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Original article

Strain on the repaired supraspinatus tendon during manual traction and translational glide mobilization on the glenohumeral joint: A cadaveric biomechanics study

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Abstract

There has been no report on the mechanical effects of joint mobilization on rotator cuffs. The purpose of this study was to determine whether it is safe to use grade 3 joint mobilization techniques after rotator cuff repair. Nine fresh frozen cadaveric shoulders were used in this study. The strains on the artificially repaired supraspinatus tendon during joint mobilization were measured at 0° and 30° of shoulder abduction and were compared with those at the maximal stretching position and relaxing position. Additionally, gap distances were measured during this experiment. The strain at 30° of abduction of the repaired tendon during each joint mobilization was significantly smaller than that at 0° abduction ($P<0.05$). At 30° of abduction, the strain during joint mobilization was not statistically different from that of the shoulder in the relaxing position, except during the inferior glide technique. Gap distances were 0 mm at 30°, while the distances were 1.06–1.46 mm at 0°. Our findings suggest that joint mobilization techniques, except inferior glide, can be performed safely without significantly straining the repaired tendon at 30° of abduction, if rotator cuff repair is performed at 0° of abduction.

Keywords: Strain; Supraspinatus tendon; Rotator cuff tear; Fresh cadaver

1. Introduction

Shoulder joint contracture can occur after repair of rotator cuff tears. This can be caused by capsular contracture, tendon shortening, scars, and adhesions of the subacromial and the subscapularis-conjoined tendon regions (Warner and Greis, 1998; Hatakeyama et al., 2001a; Matsen et al., 2004). Therefore, intensive physical therapy using range of motion exercise (ROM exercise) (Cofield, 1985; Matsen et al., 2004) and joint mobilization (Bruzga and Speer, 1999; Mangus et al., 2002) immediately after surgery is important.

Generally, in order to prevent and treat joint contracture, limited movement of the joint itself is used in ROM exercise. However, when this movement causes pain, effective stretching of the connective tissue that limits motion becomes difficult (Quillen et al., 1992). For example, when contracture of the posterior capsule occurs in the glenohumeral joint, antero-superior translation of the humeral head occurs during arm abduction and, this translation consequently leads to subacromial impingement (Harryman et al., 1990; Warner et al., 1990). In addition, contracture of the anterior capsule (Flatow et al., 1994) and the inferior

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capsule (Cofield, 1985; Hjelm et al., 1996) often lead to impingement. Therefore, in a shoulder joint with a capsular contracture, this exercise can actually worsen any injuries of the joint capsule and rotator cuff.

On the other hand, joint mobilization, such as traction and glide, is used to stretch the tendon, ligament, and capsule and to improve the physiological accessory movement. Traction is the technique that distracts one articular surface perpendicular to the other, and glide techniques translationally glide one articular surface parallel to the other (Kaltenborn, 1999). These techniques are considered capable of stretching the particular connective tissues that limit joint motion without impingement, resulting in an improvement of the limited ROM and reduction in pain (Johns and Wright, 1962; Quillen et al., 1992).

The effects of joint mobilization have been previously reported. Hsu et al. (2000a, b, 2002a) demonstrated that anterior–posterior and inferior translational gliding improved the range of abduction and external rotation in cadaveric glenohumeral joints. Conroy and Hayes (1998) investigated the effects of joint mobilization and compared them to general physical therapy on a patient with subacromial impingement syndrome. They then reported that joint mobilization was not effective on ROM and any functional outcome of the shoulder joint, but it provided effective pain relief.

However, care should be taken when joint mobilization is used on the shoulder joint after surgery. In order to prevent and treat joint contracture after rotator cuff repair, knowledge of the mechanical stresses of joint mobilization on the repaired rotator cuff is required. Hatakeyama et al. (2001a) and Zuckerman et al. (1991) observed the effects of shoulder positions on the rotator cuff under several different conditions. Although the effects and safety of joint mobilization were studied from the physiological aspect of the shoulder (Hsu et al., 2002b; Gokeler et al., 2003), the mechanical effect of joint mobilization on the rotator cuff was unclear because connective tissues of the shoulder that had different mechanical properties were not observed individually in these studies. Therefore, the mechanical effects of joint mobilization on intact and repaired rotator cuffs should be clarified first in order to perform joint mobilization without excessive stretching stress on the rotator cuff.

The purpose of this study was to measure the strain on both intact and repaired supraspinatus tendons, which is the primary site of rotator cuff tears, and the gap distance of the repair site during joint mobilization by using fresh frozen cadaveric shoulders. Furthermore, based on these results, we discuss about safely applying joint mobilization after rotator cuff repair.

2. Methods

2.1. Preparation of specimens

Nine frozen shoulders (four left shoulders and five right shoulders) harvested from nine fresh cadavers were used in the experiment. The mean age at death was 80 years (71–91 years of age). Any shoulder with macroscopic evidence of rotator cuff tears or osteoarthritis was excluded. However, none of these shoulders conformed to these criteria.

The shoulders, disarticulated from their thoraxes, were stored in a freezer at $-20\,^{\circ}$C. The thawing of the specimens at room temperature started 12 h prior to experimentation. Then, soft tissues—except the rotator cuff muscles, biceps brachii muscles, coracoacromial ligaments, and capsules—were carefully removed to avoid the loss of intra-articular negative pressure in the glenohumeral joint. The distal third of the humerus was exposed, and an acrylic stick was inserted perpendicular to the shaft indicating the direction of the forearm. Next, the humerus was amputated above the elbow. During the experiment, the specimens were kept moist by spraying saline solution on them every 5–10 min. The room temperature was maintained at $22\,^{\circ}$C.

2.2. Testing apparatus

A wooden jig, consisting of a wooden board and a square timber, was used for this experiment. The scapula of the specimen was fixed on the wooden jig so that the medial border of the scapula was perpendicular to the ground (Culham and Peat, 1993) (Fig. 1). Two anchors (Fastin RC threaded suture anchor, Mitek, Tokyo, Japan) were inserted into the bony insertion of the infraspinatus and subscapularis tendons to apply a compressive force of 11 N to each thread (total 22 N) against the glenoid fossa. In previous cadaveric studies, this compressive force was used as the minimum force required, preventing subluxation of the humeral head on application of translational loads (Warner et al., 1992; Tibone et al., 1998). Using this system, the humeral head was maintained in concentric position onto the glenoid fossa after joint mobilization was performed.

2.3. Measurement device

The strain data on the supraspinatus tendon was obtained from a precise displacement sensor (Pulse Coder, LEVEX, Kyoto, Japan) (Fig. 2a). This Pulse Coder consisted of a coil sensor and a brass pipe. The displacement was measured by detecting the position of the brass pipe relative to the coil sensor that generated the magnetic field. Analogue data of the displacement was represented and recorded on a digital scaling meter (HV35, Allied Control, Tokyo, Japan)

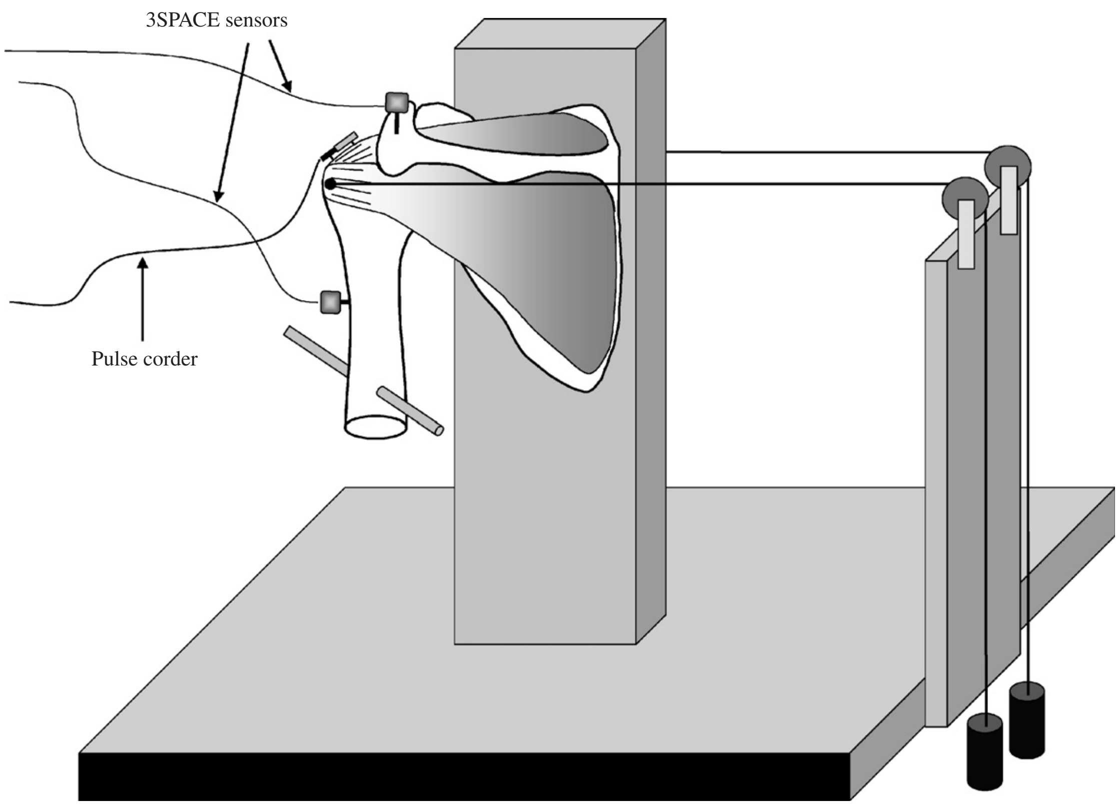

Fig. 1. Schematic illustration of the experimental setup. A scapula of a specimen was mounted vertically on the wooden jig. A Pulse Coder was attached to the supraspinatus tendon. Sensors of the 3SPACE device were attached to the acromion and the humerus.

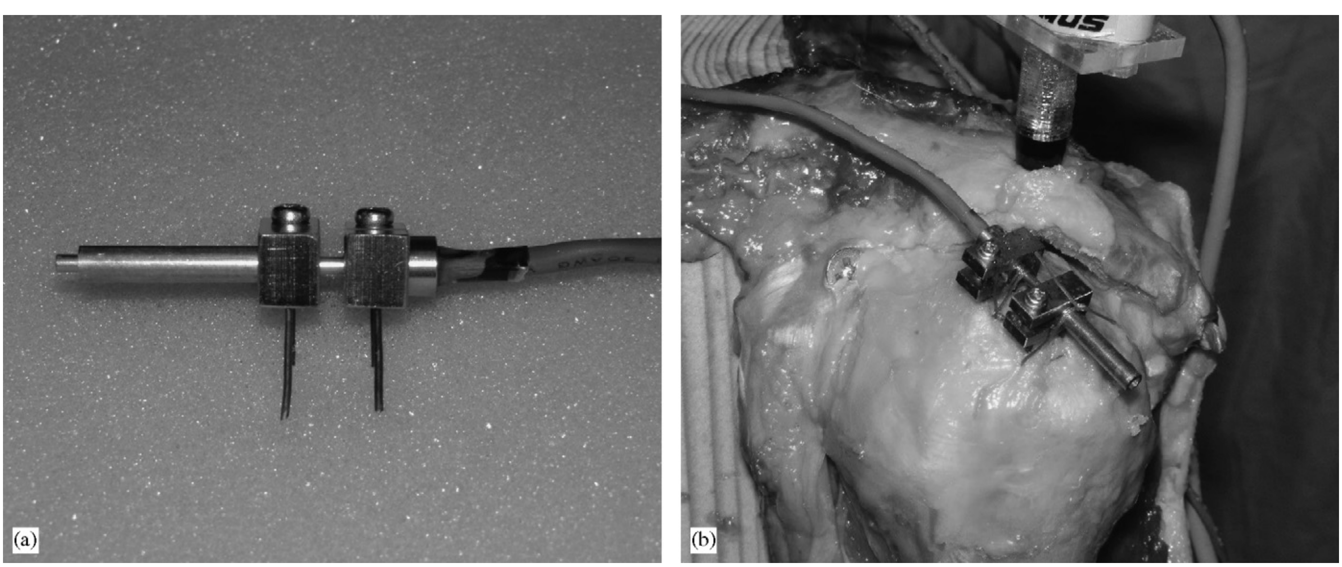

Fig. 2. Photographs of the Pulse Coder. (a) The precise displacement sensor "Pulse Coder" used to measure the strain on tendons by changes in the length between points; (b) Pulse Coder attached to the supraspinatus tendon with sutures.

that converted the obtained data into a digital form. The non-linearity of this sensor was 0.25%/full scale, and the range of measurement was 14 mm according to the manufacturer's instructions. The sensors with fishhook-like barbed points were attached to the greater tuberosity and the proximal part of the supraspinatus tendon. The sensor was placed parallel to the tendon fibre (Fig. 2b). Changes in the length between the points of the coil sensor and the brass pipe allowed the sensor to measure the strain on the supraspinatus tendon. By using a digital caliper, the accuracy of preliminary calibration of the Pulse Coder, which was attached in the supraspinatus tendon, was 0.1 mm root mean square (RMS). A similar type device, which uses the same principle, was previously used to measure strain on the supraspinatus tendon (Hatakeyama et al., 2001a, b).

A six-degree-of-freedom electromagnetic tracking device (3SPACE FASTRACK, Polhemus, Colchester, Vermont) was used to monitor the precise glenohumeral angles during this measurement. This device enabled measurement of the three-dimensional position and orientation of the sensors relative to the absolute coordination generated by the source (An et al., 1988). One sensor was placed on the acromion and the other was placed on the middle portion of the humerus (Fig. 1). In this system, the angle of arm abduction and extension was defined as the angle between the plane of the glenoid fossa and the longitudinal axis of the humerus. The rotation angle was defined as the rotation of the humerus along the longitudinal axis. With a 750-mm range of measurement from the source, the positional accuracy was 0.8 mm RMS, and the angular accuracy was 0.5° RMS. The 3SPACE device kinematically monitored the glenohumeral angles during the strain measurement.

2.4. Experimental procedure

The measurements were first performed on intact supraspinatus tendons to assess the difference of tendon conditions and then on the repaired tendon model. In the case of the model, the supraspinatus tendon was excised (width 2.0 cm, length 1.5 cm) (Hatakeyama et al., 2001a, b)(Fig. 3a) from the greater tuberosity, which simulated the retracted supraspinatus tendon, and was repaired with #2 polyester threads (Ethibond, Ethicon Inc. Somerville, NJ) passed through drill holes in the greater tuberosity. The threads were pulled out with a 3-kg force and clamped at the outlet from the bone with the arm in 30° of external rotation at 0° of arm abduction (Hatakeyama et al., 2001a, b) (Fig. 3b). Acromioplasty and removal of the coracoacromial ligament was also performed because this technique is often used in rotator cuff repair and enabled the Pulse Coder to move in the subacromial space. All these techniques were performed by an orthopaedic surgeon who was familiar with shoulder surgery.

The neutral position was defined as 30° of external rotation at 0° of abduction in the glenohumeral joint, because the scapula internally tilts 30° relative to the coronal plane in vivo (Culham and Peat, 1993; Itoi et al., 2004). For reliable comparison, the maximal stretching

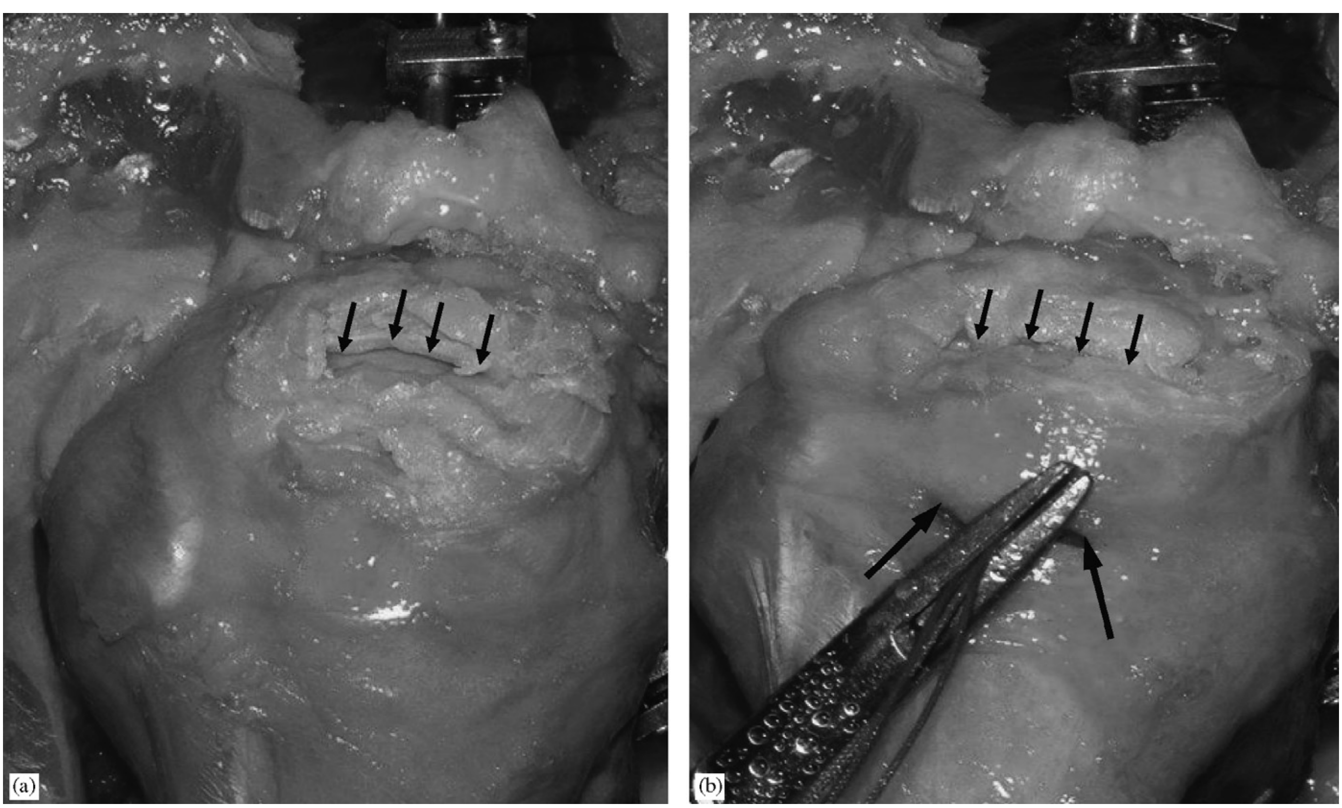

Fig. 3. Photographs of the supraspinatus tendon repair. (a) Artificial supraspinatus tear (width 2.0 cm, length 1.5 cm). Small arrows indicate the site of supraspinatus tendon tear; (b) Repair of torn supraspinatus tendon. The threads were clamped with a 3-kg force at the outlet from the bone (a large arrow). Small arrows indicate the repair site.

position (adduction at extension) (Evjenth and Hamberg, 1984) and relaxing position of the supraspinatus tendon (neutral position at 30° of abduction) (Zuckerman et al., 1991; Hatakeyama et al., 2001a) were used as reference positions producing the highest and lowest tendon strain. The shoulder positions examined in this mobilization experiment were at 0° and 30° of arm abduction in the scapular plane. In order to reproduce shoulder positions during the measurement, the positions were monitored by the 3SPACE FASTRACK device.

Four joint mobilization techniques, i.e. traction, inferior, anterior and posterior glide, were performed at each position by a physical therapist who had more than 5 years of experience in correcting shoulder disorders by using joint mobilization. The therapist had no information regarding the hypotheses of this study, and the strain data represented on the digital scaling meter was masked. The grade of joint mobilization was set at 3 as defined by Kaltenborn (1999). Grade 3 is used to stretch connective tissues by applying force to the final stop during joint mobilization. At these positions, the strains and gap distances on the supraspinatus tendon were measured and compared with those during joint mobilization techniques. The measurements were performed 3 times during each joint mobilization technique in each of the two positions. The holding time during each measurement was set at 20 s. In a clinical setting, joint mobilization for 20–60 s was used to stretch the connective tissue (Quillen et al., 1992; Conroy and Hayes, 1998; Mangus et al., 2002). Hsu et al. (2000a, b, 2002a, b) reported that the ROM improved after joint mobilization was done for 10–30 s. Therefore, we decided that the holding time should be set at 20 s as the minimal time that is effective in biomechanical study and clinical practice.

2.5. Data analysis

First, the length between the barbed points of the coil sensor and the brass pipe on the sensors at the neutral position was recorded. Next, the longitudinal displacement of the sensors at the measurement area of the tendon was recorded when the measurement positions were held for 20 s. The displacement was defined as the length change from the neutral position. The strain on the tendon was calculated by the following formula:

$$\text{Strain}(\%) = \Delta L(\text{mm})/L(\text{mm}) \times 100.$$

L indicates the length between the points at the neutral position, and ΔL indicates the displacement from L. A positive strain value indicates that the supraspinatus tendon was stretched from the neutral position, and a negative strain value indicates a slackening of the tendon.

Gap distance was regarded as the distance between the proximal edge of the torn supraspinatus tendon and its distal edge. Therefore, we defined the detected displacement by the sensor, which was placed across the repair site as gap distance (ΔL), as Pruitt et al. (1991) defined it in a previous study regarding flexor tendon repair. In the neutral position, the gap distance was 0 mm with a 3-kg tensile force on the repair site.

2.6. Statistical analysis

Intra-class correlation coefficients were calculated to determine test–retest reliability in each condition. A two-way repeated measures analysis of variance was used to determine the effects of supraspinatus tendon conditions (intact tendon and repaired tendon), shoulder positions (0° and 30° of shoulder abduction), and joint mobilization techniques (traction and inferior/anterior/posterior glide). To detect the differences among the joint mobilization techniques, Bonferroni's multiple comparison procedure was used. Moreover, Dunnett's multiple comparison test was performed to compare the strain during joint mobilization techniques occurring in both the relaxing and stretching positions. The α level was set at 0.05. All statistical analyses were performed on SPSS for Windows ver.11.5J. (SPSS Japan Inc., Tokyo, Japan).

3. Results

3.1. Reliability of these measurements

Intra-class correlation coefficients of these measurements in each condition ranged from 0.809 to 0.984. These values corresponded to almost perfect (Landis and Koch, 1977).

3.2. Strain on the intact supraspinatus tendon

The strains on the intact supraspinatus tendon are shown in Fig. 4. The strains during each joint mobilization technique at 30° of arm abduction were significantly smaller than those occurring at 0° ($P<0.005$). There were no significant differences among joint mobilization techniques both at 0° and 30° of arm abduction. At 0° of arm abduction, the strains during each joint mobilization technique did not show significant differences from those occurring in the stretching position, and were significantly larger than those occurring in the relaxing position ($P<0.001$). At 30° of arm abduction, the strains during each joint mobilization technique were significantly smaller than those occurring in the stretching position ($P<0.05$), while these strains did not show significant differences from those in the relaxing position.

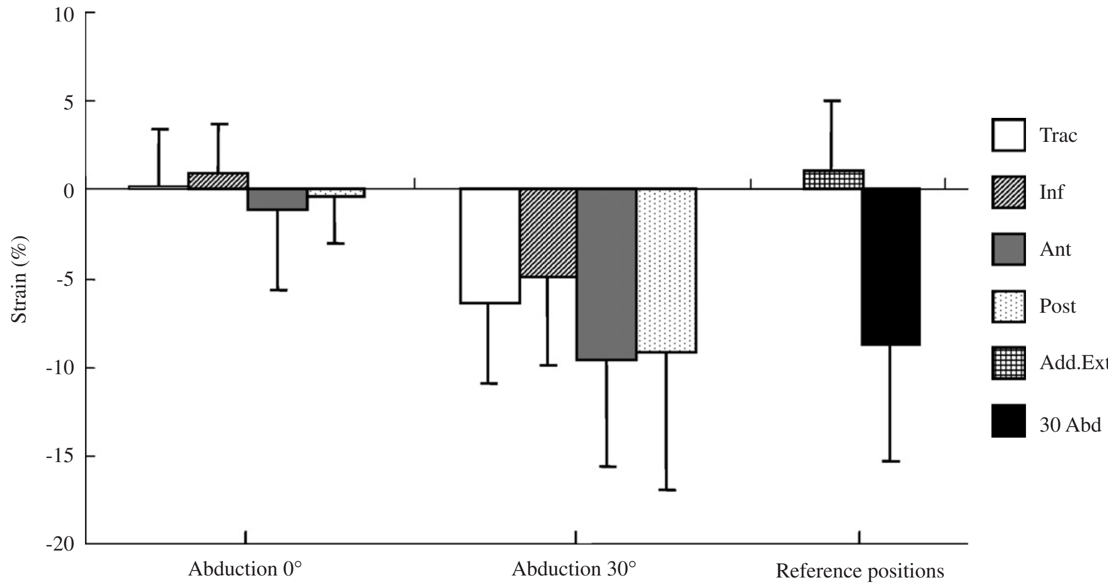

Fig. 4. Strain on intact supraspinatus tendon. The values and bars represent mean strain and standard deviation, respectively. Direction of the glenohumeral mobilization and reference positions: Trac, traction; Inf, inferior glide; Ant, anterior glide; Post, posterior glide; Add. Ext, adduction at extension; 30 Abd, 30° of arm abduction with neutral rotation.

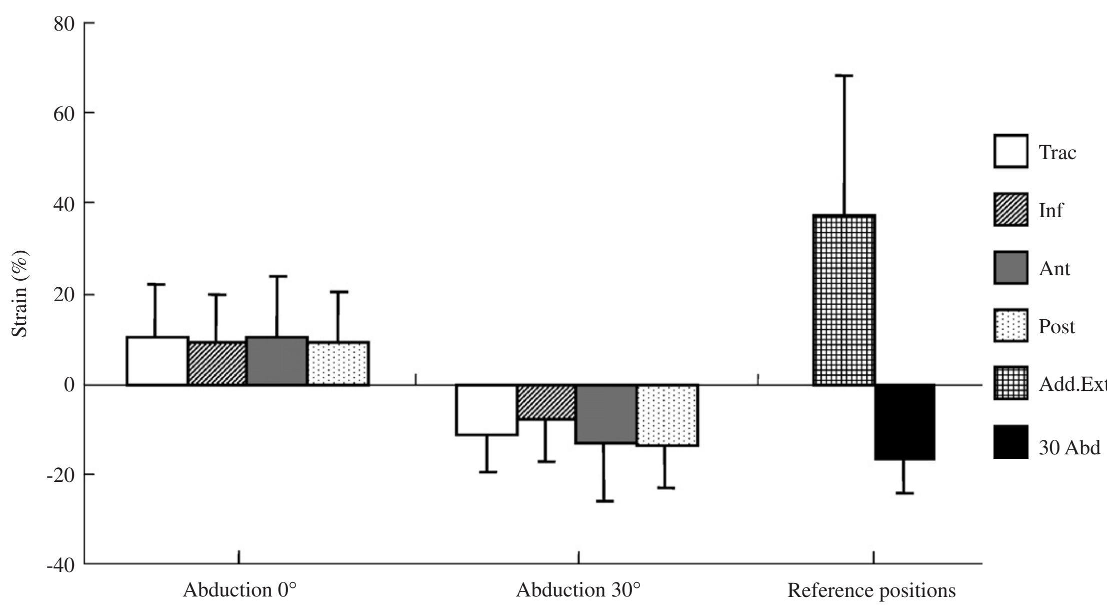

Fig. 5. Strain on repaired supraspinatus tendon. The values and bars represent mean strain and standard deviation, respectively. Direction of the glenohumeral mobilization and reference positions: Trac, traction; Inf, inferior glide; Ant, anterior glide; Post, posterior glide; Add. Ext, adduction at extension; 30 Abd, 30° of arm abduction with neutral rotation.

3.3. Strain on the repaired supraspinatus tendon

The strains on the repaired supraspinatus tendon are shown in Fig. 5. While the strain on the repaired supraspinatus tendon during joint mobilizations was significantly larger than that on the intact tendon at 0° of abduction ($P<0.05$), the strain on the repaired tendon during joint mobilizations was not different from that occurring on the intact tendon at 30° of abduction (Figs. 4 and 5). The strains during each joint mobilization technique at 30° of arm abduction were significantly smaller than those occurring at 0° ($P<0.005$). Among joint mobilization techniques, there were no significant differences in the strains at both 0° and 30° of arm abduction.

At 0° of arm abduction, the strains during each joint mobilization technique were significantly smaller than those occurring in the stretching position ($P<0.001$),

Table 1
Gap distance on the repaired supraspinatus tendon during joint mobilization, stretching position, and relaxing position[a]

	Gap distance (mm)	
	0° of abduction	30° of abduction
Traction	1.3 ± 1.2	0
Inferior glide	1.5 ± 1.3	0
Anterior glide	1.3 ± 1.3	0
Posterior glide	1.1 ± 1.0	0
Stretching position	4.5 ± 4.0	
Relaxing position	0	

[a]The values represent mean gap distance and standard deviation.

while these strains were significantly larger than those occurring in the relaxing position ($P<0.001$). At 30° of arm abduction, although the strains during each joint mobilization technique were significantly smaller than those occurring in the stretching position, only inferior glide showed a significantly larger strain than that occurring in the relaxing position ($P<0.01$). There were no significant differences in the strains between other techniques and the relaxing position.

3.4. Gap distances

The gap distances of the repaired site during joint mobilization techniques at each abduction angle are listed in Table 1. Gaps were formed in the stretching position (4.47 mm) and during all joint mobilization techniques at 0° of abduction (1.06–1.46 mm). Conversely, no gap was observed in the relaxing position and all joint mobilization techniques at 30° of abduction.

4. Discussion

Application of joint mobilization techniques immediately after rotator cuff repair has not been clarified. Quillen et al. (1992) considered the stress on immature repaired tissues as a contraindication of joint mobilization. This indicated that joint mobilization should be prohibited immediately after surgery if it stresses such tissues. Bruzga and Speer (1999) recommended joint mobilization techniques, which are performed at grade 1 or 2, after surgery if these would be useful in reducing pain and promoting joint nutrition. However, they also stated that joint mobilization at grade 3 or 4 should be used only after the healing of repaired tissue. Based on these opinions, joint mobilization techniques, which exert stress on the repaired tissue, should be avoided immediately after rotator cuff repair. On the other hand, based on the concept of joint mobilization, it is hypothesized that this technique can stretch specific tissues and can reduce the stress on tissues that should not be stretched (Conroy and Hayes, 1998). Accordingly, while stress on the repaired supraspinatus tendon can be avoided, a particular part of the capsule, which is responsible for joint contracture, may be stretched by joint mobilization techniques. In order to resolve this issue, the stress on particular tissues such as the supraspinatus tendon by joint mobilization should be quantitatively determined.

In this study, the strain and gap distance on the repaired supraspinatus tendons were measured to estimate the stress undergone by these during joint mobilization. For ideal repair, minimization of gap formation at the repair site and maintenance of mechanical stability of the repaired tendon until solid healing occurs are important (Gerber et al., 1994). Therefore, the criteria for safely performing joint mobilization are that (1) no gap is formed, and (2) the repaired tendon relaxes more than in the neutral position in which the repair was performed.

A gap was formed in the stretching position (4.5 mm) and in all joint mobilization techniques at 0° abduction (1.1–1.5 mm) in this study. In comparison with a 10-mm gap distance, which is regarded as complete gap formation (Burkhart et al., 1997a, b), joint mobilization techniques at 0° abduction corresponded to 11–15%, while the stretching position was 45%. These techniques have the risk of increasing gap formation and can lead to the failure of healing (Burkhart et al., 1998; Gerber et al., 1994, 1999). Therefore, joint mobilization at 0° abduction should be avoided immediately after tendon repair.

On the other hand, during joint mobilization at 30° abduction, strains were negative compared to neutral position and no gaps were observed. The supraspinatus tendon relaxes after abducting the arm beyond 30°. By using three-dimensional analysis using magnetic resonance imaging, Nakajima et al. (2004) observed that intact supraspinatus tendons were relaxed beyond 30° arm abduction. Zuckerman et al. (1991) demonstrated that the strain on repaired tendons, with both small and large tears, remained small above 30° abduction irrespective of the position of flexion/extension or rotation. Hatakeyama et al. (2001a) determined strain on repaired supraspinatus tendons under the same repair condition as ours. They concluded that arm abductions above 30° in the scapular plane seemed to be safe even immediately after the repair, because the strain decreased in these positions and the estimated tensile forces were less 0.5 kg. According to the estimation from their data, tensile forces caused by joint mobilization at 30° were 0–0.5 kg, compared to 3 kg in the neutral position. Therefore, joint mobilization techniques can be safely performed keeping the tendon relaxed and not forming a gap at the repair site if the torn tendon is repaired at 0°.

However, repetitive joint mobilization at 30° abduction might lead to gap formation on the repair site. The repaired tendon has less endurance to mechanical stress than the intact tendon because these two have different mechanical properties. The failure load of the repaired tendon was reported to be 72–605 N (Rossouw et al., 1997; Hatakeyama et al., 2001a; Ma et al., 2004), while that of the intact tendon was 600–800 N (Itoi et al., 1995). In addition, cyclic loading might lead to gap formation even if the mechanical properties of the repair site are strong, or the cyclic stress is small (Rossouw et al., 1997; Petit et al., 2003). Hatakeyama et al. (2001a) concluded that internal rotation at 30° abduction should be postponed until the rotator cuff healing progresses, because the strain and tensile force on the repair site during internal rotation significantly increased from neutral rotation. In this study, the strain during inferior glide was significantly larger than that occurring in the relaxing position. Therefore, of these four joint mobilization techniques, repeated use of the inferior glide technique should be avoided immediately after rotator cuff repair.

Strain on the supraspinatus tendon is commonly measured by a small linear displacement sensor. The sensor, ''Pulse corder'' in this study, is capable of directly measuring tendon behaviour along with its fibre orientation during joint mobilization, while measurements by imaging techniques are limited. Because of distorted three-dimensional movement of imaging markers buried in the cuff tendons during shoulder motion, accurate detection of strain between each marker becomes extremely difficult. In addition, the sensor could accurately measure the strain with little resistance because preliminary calibration of the Pulse Coder, which was attached in the supraspinatus tendon, demonstrated the high accuracy of 0.1 mm RMS.

There is concern that our experiment was performed on a cadaveric model. Since muscle tension in fresh cadavers is different from that of in vivo and some soft tissues were removed, the stress on the tendon due to muscle tension might also differ between them. However, the strain on the tendon in fresh cadavers might be the same or smaller than that of in vivo because physiologic muscle tone and muscle contraction stabilize the humeral head and decrease its movement (Warner et al., 1999).

This study had a few limitations. First, the strain obtained from this study was not always consistent because the specimens were obtained from aged cadavers. The supraspinatus tendon in younger adults has great endurance to stress because the connective tissues in adults are more flexible and have greater failure load than that in the aged cadavers (Reeves, 1968). Therefore, we believe that our findings are applicable to younger to middle-aged adults.

Second, the safety of joint mobilization could not be determined with regard to the strain–stress curve and endurance to repetitive loading because tensile force to the tendon was not measured. In this study, instead, the strains and gap distances in the stretching and relaxing positions were observed and tensile forces on the repaired tendon were estimated from the data in a previous study (Hatakeyama et al., 2001a).

Finally, our finding can be applied only to rotator cuff tears that are of the same size as or smaller than those studied here. Strain on a massive tear including the infraspinatus and/or subscapularis tendons during joint mobilization may be different from the results of this study. Therefore, further studies are required to clarify the strain on a massive tear.

Further research following our study should determine whether the joint mobilization techniques could prevent joint contracture after rotator cuff repair. Investigation of strain and stress on the contracted joint capsule during mobilization techniques are necessary. In addition, the effect of repetitive joint mobilization on the repaired tendon and capsule should be also determined. These studies will contribute to the making of good decisions concerning the application of joint mobilization after rotator cuff repair.

5. Conclusion

Our findings suggested that if rotator cuff repair is performed at 0° of abduction, joint mobilization techniques at 0° of arm abduction should be avoided immediately after supraspinatus tendon repair because these techniques produce large strain of the tendon and form a gap at the repair site. In the same fashion, our findings also suggest that joint mobilization techniques at 30° of arm abduction can be used without large strain of the tendon and forming a gap at the repair site. However, inferior glide, even at 30° abduction, should be postponed because relatively larger strain than that of the relaxing position may lead to failure of tendon repair. Although our findings would be useful to decide the application of joint mobilization after rotator cuff repair, further study regarding strain on the contracted joint capsule or the effect of repetitive joint mobilization would provide even more information.

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