No. 10 blade scalpel was used to elevate the insertion of the supraspinatus footprint, as well as the superior half of the infraspinatus footprint, off of the greater tuberosity. The anterior border of the supraspinatus was dissected free of the LHBT. In the third condition, PR of the LICT was performed using a 4.5-mm suture anchor (Smith & Nephew, London, UK) placed on the anterosuperior portion of the infraspinatus footprint. This was used to repair the previously cut portion of the infraspinatus tendon, which was then reloaded with 2.5 N. In the fourth condition, BR was performed additionally to PR with the specimen in 20° of glenohumeral abduction (30° of total shoulder abduction), corresponding to the clinical position of the shoulder during arthroscopic surgery, as previously described by Kim et al.[15] To mobilize and reroute the LHBT, all soft tissue at the extra-articular bicipital groove was removed, including the transverse humeral ligament. A new groove was made by a high-speed burr at the midlateral aspect of the supraspinatus footprint on the greater tuberosity. A 5.5-mm Healicoil suture anchor (Smith & Nephew) was placed at the lateral end of the new groove. Fixation of the LHBT was performed using 2 lasso-loop ties and 1 wraparound tie. A medial Healicoil suture anchor was inserted at the medial end of the new groove and used to fix the LHBT in the same manner as the lateral anchor. A load of 10 N was applied to the biceps tendon throughout the repair to ensure appropriate tension as traction of shoulder arthroscopic surgery.[10] For the final condition (BRSS), a No. 2 FiberWire was used to perform a side-to-side repair between the rerouted biceps tendon and the anterior border of the infraspinatus using the Mason-Allen technique. This effectively closed the soft tissue defect over the superior portion of the glenohumeral joint.

Testing protocol and outcome variables

The primary outcome of this study was superior translation of the center of the humeral head. Secondary outcomes included the peak subacromial contact pressure, mean subacromial contact pressure, maximum internal rotation, maximum external rotation, and total rotational range of motion (ROM).

The sequence of testing was the same for each specimen; testing was performed in the following order: intact, LICT, PR, BR, and BRSS. For each condition, the specimen was tested at 40°, then at 20°, then at 0°, and again at 20° of glenohumeral abduction. At each abduction angle, the line-and-pulley system was loaded in a balanced state, followed by the unbalanced state as mentioned earlier. After the balanced load was applied, 5 cycles of alternating internal and external rotation were performed to precondition the specimen. This was done by using a torque wrench to apply 2.2 N-m of torque without capsular stretching or

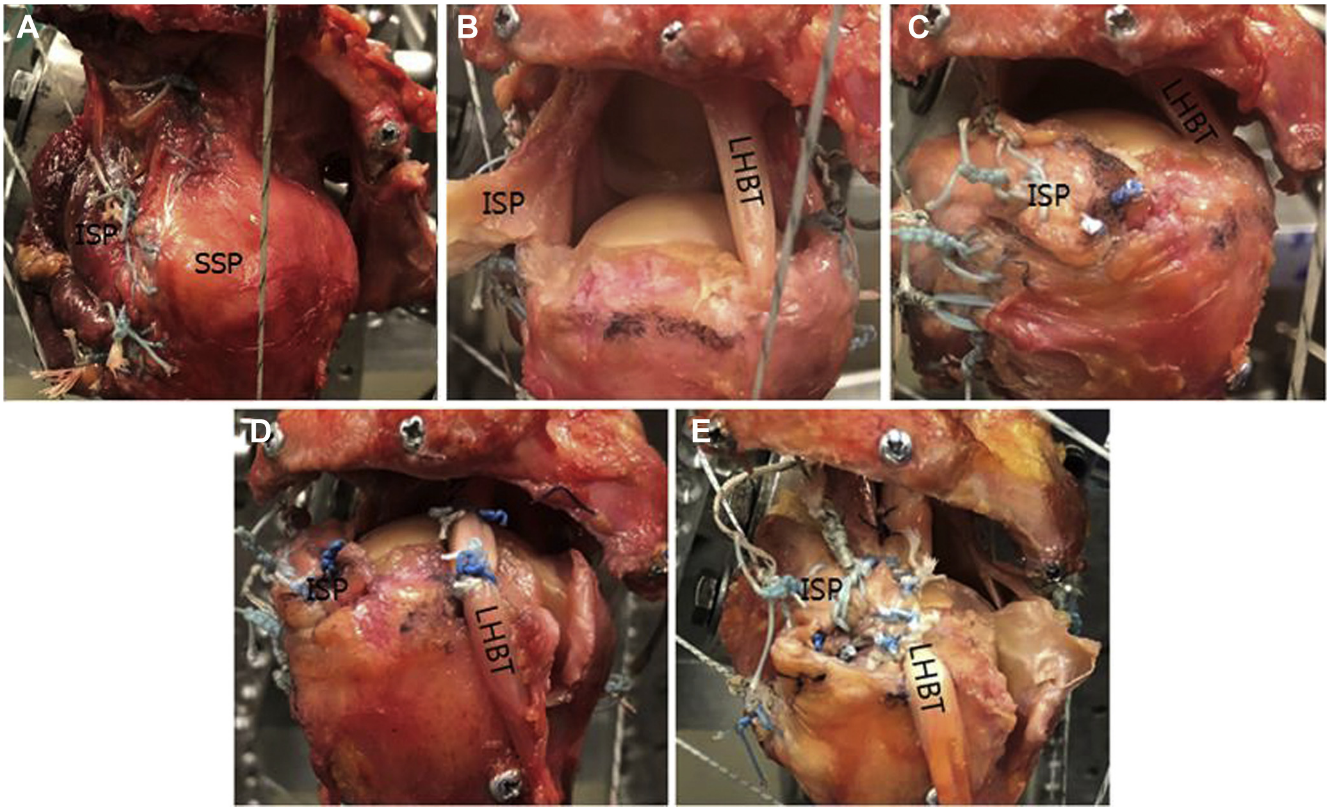

Figure 2 Testing conditions: intact shoulder (**A**), large irreparable cuff tear (**B**), partial repair (**C**), biceps rerouting (**D**), and biceps rerouting with side-to-side repair (**E**). *ISP*, infraspinatus; *SSP*, supraspinatus; *LHBT*, long head of biceps tendon.

tearing in both internal and external rotation.[2] After preconditioning, a 360° digital goniometer (Novotechnik US, Southborough, MA, USA) was used to measure the maximum internal rotation of the humerus at 2.2 N-m of torque. This was repeated in external rotation. Measurements were repeated a second time to ensure that values were reproducible to within 1° of internal and external rotation. Total rotational ROM was calculated by adding external and internal rotational ROM values.

A 3-dimensional referencing system was established using a MicroScribe 3DLX device (Revware, Raleigh, NC, USA; accuracy within <0.3 mm) to measure superior translation of the center of the humeral head. Scapular referencing was established by placing a screw in the coracoid process, a screw in the anterolateral corner of the anterior acromion, and a screw in the posterolateral corner of the acromion. Humeral referencing was established by placing a screw approximately 2 cm distal to the greater tuberosity and 5 mm posterior to the bicipital groove, a second screw 1 cm directly distal to the first screw, and a third screw 1 cm directly posterior to the second screw (Fig. 3).

The MicroScribe 3DLX device was referenced to the scapular screws at the start of each condition and then used to digitize the position of the humeral screws. For the balanced load state, humeral head screws were measured at maximum internal rotation, followed by 0°, 30°, 60°, and 90° of external rotation and maximum external rotation, at each abduction angle. Rotational measures were taken a second time to ensure repeatability to within 1 mm of the first trial. In the unbalanced state, humeral head position was measured at 0°, 30°, 60°, and 90° of external rotation at each abduction angle. In addition, peak pressure and total contact pressure in the subacromial space were measured in the unbalanced state using a Tekscan digital pressure measurement device and software (model 4000; Tekscan, South Boston, MA, USA; maximum saturation pressure, 10.3 MPa). A sensor pad was

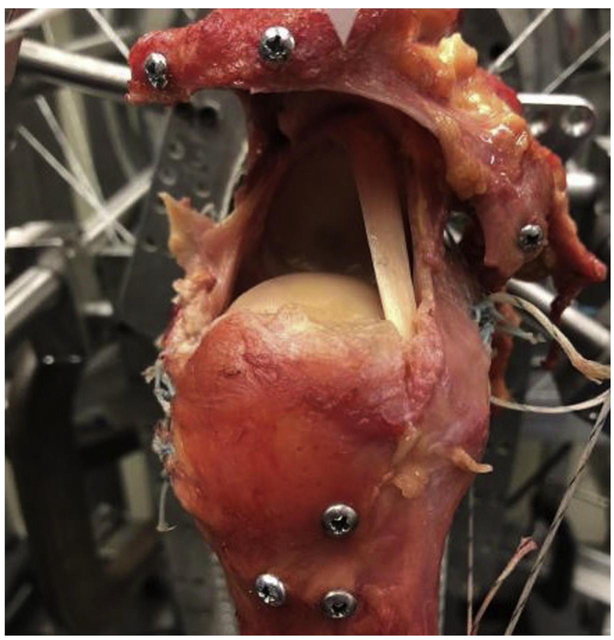

Figure 3 Scapular and humeral referencing screw position.

inserted flat into the subacromial space to measure the contact force, contact area, contact pressure, and peak contact pressure. This process was performed at 40°, 20°, and 0° of glenohumeral abduction. The specimen was then returned to 20° of abduction for a final balanced and unbalanced loading series to check for any loosening of the rerouting after abduction of the specimen to 0°.

Two-way analyses of variance with post hoc Tukey HSD (honestly significant difference) tests were used to analyze all data with SigmaPlot statistical software (version 13; Systat, San Jose, CA, USA). Data are presented as mean ± standard error, and the significance level was set at $P < .05$.

Results

Superior translation with balanced load state

For the intact condition, superior translation of the humeral head ranged from 1.8 mm (±0.8 mm) to 5.8 mm (±1.0 mm). Relative to the intact condition, superior translation in the LICT condition increased by a maximum of 2.2 mm (81% increase) ($P < .001$). Relative to the LICT, superior translation trended down as the degree of soft tissue repair increased from PR to BR to BRSS (Table I). Although PR resulted in slight depression of the humeral head relative to the LICT in all positions, these differences were not statistically significant ($P > .64$). BR resulted in a significant decrease in superior translation relative to the LICT at 0° and 20° of abduction but not at all rotation angles. Adding a side-to-side repair further depressed the humeral head and restored the humeral head position to the intact state at several positions. In balanced loading, no significant differences in superior translation were observed at abduction angles greater than 20° or external rotation greater than 60°.

Superior translation with unbalanced load state

Average superior translation for unbalanced loading is presented in Table II and Figure 4. For the intact condition, superior translation ranged from 0.9 mm (±3 mm) to 2.3 mm (±0.6 mm). After creation of the LICT, superior translation significantly increased by a maximum of 4.0 mm (222% increase) ($P < .001$). PR had no significant effect on superior translation relative to the LICT ($P > .54$). In contrast, BR decreased superior translation in all positions, but not all of these decreases were statistically significant. BR resulted in an average 1.6-mm decrease in superior translation relative to the LICT across all positions,

Table I Superior translation of humeral head with balanced load

Measurement position	Translation, mm				
	Intact	Large irreparable cuff tear	Partial repair	Biceps rerouting	Biceps rerouting with side-to-side repair
0° of GH abduction					
Maximum IR	2.7 ± 1.1	4.9 ± 1.3*	4.4 ± 1.1*	3.5 ± 1.5†	2.5 ± 1.4†,‡
0° of ER	4.9 ± 1.0	6.7 ± 1.2*	6.1 ± 0.9	5.8 ± 1.0	5.1 ± 0.9†
30° of ER	5.8 ± 1.0	7.8 ± 0.9*	7.4 ± 0.9*	6.4 ± 0.9†	6.1 ± 0.9†,‡
60° of ER	5.8 ± 1.0	7.4 ± 0.8*	7.1 ± 0.8*	5.7 ± 0.9†,‡	5.8 ± 0.9†,‡
90° of ER	4.8 ± 0.9	5.6 ± 0.8	5.3 ± 0.8	4.7 ± 0.9	5.0 ± 0.8
Maximum ER	3.5 ± 0.9	4.0 ± 0.8	4.0 ± 0.8	3.7 ± 0.9	4.0 ± 0.8
20° of GH abduction					
Maximum IR	4.6 ± 1.2	6.3 ± 1.0*	6.4 ± 1.0*	6.5 ± 1.1*	5.0 ± 0.9†,‡,§
0° of ER	4.5 ± 1.0	6.5 ± 1.0*	6.8 ± 1.4*	5.5 ± 1.0	5.0 ± 1.0†,‡
30° of ER	4.4 ± 0.9	6.1 ± 1.0*	5.9 ± 1.1*	5.4 ± 0.9	5.1 ± 0.9
60° of ER	3.7 ± 0.9	5.5 ± 0.7*	5.3 ± 0.7*	4.6 ± 0.9	4.7 ± 0.9
90° of ER	3.6 ± 0.8	4.2 ± 0.8	4.0 ± 0.8	4.1 ± 0.8	4.5 ± 0.9
Maximum ER	2.6 ± 0.9	3.0 ± 0.8	3.2 ± 0.8	3.2 ± 0.7	3.3 ± 0.8
40° of GH abduction					
Maximum IR	4.1 ± 1.0	5.4 ± 1.2*	5.3 ± 1.0*	5.2 ± 1.0*	4.6 ± 1.0
0° of ER	3.6 ± 1.2	4.3 ± 1.1	4.6 ± 1.1*	4.4 ± 1.1*	4.1 ± 1.1
30° of ER	2.7 ± 1.0	3.1 ± 0.9	2.9 ± 1.1	3.1 ± 0.9	3.1 ± 1.0
60° of ER	1.7 ± 0.8	2.4 ± 0.8	2.5 ± 0.8*	2.6 ± 0.8*	2.3 ± 0.8
90° of ER	1.8 ± 0.8	2.3 ± 0.9	2.4 ± 0.8	2.6 ± 0.7	2.4 ± 0.6
Maximum ER	1.8 ± 0.8	1.7 ± 0.6	2.1 ± 0.8	2.4 ± 0.7	1.9 ± 0.7

GH, glenohumeral; *IR*, internal rotation; *ER*, external rotation.
Data are presented as mean ± standard error.
* Statistically significant compared with intact condition ($P < .05$).
† Statistically significant compared with large irreparable cuff tear ($P < .05$).
‡ Statistically significant compared with infraspinatus repair ($P < .05$).
§ Statistically significant compared with biceps rerouting ($P < .05$).

Table II Superior translation of humeral head with unbalanced load

Measurement position	Translation, mm				
	Intact	Large irreparable cuff tear	Partial repair	Biceps rerouting	Biceps rerouting with side-to-side repair
0° of GH abduction					
0° of ER	2.1 ± 0.4	5.9 ± 0.6*	6.0 ± 0.5*	5.2 ± 0.6*	2.7 ± 0.4†,‡,§
30° of ER	1.7 ± 0.4	5.8 ± 0.4*	5.8 ± 0.5*	3.6 ± 0.3*,†,‡	1.9 ± 0.3†,‡,§
60° of ER	1.8 ± 0.4	5.8 ± 0.4*	5.7 ± 0.4*	1.4 ± 0.3‡,§	1.4 ± 0.3‡,§
90° of ER	2.1 ± 0.4	6.2 ± 0.5*	6.2 ± 0.5*	2.3 ± 0.7†,‡	2.7 ± 0.6†,‡
20° of GH abduction					
0° of ER	2.3 ± 0.6	5.8 ± 0.6*	5.3 ± 0.5*	5.0 ± 0.6*	2.9 ± 0.5†,‡,§
30° of ER	1.2 ± 0.5	4.9 ± 0.5*	4.9 ± 0.4*	4.0 ± 0.4*	2.8 ± 0.4*,†,‡,§
60° of ER	1.5 ± 0.4	5.4 ± 0.4*	5.4 ± 0.4*	3.2 ± 0.5*†‡	3.6 ± 0.4*,†,‡
90° of ER	1.7 ± 0.3	5.2 ± 0.4*	5.1 ± 0.4*	3.5 ± 0.6*†‡	4.5 ± 0.4*
40° of GH abduction					
0° of ER	1.4 ± 0.2	4.6 ± 0.6*	3.9 ± 0.8*	3.4 ± 0.6*	2.3 ± 0.4†,‡
30° of ER	0.9 ± 0.3	3.1 ± 0.6*	2.8 ± 0.5*	2.2 ± 0.6*	1.7 ± 0.6†
60° of ER	1.3 ± 0.5	3.1 ± 0.8*	3.2 ± 0.6*	2.7 ± 0.7*	2.4 ± 0.7
90° of ER	1.1 ± 0.3	3.2 ± 0.6*	3.5 ± 0.7*	3.0 ± 0.5*	3.1 ± 0.7*

GH, glenohumeral; *ER*, external rotation.
Data are presented as mean ± standard error.
* Statistically significant compared with intact condition ($P < .05$).
† Statistically significant compared with large irreparable cuff tear ($P < .05$).
‡ Statistically significant compared with infraspinatus repair ($P < .05$).
§ Statistically significant compared with biceps rerouting ($P < .05$).

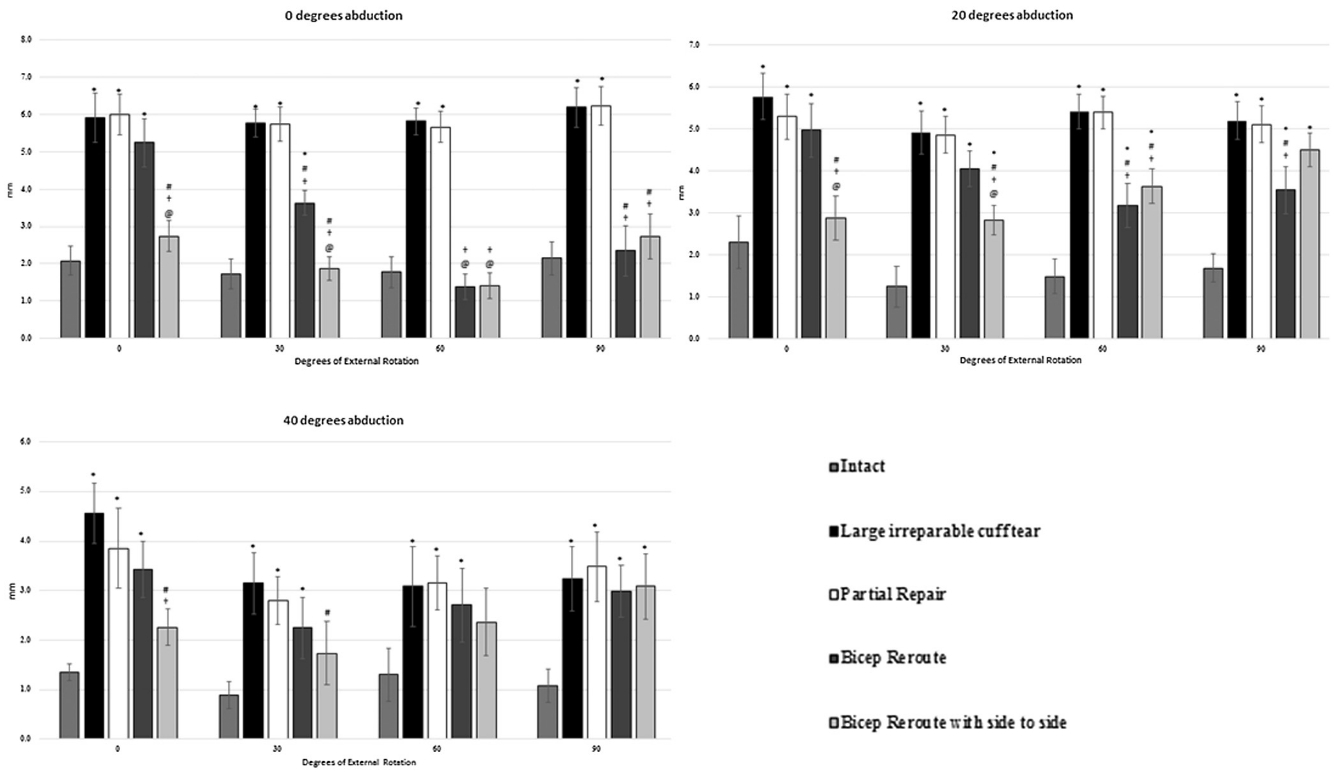

Figure 4 Superior translation of humeral head with unbalanced load. *$P < .05$ compared with intact. #$P < .05$ compared with large irreparable cuff tear. †$P < .05$ compared with partial repair. @$P < .05$ compared with biceps rerouting.

with a maximum decrease of 4.4 mm (76.2% decrease) ($P < .001$). At 0° of abduction, BR showed no significant difference in superior translation compared with the intact shoulder at 60° and 90° of external rotation ($P > .84$). At 20° of abduction, BR resulted in a significant decrease in superior translation relative to the LICT and PR at 60° and 90° of external rotation ($P < .001$). Although trends were similar at 40° of abduction, no significant differences occurred between the BR and LICT conditions. When side-to-side repair was performed, a significant decrease in superior translation was seen at 0° of abduction in 0° and 30° of external rotation relative to the LICT ($P < .001$). BRSS also led to significant decreases in superior translation at 0° and 20° of abduction in 0° and 30° of external rotation compared with the BR condition ($P < .001$). There was no significant difference between the BRSS and intact state at 0° of abduction for any of the rotational positions ($P > .41$). At 20° of abduction, there were no significant differences between BRSS and the intact state in 0° and 30° of external rotation ($P > .53$). However, the aforementioned effect was not significant at 60° and 90° of external rotation. At 40° of abduction, BRSS was the only condition that resulted in a significant decrease in superior translation relative to the LICT at 0° of external rotation ($P < .001$) and 30° of external rotation ($P = .014$).

To determine whether any loss of fixation occurred during testing of the BR condition, a second trial of testing was performed at 20° of abduction. The results were similar to those of the first trial at 20° of abduction. In the unbalanced state, there was a slight increase in superior translation of the humeral head at all angles compared with the first trial. However, this increase was only significant at 90° of external rotation ($P = .003$).

Subacromial peak pressure and contact pressure

Peak pressures and contact pressures were obtained for the unbalanced load state only. Peak pressures for the intact state varied from 427.1 kPa (±85.1 kPa) to 719 kPa (±86.6 kPa). On average, peak pressures in the LICT were 270.5 kPa greater across all positions compared with the intact state. However, only 2 positions had significant increases in peak pressures for the LICT compared with the intact state. These trends held for the PR condition. After BR, a significant decrease in peak pressure was observed in 0° of abduction at 30°, 60°, and 90° of external rotation with peak pressures as low as 114.4 kPa (±110.4 kPa) compared with the LICT and PR ($P < .007$). These decreases held for the BRSS state. No significant differences in peak pressure were observed between any of the conditions at 20° of abduction ($P = .11$). At 40° of abduction, only the BRSS resulted in a significant decrease in peak pressure compared with the LICT at 0° and 30° of external rotation ($P < .004$).

Contact pressure represents the mean pressure across the entire contact area. Contact pressure is presented in Table III. Contact pressure for the intact state ranged from 134.0 kPa (±18.3 kPa) to 214.4 kPa (±47.8 kPa) and increased to as high as 340.1 kPa (±37.4 kPa) for the LICT condition (81% increase). After BR and BRSS, contact pressure decreased significantly compared with the LICT at 0° of abduction ($P < .001$). In fact, BR and BRSS resulted

Table III Subacromial contact pressure

Measurement position	Pressure, kPa				
	Intact	Large irreparable cuff tear	Partial repair	Biceps rerouting	Biceps rerouting with side-to-side repair
0° of GH abduction					
0° of ER	162.5 ± 24.7	259.6 ± 54.7	236.1 ± 39.0	215.0 ± 45.1	97.3 ± 23.5
30° of ER	185.9 ± 29.0	290.7 ± 48.0*	299.9 ± 43.4*	164.3 ± 52.1†,‡	84.0 ± 13.0
60° of ER	186.6 ± 22.5	251.1 ± 38.2	254.5 ± 35.9	49.8 ± 40.3*,†,‡	37.5 ± 15.1
90° of ER	142.1 ± 26.0	172.0 ± 33.3	168.4 ± 24.0	45.3 ± 19.8†,‡	76.3 ± 33.6
20° of GH abduction					
0° of ER	171.9 ± 20.2	241.5 ± 52.4	179.9 ± 22.2	198.5 ± 29.4	139.2 ± 15.2
30° of ER	197.9 ± 46.0	285.2 ± 41.1	219.2 ± 29.0	276.6 ± 35.6	158.8 ± 24.4
60° of ER	214.4 ± 47.8	195.2 ± 23.9	185.3 ± 16.9	146.2 ± 31.7	173.5 ± 33.0
90° of ER	147.5 ± 17.6	208.9 ± 18.3	206.7 ± 24.5	118.9 ± 31.5	174.4 ± 32.5
40° of GH abduction					
0° of ER	167.5 ± 17.0	253.2 ± 46.2	163.3 ± 30.1	186.2 ± 19.3	126.9 ± 21.0
30° of ER	187.9 ± 31.4	340.1 ± 37.4*	308.7 ± 36.5*	277.5 ± 23.5	192.7 ± 19.8
60° of ER	205.4 ± 31.2	265.6 ± 36.0	241.0 ± 33.2	293.0 ± 68.7	262.3 ± 50.1
90° of ER	134.0 ± 18.3	133.2 ± 18.3	141.5 ± 16.4	218.4 ± 83.8	202.8 ± 67.9

GH, glenohumeral; *ER*, external rotation.
Data are presented as mean ± standard error.
* Statistically significant compared with intact condition ($P < .05$).
† Statistically significant compared with large irreparable cuff tear ($P < .05$).
‡ Statistically significant compared with infraspinatus repair ($P < .05$).

in lower contact pressures than the intact state at 0° of abduction with 60° and 90° of external rotation.

Range of motion

ROM data are presented in Table IV. Creation of an LICT resulted in greater total ROM by as much as 10° at all abduction angles ($P < .001$). After PR of the infraspinatus, total rotational ROM did not decrease relative to the intact shoulder at any abduction angle ($P < .001$). Neither BR nor BRSS decreased total rotational ROM at any glenohumeral abduction angle compared with the intact shoulder.

Discussion

The results of this study showed that BR played a positive role in resisting superior translation of the humeral head in the treatment of an LICT, although the results varied considerably at different abduction angles. BR and BRSS prevented superior humeral translation at all 3 ranges of abduction, but this finding was not significant at 40° of glenohumeral abduction, corresponding to 60° of shoulder abduction. These results suggest that the tension of the rerouted LHBT decreased at higher angles of shoulder abduction because of shortening of the distance between the origin site of the LHBT and the lateral fixation point of the rerouted LHBT. Previous biomechanical studies on the role of the rotator cuff tendon in shoulder elevation have shown that the rotator cuff tendon is more important in initiation of elevation than at a higher angle of abduction.[17,26] Therefore, restoration of glenohumeral joint stability after BR at a lower angle of abduction may occur because a rerouted LHBT supports the function of a partially repaired rotator cuff tendon as a superior stabilizer at initiation of shoulder elevation.

Consistently with previous studies,[12,21] an LICT and a partially repaired cuff tendon resulted in significant superior translation of the humeral head compared with the intact shoulder. In glenohumeral abduction of 0° and 20° (corresponding to shoulder abduction angles of 0° and 30°) with large external rotation angles (60° and 90°), BR succeeded in preventing superior humeral translation compared with an LICT and PR. This finding may have occurred because external rotation led to an increase in tension of the rerouted biceps that was strong enough to endure superior migration of the humeral head. However, decreased external rotation may not deliver quite enough tension to the BR, so additional side-to-side repair along with BR can help reinforce the posterior aspect of the BR and enable it to maintain tension.

Despite the additional anchorage or rerouted biceps on the humeral head, there was no significant reduction in ROM in our study. In contrast, Mihata et al[21] reported that SCR with TFL significantly decreased total rotational ROM compared with the intact shoulder. Our findings highlight the advantage of using the low-profile, adjacent biceps tendon instead of overstuffing a foreign object in conventional SCR. A similar study by El-Shaar et al.[8] demonstrated the technique of SCR with an LHBT autograft, but their study did not include data on ROM.

Our technique has several important differences compared with previously reported techniques such as anterior cable reconstruction described by Park et al.[27] First, instead of tenotomy of the LHBT, the LHBT was thoroughly released at the biceps groove to retain its route to the footprint without too much tension. This permitted the maximal length of the LHBT to be used as a stabilizer without sacrificing the role of the biceps by tenotomy. Second, 2 separate suture anchors were used for the rerouted LHBT only; the posterior cuff was

Table IV Rotational range of motion

Measurement position	Rotation, °				
	Intact	Large irreparable cuff tear	Partial repair	Biceps rerouting	Biceps rerouting with side-to-side repair
Maximal internal rotation					
0° of abduction	20.0 ± 3.7	24.6 ± 4.3*	26.0 ± 5.0*	28.3 ± 5.4*	27.6 ± 5.6*
20° of abduction	20.3 ± 3.8	22.9 ± 3.8	24.5 ± 4.6*	26.6 ± 4.4*	25.2 ± 4.8*
40° of abduction	16.2 ± 4.0	22.5 ± 4.5	21.8 ± 4.6*	24.0 ± 4.6*	23.1 ± 4.7*
Maximum external rotation					
0° of abduction	121.1 ± 2.8	124.0 ± 2.9*	124.8 ± 2.5*	124.3 ± 2.7*	125.7 ± 3.0*
20° of abduction	120.5 ± 3.7	124.2 ± 3.5*	125.9 ± 3.2*	124.7 ± 3.5*	126.5 ± 3.1*
40° of abduction	112.9 ± 5.5	118.6 ± 4.2*	119.8 ± 4.6*	121.1 ± 4.2*	122.4 ± 4.9*
Total range of motion					
0° of abduction	141.1 ± 5.9	148.5 ± 6.4*	150.8 ± 6.7*	152.6 ± 6.9*	153.3 ± 7.2*,†
20° of abduction	140.8 ± 7.2	147.1 ± 6.7*	150.4 ± 7.2*	151.3 ± 7.0*	151.8 ± 7.0*,†
40° of abduction	129.2 ± 9.2	141.1 ± 7.7*	141.6 ± 7.9*	145.1 ± 7.7*,†	145.6 ± 8.5*,†

Data are presented as mean ± standard error.
* Statistically significant compared with intact condition ($P < .05$).
† Statistically significant compared with large irreparable cuff tear ($P < .05$).

repaired separately using an extra anchor. In this way, we could expect the benefits of PR under low tension. Third, a new groove for the LHBT was made in the BR technique. The new groove increased the stability and healing potential of the rerouted LHBT by keeping the rerouted LHBT in a dislocated position. Subacromial contact pressure was also decreased with the new groove. By use of the BR technique, the vascularity of the original LHBT was preserved after BR because of the origin of the LHBT from the superior glenoid. We therefore expect the rerouted LHBT to have better durability than a free graft of the TFL. In addition, as the LHBT was securely fixed with medial and lateral anchors at the footprint, BR may have a tenodesis effect in LICTs with poor-quality LHBTs.[5,15]

A clinically important feature that was revealed in this study is that a tear of the rerouted LHBT occurred after testing to 0° of glenohumeral abduction and after fixating the rerouted LHBT at 30° of glenohumeral abduction, corresponding to 45° of shoulder abduction on pilot testing. This finding implies that fixating the rerouted LHBT at a larger abduction angle might result in excess tension on the LHBT during adduction repair. Therefore, when performing BR, we recommend that the operative arm be placed at less than 30° of shoulder abduction to avoid over-tightening of the rerouted LHBT.

This study had several limitations. First, the experiment was performed on avascular cadaveric tissue, and cadaveric testing systems cannot simulate the multiple factors that act in synergy to provide glenohumeral stability. Second, our measurements represent biomechanical conditions at time zero after surgery. Third, when the test was repeated at 20° of glenohumeral abduction after a complete testing protocol, slight loosening of the fixated LHBT was observed, possibly due to settling of the fixation sites and creeping of the soft tissues. This finding emphasizes the clinical importance of maintaining proper abduction angles with a shoulder brace in the immediate postoperative period. Fourth, we could not simulate all circumstances influencing chronic rotator cuff tears in a biomechanical cadaveric study. Finally, the results of the BR technique could be affected by the condition of the rerouted LHBT. In many LICTs, nobody can guarantee the healthy condition of the LHBT, and an LHBT in poor condition could potentially lead to early failure of stabilization. This study also could not explain the effect of the rerouted passage of the LHBT on the function of the biceps muscle.

Despite these limitations, the results of this cadaveric biomechanical study clearly reveal the positive potential of the BR technique in the treatment of LICTs by resisting superior translation of the humeral head. Moreover, simulation of 5 different experimental conditions for each specimen was a major strength of this study. Using this subjective apparatus, we were also able to directly measure superior translation, rotational ROM, and subacromial contact pressure at exact positions and loading conditions.

Conclusion

The BR technique can biomechanically restore shoulder stability without limiting ROM in cadaveric specimens with LICTs. The BR technique may be a feasible alternative treatment option for LICTs.

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References

1. Akagi R, Kanehisa H, Kawakami Y, Fukunaga T. Establishing a new index of muscle cross-sectional area and its relationship with isometric muscle strength. J Strength Cond Res 2008;22:82-7. https://doi.org/10.1519/JSC.0b013e31815ef675
2. Alberta FG, Elattrache NS, Mihata T, McGarry MH, Tibone JE, Lee TQ. Arthroscopic anteroinferior suture plication resulting in decreased glenohumeral translation and external rotation. Study of a cadaver model. J Bone Joint Surg Am 2006;88:179-87. https://doi.org/10.2106/JBJS.D.02974
3. Andrews JR, Carson WG Jr, McLeod WD. Glenoid labrum tears related to the long head of the biceps. Am J Sports Med 1985;13:337-41.
4. Bedi A, Dines J, Warren RF, Dines DM. Massive tears of the rotator cuff. J Bone Joint Surg Am 2010;92:1894-908. https://doi.org/10.2106/JBJS.I.01531
5. Boileau P, Baque F, Valerio L, Ahrens P, Chuinard C, Trojani C. Isolated arthroscopic biceps tenotomy or tenodesis improves symptoms in patients with massive irreparable rotator cuff tears. J Bone Joint Surg Am 2007;89:747-57. https://doi.org/10.2106/JBJS.E.01097
6. Cho NS, Yi JW, Rhee YG. Arthroscopic biceps augmentation for avoiding undue tension in repair of massive rotator cuff tears. Arthroscopy 2009;25:183-91. https://doi.org/10.1016/j.arthro.2008.09.012
7. Dubiel WT, Wigren A. Functional status of the lower extremity after resection of fascia lata. A clinical and physiological follow-up study in patients with fascia lata heart valve replacement. Acta Orthop Scand 1974;45:599-613.
8. El-Shaar R, Soin S, Nicandri G, Maloney M, Voloshin I. Superior capsular reconstruction with a long head of the biceps tendon autograft: a cadaveric study. Orthop J Sports Med 2018;6. https://doi.org/10.1177/2325967118785365. 2325967118785365.
9. Goutallier D, Postel JM, Bernageau J, Lavau L, Voisin MC. Fatty muscle degeneration in cuff ruptures. Pre- and postoperative evaluation by CT scan. Clin Orthop Relat Res 1994:78-83.

10. Hamamoto JT, Frank RM, Higgins JD, Provencher MT, Romeo AA, Verma NN. Shoulder arthroscopy in the lateral decubitus position. Arthrosc Tech 2017;6:e1169-75. https://doi.org/10.1016/j.eats.2017.04.004
11. Han F, Kong CH, Hasan MY, Ramruttun AK, Kumar VP. Superior capsular reconstruction for irreparable supraspinatus tendon tears using the long head of biceps: a biomechanical study on cadavers. Orthop Traumatol Surg Res 2019;105:257-63. https://doi.org/10.1016/j.otsr.2018.10.023
12. Ishihara Y, Mihata T, Tamboli M, Nguyen L, Park KJ, McGarry MH, et al. Role of the superior shoulder capsule in passive stability of the glenohumeral joint. J Shoulder Elbow Surg 2014;23:642-8. https://doi.org/10.1016/j.jse.2013.09.025
13. Itoi E, Kuechle DK, Newman SR, Morrey BF, An KN. Stabilising function of the biceps in stable and unstable shoulders. J Bone Joint Surg Br 1993;75:546-50.
14. Kido T, Itoi E, Konno N, Sano A, Urayama M, Sato K. The depressor function of biceps on the head of the humerus in shoulders with tears of the rotator cuff. J Bone Joint Surg Br 2000;82:416-9.
15. Kim YS, Lee HJ, Park I, Sung GY, Kim DJ, Kim JH. Arthroscopic in situ superior capsular reconstruction using the long head of the biceps tendon. Arthrosc Tech 2018;7:e97-103. https://doi.org/10.1016/j.eats.2017.08.058
16. Lin J, Qi W, Liu Z, Chen K, Li X, Yan Y, et al. An arthroscopic technique for full-thickness rotator cuff repair by transposition of the long head of biceps. Orthop Traumatol Surg Res 2019;105:265-9. https://doi.org/10.1016/j.otsr.2018.07.027
17. Liu J, Hughes RE, Smutz WP, Niebur G, Nan-An K. Roles of deltoid and rotator cuff muscles in shoulder elevation. Clin Biomech (Bristol, Avon) 1997;12:32-8.
18. Melis B, Nemoz C, Walch G. Muscle fatty infiltration in rotator cuff tears: descriptive analysis of 1688 cases. Orthop Traumatol Surg Res 2009;95:319-24. https://doi.org/10.1016/j.otsr.2009.05.001
19. Melis B, Wall B, Walch G. Natural history of infraspinatus fatty infiltration in rotator cuff tears. J Shoulder Elbow Surg 2010;19:757-63. https://doi.org/10.1016/j.jse.2009.12.002
20. Mihata T, Lee TQ, Watanabe C, Fukunishi K, Ohue M, Tsujimura T, et al. Clinical results of arthroscopic superior capsule reconstruction for irreparable rotator cuff tears. Arthroscopy 2013;29:459-70. https://doi.org/10.1016/j.arthro.2012.10.022
21. Mihata T, McGarry MH, Pirolo JM, Kinoshita M, Lee TQ. Superior capsule reconstruction to restore superior stability in irreparable rotator cuff tears: a biomechanical cadaveric study. Am J Sports Med 2012;40:2248-55. https://doi.org/10.1177/0363546512456195
22. Naugle TC Jr. Complications of fascia lata harvesting for ptosis surgery. Br J Ophthalmol 1998;82:333-4.
23. Obma PR. Free biceps tendon autograft to augment arthroscopic rotator cuff repair. Arthrosc Tech 2013;2:e441-5. https://doi.org/10.1016/j.eats.2013.07.002
24. Oh JH, Kim SH, Choi JA, Kim Y, Oh CH. Reliability of the grading system for fatty degeneration of rotator cuff muscles. Clin Orthop Relat Res 2010;468:1558-64. https://doi.org/10.1007/s11999-009-0818-6
25. Oh JH, Kim SH, Kang JY, Oh CH, Gong HS. Effect of age on functional and structural outcome after rotator cuff repair. Am J Sports Med 2010;38:672-8. https://doi.org/10.1177/0363546509352460
26. Otis JC, Jiang CC, Wickiewicz TL, Peterson MG, Warren RF, Santner TJ. Changes in the moment arms of the rotator cuff and deltoid muscles with abduction and rotation. J Bone Joint Surg Am 1994;76:667-76.
27. Park MC, Itami Y, Lin CC, Kantor A, McGarry MH, Park CJ, et al. Anterior cable reconstruction using the proximal biceps tendon for large rotator cuff defects limits superior migration and subacromial contact without inhibiting range of motion: a biomechanical analysis. Arthroscopy 2018;34:2590-600. https://doi.org/10.1016/j.arthro.2018.05.012
28. Park SR, Sun DH, Kim J, Lee HJ, Kim JB, Kim YS. Is augmentation with the long head of the biceps tendon helpful in arthroscopic treatment of irreparable rotator cuff tears? J Shoulder Elbow Surg 2018;27:1969-77. https://doi.org/10.1016/j.jse.2018.04.022
29. Rhee YG, Cho NS, Lim CT, Yi JW, Vishvanathan T. Bridging the gap in immobile massive rotator cuff tears: augmentation using the tenotomized biceps. Am J Sports Med 2008;36:1511-8. https://doi.org/10.1177/0363546508316020
30. Su WR, Budoff JE, Luo ZP. The effect of posterosuperior rotator cuff tears and biceps loading on glenohumeral translation. Arthroscopy 2010;26:578-86. https://doi.org/10.1016/j.arthro.2009.09.007
31. Veeger HE, Van der Helm FC, Van der Woude LH, Pronk GM, Rozendal RH. Inertia and muscle contraction parameters for musculoskeletal modelling of the shoulder mechanism. J Biomech 1991;24:615-29.
32. Veen EJD, Stevens M, Diercks RL. Biceps autograft augmentation for rotator cuff repair: a systematic review. Arthroscopy 2018;34:1297-305. https://doi.org/10.1016/j.arthro.2017.10.044