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Function of the supraspinatus muscle

Abduction of the humerus studied in cadavers

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We evaluated the function of the supraspinatus tendon with a dynamic shoulder model. Active glenohumeral joint motion was simulated in 10 cadaveric shoulder specimens with hydrodynamic cylinder forces at the deltoid muscle and at the rotator cuff. Computerized regulation initiated standardized cycles of glenohumeral joint motion, where the isolated effect of the supraspinatus muscle could be studied. The efficacy of the supraspinatus muscle on elevation of the glenohumeral joint was measured with an ultrasonic sensor system. Pressures underneath the coracoacromial vault were recorded with capacitive sensors, as an indicator of the impingement at the shoulder. Elimination of force of the supraspinatus muscle led to a 6 percent decrease in elevation of the glenohumeral joint. The deltoid muscle was able to reverse this loss of elevation by a force increase of one third of the lost supraspinatus force. If no force was applied to the supraspinatus muscle, average pressures underneath the coracoacromial vault decreased 8 percent. It was concluded that the supraspinatus produces less torque and more glenohumeral joint compression than the deltoid. However, the supraspinatus has no effect on depression of the humeral head during elevation.

The clinical consequence of our observations is that operative closure of supraspinatus tendon defects is not mandatory.

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The value of investigations on cadaveric shoulders for assessing shoulder joint mechanics is limited, if no active force mechanism is initiated (Inman et al. 1944). The use of in vivo experiments on the shoulder, however, is restricted by the invasiveness of most techniques. We simulated active motion of the glenohumeral joint with a dynamic shoulder model (Wuelker et al. 1994) and measured the effect of supraspinatus muscle force on elevation of the glenohumeral joint and its effect on pressures underneath the coracoacromial vault, indicating impingement between the humeral head and the acromion.

Material and methods

The dynamic shoulder model (Wuelker et al. 1994)

10 shoulders were taken from fresh adult cadavers aged 39 (22–66) years. The scapulothoracic and acromioclavicular junctions were disarticulated and the humerus amputated 20 cm distal to the center of the humeral head. Only specimens with no degenerative changes were included. The skin, the subcutaneous tissues and all muscles, except the rotator cuff, were removed. The rotator cuff muscles were resected one centimeter medial to their musculotendinous junctions.

The specimens were mounted in the physiologic resting position of the scapula. Weights represented the arm weight and were loaded onto an aluminum arm at the amputation site. Steel wire cables were attached to the shoulder muscles: one each to the deltoid, the supraspinatus and the subscapularis and one to the infraspinatus and the teres minor. Regulated forces of hydrodynamic cylinders were applied to the cables. Spatial orientation of the glenohumeral joint was recorded with ultrasonic sensors. Pressures underneath the coracoacromial vault were measured at a resolution of six sensors per square centimeter with 168 capacitive sensors (model EMED SF, Novel, Munich, Germany), enveloped in a 11 × 3 centimeters × 1 mm silicone coating (Figure 1). The accuracy of 5 percent, as indicated by the manufacturer, was probably somewhat diminished by motion and by the occurrence of shear forces. In addition, individual sensors occasionally malfunctioned during the investigation, necessitating an exchange of

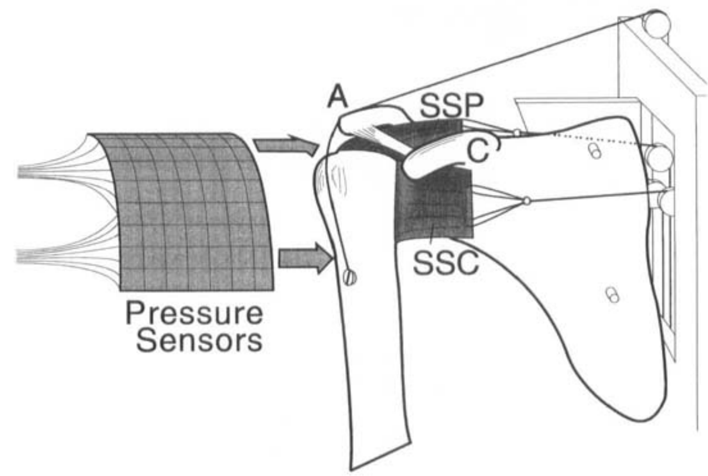

Figure 1. Ventral aspect of the mounted shoulder specimen. A acromion, C coracoid process, SSC subscapularis tendon, and SSP supraspinatus tendon. Scapular fixation device to the right with force transmitting wires to the tendons

the entire pressure sheath. The silicone coating was sutured to the tip of the acromion laterally and tied to the specimen mount medially. By assigning each sensor to the overlying anatomic structure of the coracoacromial vault, pressures under the acromion, under the coracoacromial ligament, and under the coracoid process were calculated.

Testing protocol

Force was applied to the shoulder muscles at a constant ratio. First, this ratio was calculated from the cross-sectional area of the respective muscles (Wuelker et al. 1994): deltoid muscle 43 percent, supraspinatus 9 percent, subscapularis 26 percent, infraspinatus/teres minor 22 percent. Subsequently, no force was applied to the supraspinatus muscle: deltoid muscle 47 percent, subscapularis 29 percent, infraspinatus/teres minor 24 percent.

At the beginning of each experiment, a small amount of force (deltoid muscle 26 *4 (SD)* N) was applied to prevent the loaded arm from subluxating inferiorly. This resulted in a position of elevation of 17 *5* degrees (starting position). Maintaining the described force ratio, the total force was then increased in increments of 20 N until the arm reached approximately 90 degrees of elevation.

Cylinder forces were recorded during elevation. Subsequently, the cycle of elevation was run automatically. Each cycle of elevation was repeated 5 times. Statistics were calculated by analysis of variance (two-way layout with equal numbers of observations in the cells).

Results

Reliability of glenohumeral joint motion was previously demonstrated (Wuelker et al. 1994). Insertion of the sensors resulted in an average position change of 7.4 degrees of abduction, 6.9 degrees of flexion/extension and 13 degrees of rotation.

The horizontal position of the arm (87 *6* degrees, Figure 3) was reached at an average deltoid force of 251 *35* N and an average supraspinatus force of 52 *8* N (Figure 2). Elimination of supraspinatus muscle force resulted in a loss of elevation of 6 percent ($P < 0.05$). This loss of elevation was compensated with a mean increase of deltoid force of 7 percent (Figure 4), which amounted to only one third of the force lost at the supraspinatus muscle (Figure 5).

Repeatability variance of pressure measurements underneath the coracoacromial vault for 5 elevation cycles in the 10 specimens averaged 5 mbar, but readings varied markedly between the specimens. The average pressure during one cycle of elevation with an estimated physiologic muscle force ratio was 111 *100* mbar underneath the acromion, 10 *12* mbar underneath the coracoacromial ligament and 72 *96* mbar underneath the coracoid process. The mean pressure underneath all structures in the coracoacromial vault was 65 *46* mbar.

If no force was applied to the supraspinatus muscle, the mean pressure was 110 *126* mbar underneath the acromion, 11 *9* mbar underneath the coracoacromial ligament and 57 *77* mbar underneath the coracoid process, 59 *46* mbar on average underneath all structures in the subacromial vault. This represented an 8 percent decrease from the average pressure under estimated physiologic conditions (NS).

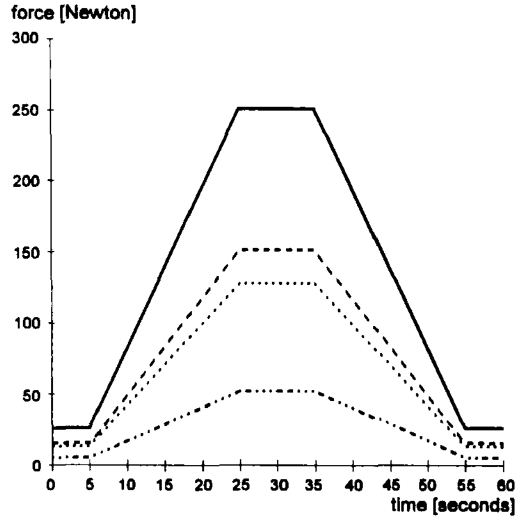

Figure 2. The elevation cycle: 0–4 sec starting position, 5–24 sec linear force increase at prescribed force ratio, 25–34 sec maximum force, 35–54 sec linear force decrease at prescribed force ratio, and 55–60 sec starting position. Cylinder forces prescribed by the controller during elevation cycle of 60 seconds. Average of 10 shoulder specimens. Muscles: deltoid (——), subscapularis (- - - -), infraspinatus with teres minor (····), and supraspinatus (- - · · ·).

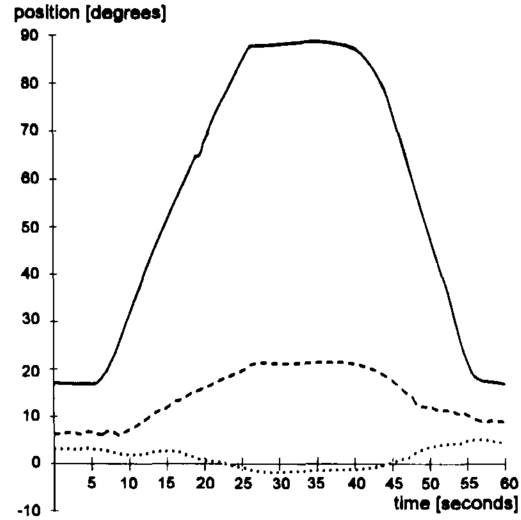

Figure 3. Glenohumeral joint position measured by the ultrasonic sensor system during elevation cycle of 60 seconds. Average of 10 shoulder specimens.
Abduction (——), flexion (- - - -), internal rotation (····).

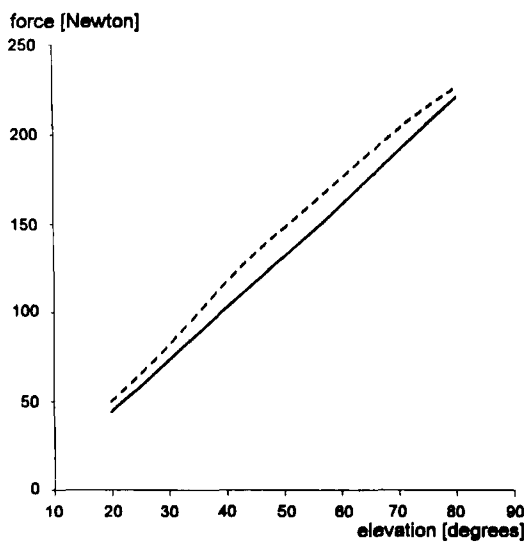

Figure 4. Deltoid muscle force in various positions of glenohumeral joint elevation under estimated physiologic conditions (——), and with force elimination of supraspinatus (- - - -). The loss of elevation due to elimination of the supraspinatus force was compensated by a deltoid force increase of 7 percent.

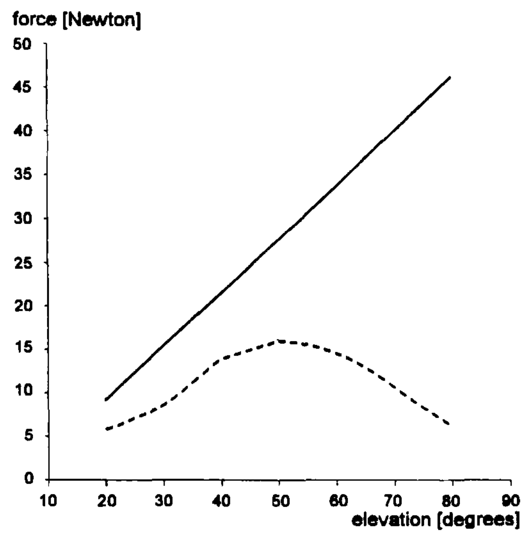

Figure 5. Amount of supraspinatus force eliminated in various positions of glenohumeral joint elevation (——), and increase in deltoid force required to compensate for loss of supraspinatus force (- - - -). On average, one third of the eliminated supraspinatus force was required.

Discussion

Our shoulder model was designed to simulate the effect of muscle force on shoulder motion. Studies using inert specimens are of limited value at the shoulder, the mechanics of which are so largely dominated by active, muscular control. Theoretical calculations of isolated forces within this system are not feasible. Pressures in the subacromial bursa were recorded in human volunteers by Sigholm et al. (1988), but not in regard to suprapinatus muscle function. The development of computer models of the shoulder has only just begun (Wood et al. 1989, Karlsson and Peterson 1992, Van der Helm et al. 1992).

Some elements of physiologic shoulder motion were not yet included in the model. Scapulothoracic motion was not simulated in the present investigation. An attempt was made also to include variations in muscle activity related to the position of elevation of the arm, as available from electromyography readings (Inman et al. 1944, Ringelberg 1985, Kronberg et al. 1987, Perry 1988, Habermeyer 1989). The respective measurements, however, are so unreliable that their use does not seem appropriate. In the dynamic shoulder model, the ratio of all muscle forces was therefore kept constant during the entire cycle of elevation. In addition, a small but noticeable change in glenohumeral motion was caused by the pressure sensor sheath.

At the beginning of each motion cycle, the arm was slightly elevated to prevent inferior subluxation of the loaded humerus. The first 20 degrees of elevation could therefore not reliably be studied. Electromyography recordings have indicated high (Kronberg et al. 1987, Habermeyer 1989) and low (Inman et al. 1944) supraspinatus activity in this segment of glenohumeral joint motion.

The reported cross-sectional area of the supraspinatus muscle averages 7 square centimeters in the literature (Fick 1910, Shiino 1913, Strasser 1917, Poppen and Walker 1978). Estimates of the physiologic, maximum force of skeletal musculature vary between 23 and 65 N per square centimeter (Fick 1910, Recklinghausen 1920, Morris 1948, Ikai and Fukunaga 1968, Bechtol 1980, Perry 1988), and average 32 N per square centimeter. According to electromyograpic recordings (Kronberg et al. 1987), the supraspinatus reaches only 52 percent of its maximum activity during elevation of the arm. A peak supraspinatus muscle force of 118 N is thus calculated theoretically, with a wide margin of error. In the dynamic shoulder model, the supraspinatus force during elevation of the arm under estimated physiologic conditions was lower.

Lack of force in the supraspinatus muscle reduced the position of elevation of the glenohumeral joint, compared to estimated physiologic conditions. The deltoid was able to compensate for this loss of elevation with only one third of the supraspinatus force. The deltoid thus acts as a more effective elevation muscle than does the supraspinatus at the glenohumeral joint, due to its longer moment arm (Perry 1988). The supraspinatus muscle appears to cause more glenohumeral joint compression than elevation torque. Poppen and Walker (1978), Kapandij (1984) and Habermeyer (1989) also indicated major joint compression by the supraspinatus muscle. Perry (1988) even reported that joint compression comprised 94 percent of the supraspinatus muscle force. Linge and Mulder (1963) noted only a small loss of shoulder function with selective nerve block of the supraspinatus, and this loss was easily compensated by the deltoid muscle. Howell et al. (1986), however, presented autopsy measurements and electromyography data indicating that the moment arm of the supraspinatus (25 2 mm) was insignificantly shorter than that of the deltoid (28 2 mm). The authors concluded that both muscles contributed equally to elevation of the arm.

Compression of the glenohumeral joint surfaces by the supraspinatus muscle supposedly centers the humeral head on the glenoid during elevation of the arm (Poppen and Walker 1978, Kapandji 1984, Perry 1988, Habermeyer 1989). This is of particular interest at the shoulder, where the upward-oriented force element of the deltoid muscle must be compensated during elevation. Otherwise, an increase in pressures underneath the coracoacromial vault, i.e., an impingement will occur. According to the present data, however, the supraspinatus muscle does not contribute to pressure reduction in the subacromial space. Because of marked differences between specimens, no level of statistical significance was reached. It must be assumed, however, that the supraspinatus causes an increase in subacromial pressures and thus acts like the deltoid muscle. Therefore, the supraspinatus does not prevent impingement between the humeral head and the acromion. Centering of the humeral head appears to be effected by the more inferior muscles of the rotator cuff.

In conclusion, loss of force at the supraspinatus muscle produced only minor alterations in the glenohumeral joint mechanics. This explains why defects of the respective tendon may remain asymptomatic (Cooton and Rideout 1964, Rothman and Parke 1965, Wuelker et al. 1991). A decision to surgically close supraspinatus tendon defects must therefore weigh the relatively minor functional improvement that can be expected, and the extent of the required surgery, as well as the general condition of the patient. If the impingement mechanism of the shoulder results in isolated supraspinatus defects, the impingement alone may be treated by anterior acromioplasty, and the defect be left open.

Acknowledgements

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