Original Article

Anterolateral Acromioplasty Reduces Gliding Resistance Between the Supraspinatus Tendon and the Coracoacromial Arch in a Cadaveric Model

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Purpose: To investigate the gliding resistance dynamics between the supraspinatus (SSP) tendon and the coracoacromial arch, both before and after subacromial decompression (anterolateral acromioplasty) and acromion resection (acromionectomy). **Methods:** Using 4 fresh-frozen cadaveric shoulders, acromion shapes were classified (2 type I and 2 type III according to Bigliani). Subacromial bursa and coracoacromial ligament maintenance replicated physiologic sliding conditions. Gliding resistance was measured during glenohumeral abduction (0° to 60°) in internal rotation (IR) and external rotation (ER). Peak gliding resistance between the SSP tendon and the coracoacromial arch was determined and compared between intact, anterolateral acromioplasty, and acromionectomy. **Results:** Peak SSP gliding resistance during abduction in an intact shoulder was significantly higher in IR than in ER (4.1 vs 2.1 N, $P < .001$). The mean peak SSP gliding resistance during 0° to 60° glenohumeral abduction in IR in the intact condition was significantly higher compared with the subacromial decompression condition (4.1 vs 2.8 N, $P = .021$) and with the acromionectomy condition (4.1 vs 0.9 N, $P < .001$). During 0° to 60° glenohumeral abduction in ER, mean peak SSP gliding resistance in the intact condition was not significantly different compared with the subacromial decompression condition (2.1 vs 2.0 N, $P = .999$). The 2 specimens with a hooked (i.e. type III) acromion showed significantly higher mean peak SSP gliding resistance during glenohumeral abduction in IR and ER when compared with the 2 specimens with a flat (i.e. type I) acromion (IR: 5.8 vs 3.0 N, $P = .006$; ER: 2.8 vs 1.4 N, $P = .001$). **Conclusions:** In this cadaveric study, peak gliding resistance between the SSP tendon and the coracoacromial arch during combined abduction and IR was significantly reduced after anterolateral acromioplasty and was significantly higher in specimens with a hooked acromion. **Clinical Relevance:** The clinical benefit of subacromial decompression remains unclear. This study suggests that anterolateral acromioplasty might reduce supraspinatus gliding resistance in those with a hooked acromion and in the typical "impingement" position.

Numerous theories have been proposed to attempt to explain rotator cuff tears (RCTs). Some authors believe that the intrinsic mechanism is the main cause in the development of RCT, which can be the result of an intrinsic ischemic lesion of a poorly vascularized critical zone of the rotator cuff tendon[1-6] or due to rotator cuff overloading in shoulders with an increased critical shoulder angle.[7-10] Others believe that an extrinsic mechanism such as a mechanical impingement due to an acromial spur could be responsible for (bursal-sided) RCT.[11-18]

Although the clinical implication of removing such an acromial spur on the development of RCTs is uncertain,[19-21] experimental studies have shown that mechanical impingement can lead to RCT. Soslowsky et al.[22] showed in a rat model that overuse of the tendon plus experimental subacromial impingement generated by extrinsic compression of the supraspinatus (SSP) tendon caused greater tendon injury than

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overuse or extrinsic compression alone. Similarly, Schneeberger et al.[23] found in their rat study that experimental subacromial impingement results in bursal-sided RCT. Other studies measured subacromial contact pressure during different shoulder movements in an attempt to understand the mechanism of subacromial impingement.[24,25] These have shown direct contact between the rotator cuff tendons and the coracoacromial arch in all arm positions with increasing contact pressure during shoulder abduction.

Subacromial impingement, however, includes not only a compressive force but also gliding resistance due to 2 surfaces in contact gliding against each other during shoulder motion, thus causing a dynamic mechanical stress. Such gliding resistance was also observed after flexor tendon repairs, showing that increased gliding resistance can lead to formation of adhesions.[26] Gliding resistance is also critical for rotator cuff abrasion and wear, which can cause tendon injury and initiate an inflammatory process.[27,28] High gliding resistance between the SSP tendon and the coracoacromial arch could potentially lead to an unbalanced injury, resulting in RCT. It seems that gliding characteristics are a crucial component to take into account in understanding the development of thickening and inflammation of the subacromial bursa, rotator cuff tendinopathy, and ultimately RCT, but this factor has not yet been studied.

It was therefore the purpose of this cadaveric study to investigate the gliding resistance dynamics between the SSP tendon and the coracoacromial arch, both before and after subacromial decompression (anterolateral acromioplasty) and acromion resection (acromionectomy). It was hypothesized that acromioplasty significantly reduces gliding resistance between the SSP tendon and the coracoacromial arch compared to the intact condition.

Materials and Methods

Ethical approval for this study was obtained from the Mayo Clinic Biospecimens Review Committee (project number: 14-003208).

Specimen Preparation

Four fresh-frozen shoulders were acquired from a donor sample, which were donated to the institutional anatomy laboratory, consisting of 4 females with a mean age of 62.5 (range, 61-64) years at the time of death. All cadaveric shoulders were inspected macroscopically to rule out rotator cuff tears and had plain radiographs to rule out osteoarthritis of the glenohumeral joint and fractures of the acromion or scapular spine. Based on these plain films, the acromion of each subject was classified according to Bigliani's classification[29] by 2 independent fellowship-trained shoulder surgeons (L.E. and J.-D.W.). Two specimens had a flat (type I) acromion and the other 2 had a hooked (type III) acromion.

Specimens were thawed at room temperature for 24 hours prior to experimental testing.[30-33] Two fellowship-trained shoulder surgeons (L.E. and J.-D.W.) performed all specimen preparation and surgeries. All shoulders were dissected using a deltopectoral approach. After removing the skin and fascia, the humeral shaft was transected 2 cm distal to the deltoid tuberosity. The deltoid muscle was cut above its distal insertion and removed from its acromial insertion to expose the underlying subacromial bursa. The subacromial bursa and the coracoacromial ligament were maintained to reproduce physiologic sliding conditions between the rotator cuff and the coracoacromial arch. The rotator cuff and the capsule were left intact. A fabric strap was sutured to the deltoid tendon insertion, guided over the acromion through eyelets. In the conditions where the acromion was resected, 2 plastic rods with a U-shaped pulley on top were mounted to the base of the resected scapular spine to redirect the strap. The strap was loaded to simulate the upward-oriented force of the deltoid. The shoulders were attached on a shoulder-positioning frame, allowing motion of the humerus. A fiberglass rod was fitted into the medullary canal in a press-fit manner, and an acrylic plate was attached to the positioning device and fixed to the scapular body by means of plastic screws. The device allowed the humerus to be placed in a given plane of elevation (scapular plane), between a given range of glenohumeral abduction (0° and 60°) and at a given angle of humeral rotation (external or internal) (Fig 1). The plane including the long axis of the scapular body was defined as the scapular plane of the glenohumeral joint.

Experimental Setup

Each medial tendon of the rotator cuff was attached with a weight to maintain tension during testing. This consisted of a 22 N compressive force applied to the humeral head against the glenoid fossa through No. 2 FiberWire sutures (Arthrex) attached to the subscapularis (10 N), SSP (3.5 N), and infraspinatus/teres minor (8.5 N) tendons with pulleys and weights to keep the humeral head centered within the glenohumeral joint according to previous studies.[25,34-36] The insertion of the SSP tendon was carefully separated from the infraspinatus tendon and sharply transected from its insertion (footprint) on the greater tuberosity. Three transosseous tunnels were established with the ArthroTunneler transosseous tunneling device (Tornier) by creating a 2.9-mm medial tunnel close to the articular margin, which was completed by a second 2.5-mm lateral tunnel, positioned 1.5 cm from the lateral edge of the greater tuberosity.[37] Two No. 2 FiberWire sutures (Arthrex) were passed through the SSP tendon in a reversed-mattress fashion to create 1 anterior and 1

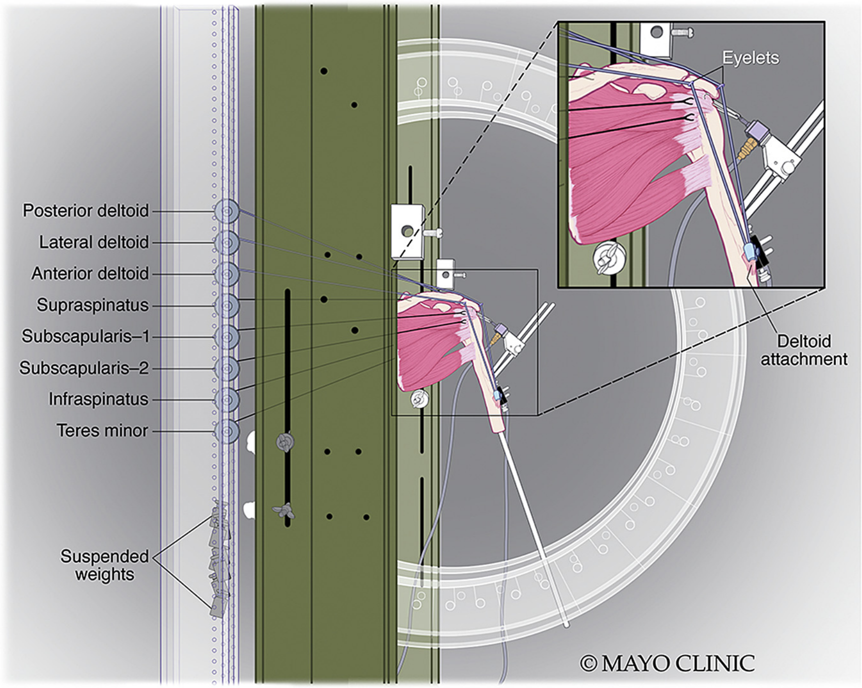


Fig. 1. Illustration of the customized shoulder-positioning frame.

posterior suture pair. The anterior and posterior suture limbs of each suture pair were passed through the respective anterior and posterior transosseous tunnel, whereas the inner 2 suture limbs of each suture pair were passed through the central transosseous tunnel. The anterior and posterior suture pairs were then tied to a load cell (MDB-5, 5 lbs.; Transducer Techniques). This lateral load cell was clamped with a customized clamp to 2 threaded 5-mm fiberglass pins. These fiberglass rods were then pinned to the lateral humeral shaft in line with the SSP tendon (Fig 2). The medial end of the SSP tendon was connected to a second load cell (MDB-5, 5 lbs.; Transducer Techniques), which was then connected to the potentiometer.

Mechanical Testing

To control for vertical displacement of the humeral head, a centered humeral head position in each specimen before starting the test was confirmed by fluoroscopy.

Data from the medial and lateral load cells were recorded by a computer at a sampling rate of 20 Hz. The accuracy and reliability of this setup with 2 load cells had been reported previously.[38,39] The difference in measured forces between the lateral and medial load cells during excursion defined the gliding resistance (N) between the SSP tendon and the coracoacromial arch.[38-40] The peak gliding resistance over the excursion range was calculated. The differences in SSP gliding resistance were assessed for the following conditions: (1) intact subacromial bursa and coracoacromial arch, (2) after subacromial decompression, and (3) after acromionectomy (Fig 3).

Subacromial decompression consisted of bursectomy and acromioplasty. Acromioplasty was done by resecting an area of 1.5 × 1.5 cm of the anterolateral acromion, as resection of this area is necessary to remove all of the impinging bone.[41] The exact area of resection was marked with a handheld ruler and resected using a 4.0-mm burr (Acromionizer Burr, Dyonics; Smith & Nephew). The insertion of the coracoacromial ligament was carefully debrided in the area of the osseous acromioplasty until it was flush with the resected bone. Acromionectomy was conducted by resecting the acromion at the level of the spinoglenoid notch using an oscillating saw. In each of the 3 testing conditions, peak gliding resistance of the SSP tendon was recorded during the following motions: (1) glenohumeral abduction in the scapular plane between 0° and 60° and the arm in 30° of external rotation (ER) and (2) glenohumeral abduction in the scapular plane between 0° and 60° and the arm in 30° of internal rotation (IR). Scapular-plane glenohumeral abduction of 60°, which corresponds to 90° of scapular-plane shoulder abduction, was chosen as it is known that the SSP tendon and the undersurface of the coracoacromial arch are in closest proximity in this position.[42-44] Neutral rotation was defined as the biepicondylar line of the humerus perpendicular to the coronal plane, which is equivalent to 30° of ER relative to the scapular plane. As previously described,[45,46] a 6 degree-of-freedom electromagnetic tracking system (Polhemus) with accompanying MotionMonitor

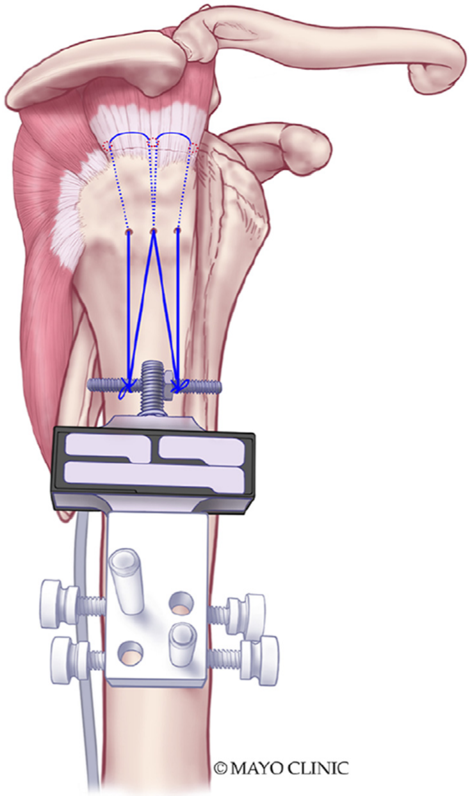


Fig. 2. Illustration of the experimental setup. The supraspinatus tendon was sharply taken off its insertion on the greater tuberosity. Two reverse-mattress sutures were used to repair the tendon. The free suture limbs were then passed through 3 transosseous tunnels in the greater tuberosity and tied to a load cell. The load cell was mounted to the humeral shaft with 2 threaded 5-mm fiberglass pins and a customized clamp.

software (Innovative Sports Training) was used to record and control for glenohumeral motion within the shoulder-position frame that was executed by one of the authors (L.E.). Sensors of the tracking system were fixed to the scapula and humerus, and anatomic coordinate systems were defined using a calibrated digitizing stylus attached to a sensor.[46] The tracking system has a static accuracy of 0.8 mm and an angular accuracy of 0.15°. To ensure repeatability of the measurements, each trial was repeated 3 times. The specimens were kept moist with a spray of saline solution applied every 10 to 15 minutes during the test, which was performed at room temperature (24°C).

Statistical Analysis

As this was a pilot study, an interim analysis was conducted after completion testing of 4 specimens and revealed that a sample size of 4 reveals sufficient power (80%) to reach significant differences in mean peak SSP gliding resistance between the intact condition and after subacromial decompression with an effect size of Cohen's $d = 0.6$ (i.e., medium to large effect), which was defined as the primary outcome measure. Distribution of the data was assessed with the Shapiro-Wilk test. The 3 different conditions were compared using repeated-measures analysis of variance and Bonferroni adjustments. Subgroup analysis consisted of analysis of the influence of humeral rotation (IR vs ER) during glenohumeral abduction and acromial shape according to the Bigliani classification (type I vs type III) on peak SSP gliding resistance, which was conducted with an unpaired *t* test. Significance was set as $P < .05$, and all P values were 2-tailed.

Results

Peak SSP gliding resistance during abduction in an intact shoulder was significantly higher in IR than in ER (4.1 vs 2.1 N; $P < .001$). Acromial shape according to the Bigliani classification had a significant influence on mean peak SSP gliding resistance in the intact condition. The 2 specimens with a hooked (Bigliani type III) acromion showed significantly higher mean peak SSP gliding resistance during glenohumeral abduction with the arm in IR and with the arm in ER when compared with the 2 specimens with a flat (Bigliani type I) acromion (IR: 5.8 vs 3.0 N, $P = .006$; ER: 2.8 vs 1.4 N, $P = .001$) (Fig 4).

Mean peak SSP gliding resistance during 0° to 60° of scapular-plane glenohumeral abduction in IR in the intact condition was significantly higher compared with the subacromial decompression condition (4.1 vs 2.8 N, $P = .021$) and with the acromionectomy condition (4.1 vs 0.9 N, $P < .001$). The mean peak SSP gliding resistance after subacromial decompression was also significantly higher than after acromionectomy ($P = .001$) (Fig 5).

During 0° to 60° of scapular-plane glenohumeral abduction in ER, mean peak SSP gliding resistance in the intact condition was not significantly different compared with the subacromial decompression condition (2.1 vs 2.0 N, $P = .999$). When compared with the acromionectomy (0.8 N), both the intact and the subacromial decompression conditions showed significantly higher mean peak SSP gliding resistance ($P < .001$ for both comparisons) (Fig 6).

Discussion

The most important finding of this experimental study is that peak gliding resistance between the SSP tendon and the coracoacromial arch in the typical "impingement" position (i.e., scapular-plane abduction in internal rotation[42-44]) was significantly reduced by anterolateral acromioplasty compared to the intact condition. Another main finding is that peak SSP gliding resistance is dependent not only on the arm position but also on the shape of the acromion. A hooked acromion significantly increased peak SSP gliding resistance.

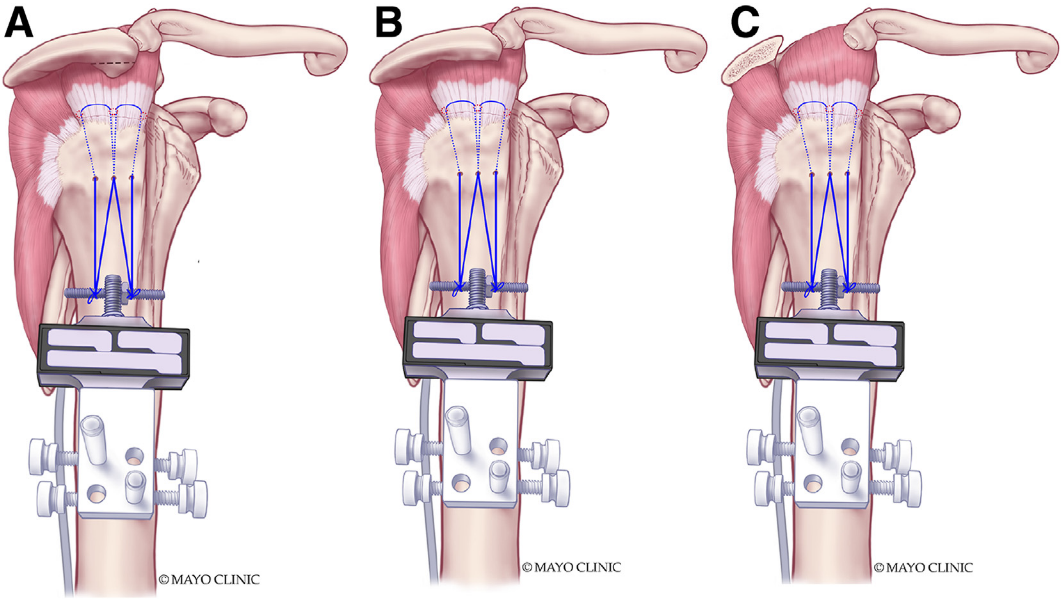


Fig. 3. Illustration of the different testing conditions. Peak gliding resistance between the supraspinatus tendon and the coracoacromial arch was measured (A) in the intact condition, (B) after anterolateral acromioplasty, and (C) after acromionectomy.

Two possible reasons that have been proposed in an attempt to understand the development of RCT are the intrinsic and extrinsic mechanisms. While the intrinsic mechanism is thought to be associated with an ischemic lesion of a poorly vascularized tendon[1-6] or chronic overloading of the tendon due to an increased critical shoulder angle,[7-10] the extrinsic mechanism postulates that a mechanical impingement between the rotator cuff and the coracoacromial arch leads to RCT.[11-18] Which mechanism eventually results in the actual pathology of RCT is yet to be defined, and it is highly uncertain that one theory can be seen as the isolated cause for RCTs. Even more so, other factors, including genetically influenced,[47,48] degenerative,[49] or process related to aging,[50,51] have been proposed, and these factors together with other intrinsic factors are thought to result in articular-sided RCTs. On the other side, the extrinsic pathway is thought to result in bursal-sided RCTs. Accordingly, it is known that there is a very close proximity or even a contact phenomenon between the rotator cuff and the coracoacromial arch and that contact pressure is higher during shoulder abduction and internal rotation.[25,42-44] Our results showed for the first time that “impingement” of the SSP tendon under the coracoacromial arch consists of not only a compressive force but also a gliding resistance due to 2 surfaces in contact gliding against each other during shoulder motion, thus causing a dynamic mechanical stress. This is also supported by the fact that after experimental acromionectomy, the measured peak gliding resistance was negligible.

Several authors have tried to relate certain bony morphologies of the shoulder with RCT and showed recently that in shoulders with a more laterally projecting acromion and with a glenoid that has a greater upward tilt (i.e., increased critical shoulder angle), the SSP tendon needs to counteract a more vertically directed (destabilizing) force of the deltoid muscle and thus might result in chronic overload of the SSP tendon and RCT, respectively.[7-10,52] The morphology of the acromion is also thought to play a role in the development of RCT via the extrinsic pathway. Bigliani et al.[53] described 3 different types of acromion: type I (flat), type II (curved), and type III (hooked). While some authors have reported that a hooked acromion can be associated with development of RCT,[18,54,55] others refuted this theory.[56] Our results showed that a hooked acromion resulted in (significant) twice as high peak SSP gliding resistance compared with a flat acromion.

Since the description of anterior acromioplasty by Neer[57] in 1972, its clinical implication has been discussed thoroughly. Consequently, the benefit as an isolated or adjunct procedure has been questioned. Conflicting results have been reported, with some studies showing no clinical benefit after this procedure[19-21,58] and others reporting on significant benefit over nonoperative treatment at long-term follow-up.[59] Anterolateral acromioplasty in our study was executed in a standardized fashion and resulted in a significant decrease in peak SSP gliding resistance. In fact, in the impingement position of combined abduction and IR,

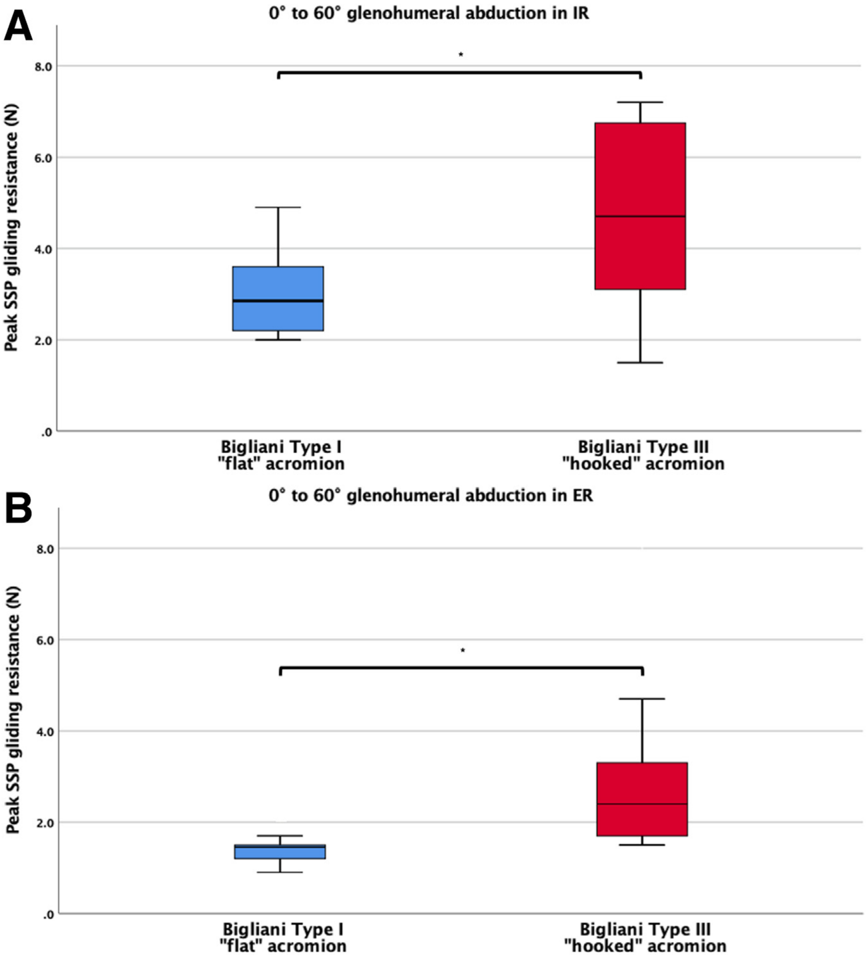
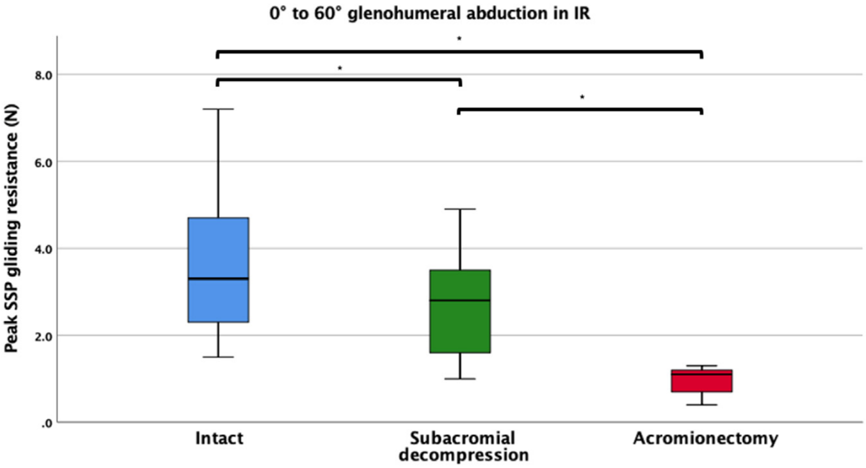


Fig. 4. Differences in mean peak supraspinatus (SSP) gliding resistance based on the shape of the acromion according to the Bigliani classification. (A) Mean peak SSP gliding resistance during 0° to 60° of scapular-plane glenohumeral abduction in internal rotation (IR) was significantly higher in specimens with a hooked (Bigliani type III) acromion (red box plot) compared with the specimens with a flat (Bigliani type I) acromion (blue box plot). (B) A) Mean peak SSP gliding resistance during 0° to 60° of scapular-plane glenohumeral abduction in external rotation (ER) was significantly higher in specimens with a hooked (Bigliani type III) acromion (red box plot) compared with the specimens with a flat (Bigliani type I) acromion (blue box plot). Values are presented as means and 95% confidence interval error bars. *Level of significance: $P < .05$.

subacromial decompression reduced peak SSP gliding resistance to almost half of the value observed in the intact condition. We tried to understand whether there is a relevant gliding resistance between the SSP tendon and the coracoacromial arch in the intact condition and whether a systematically performed anterolateral acromioplasty and acromionectomy significantly reduce this gliding resistance. It was, however, not the aim of this study to conclude whether our observations warrant the usage of anterolateral acromioplasty

Fig. 5. Differences in mean peak supraspinatus (SSP) gliding resistance during 0° to 60° of scapular-plane glenohumeral abduction in internal rotation (IR) comparing the intact condition (blue box plot) with the subacromial decompression (green box plot) and the acromionectomy (red box plot) conditions. Values are presented as means and 95% confidence interval error bars. *Level of significance: $P < .05$.



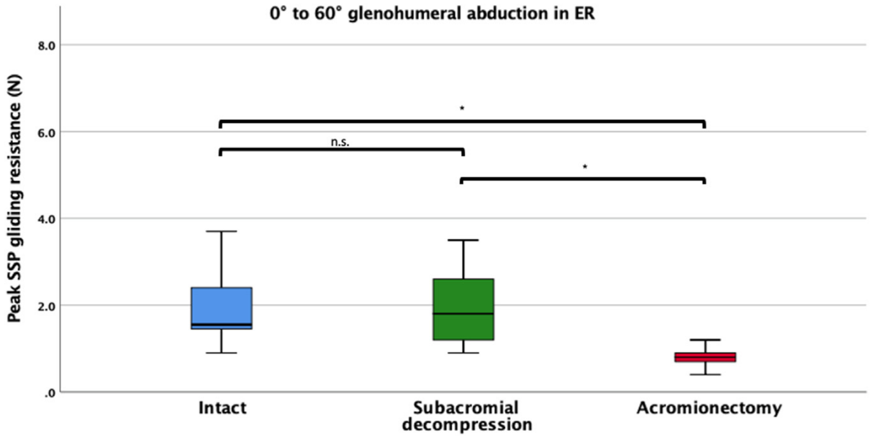


Fig. 6. Differences in mean peak supraspinatus (SSP) gliding resistance during 0° to 60° of scapular-plane glenouhumeral abduction in external rotation (ER) comparing the intact condition (blue box plot) with the subacromial decompression (green box plot) and the acromionectomy (red box plot) conditions. Values are presented as means and 95% confidence interval error bars. *Level of significance: $P < .05$. n.s., nonsignificant.

in vivo, although it certainly showed that resection of the anterolateral acromion can significantly reduce gliding resistance between the SSP tendon and the coracoacromial arch in an experimental setup. The meaning and clinical implication of our observations need to be further investigated.

Limitations

This study has several limitations. First, we had no complete information regarding the medical history or any symptoms of the shoulder joint of the donors, and therefore we were not able to say that the shoulders were with no (microscopic) shoulder pathology; however, the shoulders were screened using macroscopic and radiographic examination before testing. Second, the calculated gliding resistance values are not only between the coracoacromial arch and the SSP tendon but also between the tendon and the supraspinatus fossa, the distal end of the clavicle, and between the sutures and the transosseous tunnels. To ascertain the quantity of all peritendinous gliding resistance, a third condition after resection of the acromion was included, which showed that the range of dispersion was reasonable and averaged below 1 N in both arm positions. Third, the gathered results of peak SSP gliding resistance represent the cadaveric condition. Although we took care of the soft tissues during dissection and kept all specimens moist during testing, this does not represent the in vivo conditions and therefore cannot be directly translated into clinical practice. Fourth, although an interim analysis was conducted and revealed sufficient power for the primary outcome, the little number of specimens remains a limitation of this study. Lastly, no type II acromions according to the Bigliani classification were included in this study.

Conclusions

In this cadaveric study, peak gliding resistance between the SSP tendon and the coracoacromial arch during combined abduction and IR was significantly reduced after anterolateral acromioplasty and significantly higher in specimens with a hooked acromion.

Disclosure

The authors report no conflicts of interest in the authorship and publication of this article. Full ICMJE author disclosure forms are available for this article online, as supplementary material.

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