The Effect of Postoperative Passive Motion on Rotator Cuff Healing in a Rat Model

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Background: Surgical repairs of torn rotator cuff tendons frequently fail. Immobilization has been shown to improve tissue mechanical properties in an animal model of rotator cuff repair, and passive motion has been shown to improve joint mechanics in animal models of flexor tendon repair. Our objective was to determine if daily passive motion would improve joint mechanics in comparison with continuous immobilization in a rat rotator cuff repair model. We hypothesized that daily passive motion would result in improved passive shoulder joint mechanics in comparison with continuous immobilization initially and that there would be no differences in passive joint mechanics or insertion site mechanical properties after four weeks of remobilization.

Methods: A supraspinatus injury was created and was surgically repaired in sixty-five Sprague-Dawley rats. Rats were separated into three postoperative groups (continuous immobilization, passive motion protocol 1, and passive motion protocol 2) for two weeks before all underwent a remobilization protocol for four weeks. Serial measurements of passive shoulder mechanics (internal and external range of motion and joint stiffness) were made before surgery and at two and six weeks after surgery. After the animals were killed, collagen organization and mechanical properties of the tendon-to-bone insertion site were determined.

Results: Total range of motion for both passive motion groups (49% and 45% of the pre-injury values) was less than that for the continuous immobilization group (59% of the pre-injury value) at two weeks and remained significantly less following four weeks of remobilization exercise. Joint stiffness at two weeks was increased for both passive motion groups in comparison with the continuous immobilization group. At both two and six weeks after repair, internal range of motion was significantly decreased whereas external range of motion was not. There were no differences between the groups in terms of collagen organization or mechanical properties.

Conclusions: In this model, immediate postoperative passive motion was found to be detrimental to passive shoulder mechanics. We speculate that passive motion results in increased scar formation in the subacromial space, thereby resulting in decreased range of motion and increased joint stiffness. Passive motion had no effect on collagen organization or tendon mechanical properties measured six weeks after surgery.

Clinical Relevance: The results of the present study demonstrated a detrimental effect of early controlled passive motion following surgery in a rat model of rotator cuff injury and repair. When considered together with previous studies involving this model that have illustrated the beneficial effects of immobilization and the transient nature of range-of-motion losses associated with immobilization, these findings further support the need for clinical studies designed to investigate the effects of postoperative immobilization on rotator cuff tendon-to-bone healing.

Rotator cuff tears are a common clinical problem that can cause pain and limit shoulder function. In addition, the ability of rotator cuff tendons to heal back to bone

following injury is limited. Recurrent tears after repair of the torn insertion site are common and have been found to occur in 20% to 90% of cases¹⁻³. Because of the high rate of repair

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failure, much research has been focused on strategies to improve rotator cuff healing following surgical repair. A rat model of rotator cuff injury and repair has been used extensively in our laboratory and others⁴⁻¹⁷. Previous studies involving this model have shown that while long periods of immobilization improved the mechanical properties of the repaired insertion site¹⁸, even short periods of immobilization increased shoulder stiffness and decreased shoulder range of motion, although transiently¹¹.

Clinically, there is a history of immobilization following rotator cuff repair surgery. Several studies have demonstrated only a transient increase in shoulder stiffness in association with postoperative immobilization¹⁹⁻²¹. Shortly after the publication of those studies, immobilization as a postoperative treatment fell out of popularity, largely because of the emergence of studies in the flexor tendon repair literature illustrating the detrimental effects of immobilization on range of motion in the hand²²⁻²⁴. However, there was little, if any, fundamental research to support a relationship between flexor tendon repair and rotator cuff tendon repair.

To address the detrimental effects of immobilization on flexor tendons, passive motion has become the standard of care^{25,26}. In both humans and a dog model, passive motion has been found to significantly decrease the formation of adhesions and thereby decrease finger joint stiffness and improve range of motion following flexor tendon repair^{23,27-29}. Unlike passive motion in the hand, the effect of passive motion in the shoulder has been largely unstudied. A small number of clinical studies have investigated the effect of passive motion following rotator cuff repair. Those studies were performed in the absence of shoulder immobilization, and the results were inconclusive^{30,31}. In addition, the effect of passive motion has not been examined in a controlled animal model of tendon-to-bone healing following rotator cuff repair in the shoulder. Therefore, the objective of the present study was to determine the effect of daily passive motion of the shoulder during a short immobilization period following supraspinatus injury and repair in a rat model. We hypothesized that (1) initially, daily passive motion would result in improved passive shoulder joint mechanics in comparison with those after injury and repair with continuous immobilization alone and (2) after four weeks of remobilization, there would be no differences in passive joint mechanics, insertion site mechanical properties, or collagen organization.

Materials and Methods

Sixty-five Sprague-Dawley rats weighing 400 to 450 g (Charles River, Wilmington, Massachusetts) were used in this study, which was approved by the Institutional Animal Care and Use Committee. All animals underwent unilateral supraspinatus detachment and surgical repair as previously described¹². Incisions were made through the skin and the superficial shoulder musculature before the full thickness and width of the supraspinatus tendon were sharply detached from the insertion on the humerus. Before repair, any remaining fibrocartilage at the insertion site was removed with use of a

high-speed burr in order to allow for recreation of the insertion site. A single 0.5-mm drill hole was then made through the humerus, and the tendon was grasped with use of a modified Mason-Allen technique. The suture was passed through the drill hole, and the tendon was reaposed to its insertion site. Six suture knots were tied (with use of 5-0 polypropylene), the muscle incision was closed in a layered fashion, and the skin was closed with staples.

Immediately after surgery, all rats were immobilized for two weeks in a manner similar to that described previously¹⁵. Webril (Medco Sports Medicine, Tonawanda, New York) was placed around the injured arm and the upper torso, forming a modified sling. This Webril sling was then covered in a layer of adhesive bandage (Vetrap; 3M, St. Paul, Minnesota). During this immobilization period, animals were managed with one of three postoperative treatment protocols: (1) continuous immobilization, (2) passive motion protocol 1, or (3) passive motion protocol 2 (Fig. 1). Rats in the continuous immobilization group were returned to their cages and were checked daily for continued immobilization for two weeks. The remaining animals were assigned to one of the two passive motion protocols for five days per week for two weeks. During this period, immobilization materials were removed once a day and the assigned passive motion protocol was applied, followed by a return to immobilization. Passive motion protocols were derived from human and dog passive motion studies in the hand flexor tendon repair literature²³. The first passive motion protocol, shown to be beneficial to joint mechanics following flexor tendon repair in the hand, consisted of 600 cycles per day at a frequency of 1 Hz during one ten-minute period. The arc of motion in this protocol consisted of motion in both internal and external rotation from the neutral position in the rat (90° of forward flexion and 0° of abduction, which, because of a difference in scapular position, is analogous to 0° of forward flexion and 90° of abduction in the human) to 90% of the average pretreatment range of motion in both directions. The second passive motion protocol consisted of 300 cycles per day at a frequency of 0.5 Hz. In this protocol, motion was performed only in the external direction in an attempt to minimize the force on the healing tendon-to-bone insertion site. One cycle consisted of rotation from neutral to 90% of the average pretreatment external rotation and a return to neutral.

After the initial two weeks, all three groups underwent a four-week protocol of gradual remobilization. The first week of remobilization consisted of cage activity only. Following cage activity, rats ran on a treadmill for five days per week at a moderate speed of 10 m/min, beginning with seven minutes on the first day and gradually increasing over the three-week period to one session of 60 min/day.

Passive shoulder joint mechanics (range of motion and joint stiffness) were measured for all animals prior to assignment to an experimental group and at two and six weeks after repair, similar to what has been previously described¹¹. At each time point, the animal was anesthetized and its arm was placed in a rotating clamp at its neutral position. This position was

Fig. 1

After surgery (at time 0), rats were separated into three groups according to their immediate postoperative treatment: continuous immobilization (CI) or one of two passive motion protocols (PM1 or PM2). After two weeks, all animals received four weeks of remobilization involving treadmill running.

defined as neutral, and a torque was applied to the arm for three internal and external rotation loading and unloading cycles to a prescribed torque target (Fig. 2). Internal rotation, external rotation, and the total range of motion were determined with use of data from all three cycles. The internal and external rotation data from all three cycles were pooled, and a bilinear fit utilizing least-squares optimization was applied to calculate joint stiffness in the toe and linear regions in both directions (Fig. 2).

After the animals were killed, muscle-tendon-bone segments were dissected for histological examination ($n = 3$ for continuous immobilization and $n = 4$ for passive motion protocol 2) or mechanical testing ($n = 17$ for continuous

immobilization, $n = 20$ for passive motion protocol 1, and $n = 10$ for passive motion protocol 2). Collagen organization of the healing tendon-to-bone insertion site was evaluated with use of 5- μm -thick sections stained with hematoxylin and eosin³². Quantitative measures of collagen organization were obtained with use of a previously described polarized light microscopy method³². The circular angular deviation of the collagen, a measure of the disorganization of collagen fibers, was determined with use of a circular statistics software package (Oriana; Kovach Computing Services, Wales, United Kingdom).

For mechanical testing assays, the associated muscle was removed and fine dissection of the tendons was performed under a microscope. During this fine dissection, gross scar

Fig. 2

Representative torque-angle curve illustrating three loading and unloading cycles of internal rotation (negative angles) and external rotation (positive angles). Toe (T) and linear (L) regions and corresponding stiffnesses as determined from a bilinear fit are shown.

Fig. 3

Illustration depicting the mechanical testing protocol, which included preconditioning (A), stress relaxation (B), return to initial preload (C), and ramp to failure (D).

tissue that had formed at the insertion site was removed by an experienced investigator (C.D.P.) in a consistent and blinded fashion. Any scar tissue that was not well-formed enough to bear load was removed, whereas any tissue that was observed to bear load was retained. Four Verhoeff stain lines for optical strain measurements were then placed along the length of each tendon with use of 6-0 silk suture. The first stain line was placed at the insertion site (defined as the apposition of tendon into bone), the second stain line was placed 2 mm proximal to the insertion site, the third stain line was placed 4 mm proximal to the insertion site, and the fourth and final stain line

(indicating grip placement) was placed 8 mm proximal to the insertion site. The length of the insertion site was defined as the distance between the first and second stain lines; this length was established histologically in a previous study¹⁴. Tendon cross-sectional area was measured with use of a laser-based system³³.

For biomechanical testing, the humerus was embedded in a holding fixture with use of polymethylmethacrylate and the holding fixture was inserted into a custom testing fixture. The proximal end of the tendon was then held at the fourth stain line (8 mm) in a screw clamp lined with fine-grit sand-

Fig. 4

After two weeks of continuous immobilization (CI) or either passive motion protocol (PM1 or PM2), total range of motion (ROM) was significantly decreased in both passive motion groups as compared with the control group. *Significant ($p < 0.017$) compared with continuous immobilization. Error bars represent the standard deviation.

TABLE I Internal and External Range of Motion at Two and Six Weeks After Supraspinatus Injury and Repair*

	Range of Motion (% of preinjury value)					
	2 Weeks Postop.			6 Weeks Postop.		
	CI	PM1	PM2	CI	PM1	PM2
Internal	65 ± 27	47 ± 13†	38 ± 13†	78 ± 21	65 ± 15†	55 ± 27†
External	53 ± 15	50 ± 13	58 ± 17	65 ± 17	61 ± 14	69 ± 14

*CI = continuous immobilization, PM1 = passive motion protocol 1, and PM2 = passive motion protocol 2. †Significant ($p < 0.017$) compared with continuous immobilization group.

paper. The specimen was immersed in a 39°C phosphate-buffered saline solution bath, preloaded to 0.1 N, preconditioned for ten cycles from 0.1 to 0.5 N at a rate of 1%/sec, and held at 0.1 N for 300 seconds. Immediately thereafter, a stress relaxation experiment was performed by elongating the specimen to a strain of 5% (on the basis of the optical gauge length) at a rate of 5%/sec (0.4 mm/sec) followed by a 600-second relaxation period. Specimens were then returned to the initial preload and were held for sixty seconds. Ramp to failure was applied at a rate of 0.3%/sec (Fig. 3). With use of the applied stain lines, local tissue strain at the insertion site was measured optically with a custom texture-tracking program (MATLAB; Mathworks, Natick, Massachusetts).

The elastic properties of stiffness and modulus were calculated with use of linear regression from the visually determined linear region of the load-displacement and stress-strain curves, respectively. As measures of viscoelastic properties, peak and equilibrium load (the load at the peak of the stress-relaxation test and the load after the 600-second hold, respectively) were determined from the stress-relaxation curve for each specimen, and the percent relaxation was calculated from these values ($[\text{peak load} - \text{equilibrium load}]/\text{peak load}$).

Passive shoulder mechanics and biomechanical properties were compared between groups at each time point with use of one-way analysis of variance with Bonferroni correction. The level of significance for these parameters was set at $p < 0.017$ (0.05/3). Statistical analysis of angular deviation for collagen organization was performed with use of a two-tailed t test (with the level of significance set at $p < 0.05$).

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Results

Two weeks after supraspinatus tendon injury and repair, which corresponded to the last day of immobilization with or without passive motion, there were several differences in passive shoulder mechanics. The total range of motion in both passive motion groups was significantly less than that in the

TABLE II Rotational Stiffness Two and Six Weeks After Supraspinatus Injury and Repair*

	Rotational Stiffness (N-mm/deg)					
	2 Weeks Postop.			6 Weeks Postop.		
	CI	PM1	PM2	CI	PM1	PM2
Internal						
Toe	0.09 ± 0.08	0.14 ± 0.06†	0.16 ± 0.10†	0.09 ± 0.06	0.09 ± 0.04	0.11 ± 0.04
Linear	0.13 ± 0.05	0.21 ± 0.05†	0.22 ± 0.07†	0.11 ± 0.03	0.15 ± 0.04†‡	0.11 ± 0.05
External						
Toe	0.16 ± 0.07	0.19 ± 0.07	0.17 ± 0.05	0.11 ± 0.07	0.15 ± 0.08	0.12 ± 0.04
Linear	0.22 ± 0.07	0.24 ± 0.05‡	0.18 ± 0.05	0.20 ± 0.05	0.22 ± 0.05	0.20 ± 0.03

*The values are expressed as the mean and the standard deviation. Toe and linear values represent the rotational stiffness in the toe and linear regions of the torque-angle curve after a bilinear fit. CI = continuous immobilization, PM1 = passive motion protocol 1, and PM2 = passive motion protocol 2. †Significant ($p < 0.017$) compared with continuous immobilization. ‡Significant ($p < 0.017$) compared with passive motion protocol 2.

Fig. 5

After four weeks of remobilization, range of motion was still significantly decreased with both passive motion protocols. CI = continuous immobilization, PM1 = passive motion protocol 1, and PM2 = passive motion protocol 2. *Significant ($p < 0.017$) compared with continuous immobilization. Error bars represent the standard deviation.

continuous immobilization group (Fig. 4) (see Appendix). Total range of motion was 49% of uninjured values after passive motion protocol 1 and 45% of uninjured values after passive motion protocol 2, compared with 59% with continuous immobilization. The internal range of motion was also significantly less in both passive motion groups, whereas the external range of motion was not different (Table I) (see Appendix). There were no differences in range of motion between the two passive motion groups. Animals in both passive motion groups had significantly increased values for internal toe stiffness and internal linear joint stiffness in comparison with those in the continuous immobilization group (Table II). External linear joint stiffness was significantly increased in the

group treated with passive motion protocol 1 as compared with that treated with passive motion protocol 2 (Table II).

After four weeks of remobilization by means of treadmill running, there were still significant differences in range of motion and joint stiffness. Total range of motion continued to be significantly lower in the passive motion groups as compared with the continuous immobilization group (Fig. 5) (see Appendix). Again, range of motion was significantly decreased in the internal direction and not the external direction (Table I) (see Appendix). At this time point, the only significant joint stiffness increase was seen in terms of internal linear stiffness when passive motion protocol 1 was compared with passive motion protocol 2 and continuous immobilization (Table II).

TABLE III Tendon Organization, Area, and Mechanical Measures at Six Weeks After Supraspinatus Injury and Repair

	Six Weeks Postop.*		
	CI	PM1	PM2
Angular deviation (deg)	55.6 ± 20.1	NA	56.3 ± 29.7
Area (mm ²)	4.5 ± 1.8	4.9 ± 1.1	4.1 ± 1.4
Modulus (MPa)	37.6 ± 24.1	30.4 ± 13.4	51.9 ± 36.1
Stiffness (N/mm)	11.2 ± 2.4	10.6 ± 2.7	10.9 ± 1.7
Percent relaxation	87.8 ± 4.2	87.8 ± 6.4	85.4 ± 3.6

*The values are given as the mean and the standard deviation. CI = continuous immobilization, PM1 = passive motion protocol 1, and PM2 = passive motion protocol 2. NA = not available.

There was no difference in collagen organization between the group treated with continuous immobilization and the group treated with passive motion protocol 2. In both groups, regardless of postoperative treatment, collagen was still highly disorganized six weeks after surgery, as indicated by the high angular deviation values (Table III).

Six weeks after supraspinatus injury and repair, the results of mechanical testing at the insertion site showed no differences in terms of area ($p = 0.29$), stiffness ($p = 0.78$), modulus ($p = 0.29$), or percent relaxation ($p = 0.46$) between any of the groups (continuous immobilization, passive motion protocol 1, passive motion protocol 2) (Table III).

Discussion

We hypothesized that passive motion would reduce the transient loss in shoulder range of motion that we previously observed in association with immobilization following rotator cuff repair in the rat. Surprisingly, our results contradicted this hypothesis as two weeks of either passive motion protocol caused a loss in range of motion in comparison with injury and repair followed by continuous immobilization over the same period. Furthermore, both passive range of motion protocols resulted in increased joint stiffness in comparison with immobilization alone. We also hypothesized that four weeks of remobilization would negate differences between groups. However, we found that both passive motion groups continued to have inferior shoulder mechanics (in terms of both range of motion and joint stiffness) after this remobilization period. Scar-tissue formation is the likely source of the detrimental changes in passive shoulder mechanics; we speculate that passive motion in our model may promote excessive matrix formation around the insertion site and increased scar formation, thereby worsening passive shoulder mechanics.

The results of the present study in terms of range of motion and joint stiffness are different from those in the literature regarding the positive effects of similar passive motion protocols following flexor tendon repair in the hand^{22,23,29,34}. We believe that these differences are due in part to the inherent differences between rotator cuff and flexor tendons. First, flexor tendons function in a one-degree-of-freedom hinge joint whereas rotator cuff tendons function in a ball and socket-like joint with three degrees of freedom. Second, when flexor tendons are injured, they are typically repaired in a tendon-to-tendon fashion^{22,23,29,34}. Rotator cuff tendons are most often repaired in a tendon-to-bone fashion at the site of their insertion on the humerus. Third, flexor tendons slide in a sheath whereas no tendon sheaths surround rotator cuff tendons. Finally, the primary complication following flexor tendon repair is scar formation and subsequent adhesion to the surrounding sheath. The primary complication following rotator cuff repair is rerupture of the repaired insertion site.

In the hand, passive motion disrupts adhesions forming between the repaired tendon and its surrounding sheath, resulting in increased range of motion, without detrimental effects on tendon-to-tendon healing^{23,28}. In the shoulder, where

the tendons are not surrounded by a sheath, we speculate that passive motion results in micromotion near the tendon-to-bone insertion site, stimulating excess matrix formation around the insertion site. It is further speculated that this leads to increased scar formation around the insertion site within the subacromial space. This scar formation could explain the decreased range of motion and increased joint stiffness in internal rotation, which was the biggest contributor to loss of range of motion and increased stiffness with both passive motion protocols. While histological analysis was available for the groups treated with continuous immobilization and passive motion protocol 2, we could not reliably and quantitatively measure gross scar formation and therefore we can only speculate that it was responsible for the loss in range of motion in the present study. In internal rotation, the repair site would normally move away from the acromion, toward the coracoid. The presence of increased scar tissue at the repair site and between the repair site and the acromion may be a factor in limiting that motion. It is also possible that the increased scar tissue that we speculate occurs with passive motion may be compressing against the coracoid. This speculation is further supported when we consider that whereas only one of the passive motion protocols included motion in the internal direction, both protocols resulted in a similar decrease in internal range of motion.

Our hypothesis that there would be no differences in insertion site organizational or mechanical properties between the groups at six weeks postoperatively was supported. Interestingly, detrimental changes in passive shoulder mechanics were still present at this time point, although these changes did not translate to inferior tendon mechanical properties. It should be noted that the tendon-to-bone insertion site was finely dissected before organization or mechanical measurements were made, thereby removing any gross scar formation that we speculate to be a major contribution to the loss in range of motion.

It is possible that a two-week period of immobilization or passive motion is too short to result in any changes in organization or mechanics after four weeks of treadmill running. Although superior mechanical changes were not seen until after longer periods of immobilization, we chose a two-week immobilization time point because previous studies identified this interval as the earliest time at which positive changes were seen with immobilization, specifically in an extracellular matrix more closely resembling that of uninjured tissue¹⁵. We do not believe that this period of treadmill running resulted in any detrimental changes in any of the groups because previous studies have shown no differences between animals that were assigned to cage activity and those that were assigned to this remobilization protocol involving treadmill running when it was applied for four weeks directly after injury and repair surgery^{15,18}.

There is little consensus in current clinical practice on postoperative activity in the shoulder, and our results only further establish the need for clinical studies investigating the role of postoperative activity level on both joint mechanics and tendon-to-bone healing. We attempted to recreate the passive motion protocol from the hand literature that has been shown

to decrease joint stiffness while not adversely affecting tissue mechanics following tendon repair in the hand. Specifically, the first protocol (passive motion protocol 1) recreated the number of cycles and the frequency used in a canine flexor tendon study²³. In that protocol, motion involved both internal and external rotation because we believed that achieving close to a total range of motion was important for full recovery. We acknowledge that the variables found to be effective in flexor tendon repair may not be applicable to a rat model of rotator cuff repair. However, clinical practice in the shoulder has been influenced by the flexor tendon literature, and we believed that these established animal study protocols would be an appropriate place to start. After the first protocol was found to be detrimental, a second protocol (passive motion protocol 2) that imparted less stress on the repair was developed. In passive motion protocol 2, passive motion was prescribed at half the number of cycles and frequency as in passive motion protocol 1. In an attempt to minimize stress at the repair site in this protocol, a preliminary rat study was conducted to determine the direction that did not stress the repair site. After the animal was killed, the tendon was threaded with suture near the repair site with the limb in a neutral position. The opposite end of the suture was attached to a spring balance, and internal and external rotation was applied. Tension was present in the suture during internal rotation, whereas the suture was slack during external rotation, resulting in no tension on the repair in this direction, and, consequently, motion in this protocol was prescribed in only the external direction.

The present study is not without limitations. Our passive motion protocols were limited in that they included motion only in internal and external rotation, both during the application of passive range of motion and during the measurement of passive shoulder mechanics. To our knowledge, this is the first study to evaluate passive range of motion in the rat shoulder model, and we wanted to apply passive motion in the same direction as our established method in order to measure shoulder mechanics as well as to focus on a direction that is often evaluated postoperatively clinically. Second, the rotator cuff tendon tears in the present study were made acutely and did not represent the most common human condition, in which degeneration is thought to lead to tendon rupture³⁵. Also, the present study utilized the rat model for rotator cuff repair, and, while we acknowledge that the rat is not an exact model of the human condition, the rat shoulder has been shown to be very similar to the human shoulder in terms of osseous anatomy, articulations, and motion and has been a widely used model for more than ten years⁴⁻¹⁷. In addition, we did not measure passive shoulder mechanics immediately after surgery; instead, the differences in range of motion and joint stiffness were determined relative to the uninjured state. However, all procedures in the present study were consistently performed by the same surgeon (G.R.W.) and therefore we assumed that the change in range of motion due to surgery alone was the same across animals and groups. Furthermore, while we did not attempt to measure gap formation at the repair site, we did not see evidence of gap formation in any

group on the basis of gross observation during tissue harvest. Last, collagen organization was measured on histological sections only for the groups treated with continuous immobilization and passive motion protocol 2. When our data began to show that passive motion protocol 1 was detrimental in terms of range of motion and stiffness, we decided against allocating additional animals for histological analyses and instead developed the passive motion protocol 2.

The results of the present study demonstrate that two early passive motion protocols, one of which has been shown to be beneficial for joint mechanics following flexor tendon repair in the human hand and dog forepaw and the second of which was designed for less force on the healing tendon-insertion site, were both detrimental to joint mechanics following supraspinatus tendon repair in the rat shoulder. Furthermore, the results of the present study highlight that protocols designed specifically for one joint may not be directly applicable to, and may not produce the same effect in, another joint. For this application, the shoulder might benefit from delaying passive motion until after a period of continuous immobilization has allowed for better formation of the repaired insertion site. Future studies will investigate the mechanism that leads to these changes, and clinical studies will investigate the effect of immobilization and passive motion in humans. The data presented here demonstrating the detrimental effects of early passive motion after surgery as well as our previous studies illustrating the transient nature of range-of-motion losses with immobilization support the conduct of clinical studies to examine the effect of postoperative immobilization on rotator cuff tendon-to-bone healing.

Appendix

eA A table showing the difference from preinjury values in terms of external, internal, and total range of motion for all three groups at two and six weeks after surgery is available with the electronic versions of this article, on our web site at jbjs.org (go to the article citation and click on "Supplementary Materials") and on our quarterly CD/DVD (call our subscription department, at 781-449-9780, to order the CD or DVD). ■

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References

1. Harryman DT 2nd, Mack LA, Wang KY, Jackins SE, Richardson ML, Matsen FA 3rd. Repairs of the rotator cuff. Correlation of functional results with integrity of the cuff. *J Bone Joint Surg Am.* 1991;73:982-9.
2. Yamaguchi K, Ditsios K, Middleton WD, Hildebolt CF, Galatz LM, Teefey SA. The demographic and morphological features of rotator cuff disease. A comparison of asymptomatic and symptomatic shoulders. *J Bone Joint Surg Am.* 2006;88:1699-704.
3. Galatz LM, Ball CM, Teefey SA, Middleton WD, Yamaguchi K. The outcome and repair integrity of completely arthroscopically repaired large and massive rotator cuff tears. *J Bone Joint Surg Am.* 2004;86:219-24.
4. Cohen DB, Kawamura S, Ehteshami JR, Rodeo SA. Indomethacin and celecoxib impair rotator cuff tendon-to-bone healing. *Am J Sports Med.* 2006;34:362-9.
5. Galatz LM, Rothenmich SY, Zaegel M, Silva MJ, Havlioglu N, Thomopoulos S. Delayed repair of tendon to bone injuries leads to decreased biomechanical properties and bone loss. *J Orthop Res.* 2005;23:1441-7.
6. Galatz LM, Silva MJ, Rothenmich SY, Zaegel MA, Havlioglu N, Thomopoulos S. Nicotine delays tendon-to-bone healing in a rat shoulder model. *J Bone Joint Surg Am.* 2006;88:2027-34.
7. Gimbel JA, Mehta S, Van Kleunen JP, Williams GR, Soslowky LJ. The tension required at repair to reappose the supraspinatus tendon to bone rapidly increases after injury. *Clin Orthop Relat Res.* 2004;426:258-65. Erratum in: *Clin Orthop Relat Res.* 2004;427:280.
8. Gimbel JA, Van Kleunen JP, Lake SP, Williams GR, Soslowky LJ. The role of repair tension on tendon to bone healing in an animal model of chronic rotator cuff tears. *J Biomech.* 2007;40:561-8.
9. Murray DH, Kubiak EN, Jazrawi LM, Araghi A, Kummer F, Loebenberg MI, Zuckerman JD. The effect of cartilage-derived morphogenetic protein 2 on initial healing of a rotator cuff defect in a rat model. *J Shoulder Elbow Surg.* 2007;16:251-4.
10. Perry SM, Gupta RR, Van Kleunen J, Ramsey ML, Soslowky LJ, Glaser DL. Use of small intestine submucosa in a rat model of acute and chronic rotator cuff tear. *J Shoulder Elbow Surg.* 2007;16(5 Suppl):S179-83.
11. Sarver JJ, Peltz CD, Dourte L, Reddy S, Williams GR, Soslowky LJ. After rotator cuff repair, stiffness—but not the loss in range of motion—increased transiently for immobilized shoulders in a rat model. *J Shoulder Elbow Surg.* 2008;17(1 Suppl):108S-113S.
12. Thomopoulos S, Hattersley G, Rosen V, Mertens M, Galatz L, Williams GR, Soslowky LJ. The localized expression of extracellular matrix components in healing tendon insertion sites: an in situ hybridization study. *J Orthop Res.* 2002;20:454-63.
13. Thomopoulos S, Soslowky LJ, Flanagan CL, Tun S, Keefer CC, Mastaw J, Carpenter JE. The effect of fibrin clot on healing rat supraspinatus tendon defects. *J Shoulder Elbow Surg.* 2002;11:239-47.
14. Thomopoulos S, Williams GR, Gimbel JA, Favata M, Soslowky LJ. Variation of biomechanical, structural, and compositional properties along the tendon to bone insertion site. *J Orthop Res.* 2003;21:413-9.
15. Thomopoulos S, Williams GR, Soslowky LJ. Tendon to bone healing: differences in biomechanical, structural, and compositional properties due to a range of activity levels. *J Biomech Eng.* 2003;125:106-13.
16. Uggen JC, Dines J, Uggen CW, Mason JS, Razzano P, Dines D, Grande DA. Tendon gene therapy modulates the local repair environment in the shoulder. *J Am Osteopath Assoc.* 2005;105:20-1.
17. Würgler-Hauri CC, Dourte LM, Baradet TC, Williams GR, Soslowky LJ. Temporal expression of 8 growth factors in tendon-to-bone healing in a rat supraspinatus model. *J Shoulder Elbow Surg.* 2007;16(5 Suppl):S198-203.
18. Gimbel JA, Van Kleunen JP, Williams GR, Thomopoulos S, Soslowky LJ. Long durations of immobilization in the rat result in enhanced mechanical properties of the healing supraspinatus tendon insertion site. *J Biomech Eng.* 2007;129:400-4.
19. Debeyre J, Patie D, Elmelik E. Repair of ruptures of the rotator cuff of the shoulder. *J Bone Joint Surg Br.* 1965;47:36-42.
20. McLaughlin HL, Asherman EG. Lesions of the musculotendinous cuff of the shoulder. IV. Some observations based upon the results of surgical repair. *J Bone Joint Surg Am.* 1951;33:76-86.
21. Nixon JE, DiStefano V. Ruptures of the rotator cuff. *Orthop Clin North Am.* 1975;6:423-47.
22. Gelberman RH, Amifl D, Gonsalves M, Woo S, Akeson WH. The influence of protected passive mobilization on the healing of flexor tendons: a biochemical and microangiographic study. *Hand.* 1981;13:120-8.
23. Gelberman RH, Woo SL, Lothringer K, Akeson WH, Amiel D. Effects of early intermittent passive mobilization on healing canine flexor tendons. *J Hand Surg Am.* 1982;7:170-5.
24. Woo SL, Gelberman RH, Cobb NG, Amiel D, Lothringer K, Akeson WH. The importance of controlled passive mobilization on flexor tendon healing. A biomechanical study. *Acta Orthop Scand.* 1981;52:615-22.
25. Amadio P, An KN, Ejekär A, Guimberteau JC, Harris S, Savage R, Pettengill KS, Tang JB. IFSSH Flexor Tendon Committee report. *J Hand Surg Br.* 2005;30:100-16. Erratum in: *J Hand Surg Br.* 2005;30:238.
26. Pettengill KM. The evolution of early mobilization of the repaired flexor tendon. *J Hand Ther.* 2005;18:157-68.
27. Boyer MI, Goldfarb CA, Gelberman RH. Recent progress in flexor tendon healing. The modulation of tendon healing with rehabilitation variables. *J Hand Ther.* 2005;18:80-5.
28. Gelberman RH, Nunley JA 2nd, Osterman AL, Breen TF, Dimick MP, Woo SL. Influences of the protected passive mobilization interval on flexor tendon healing. A prospective randomized clinical study. *Clin Orthop Relat Res.* 1991;264:189-96.
29. Silva MJ, Boyer MI, Gelberman RH. Recent progress in flexor tendon healing. *J Orthop Sci.* 2002;7:508-14.
30. Lastayo PC, Wright T, Jaffe R, Hartzel J. Continuous passive motion after repair of the rotator cuff. A prospective outcome study. *J Bone Joint Surg Am.* 1998;80:1002-11.
31. Raab MG, Rzeszutko D, O'Connor W, Greatting MD. Early results of continuous passive motion after rotator cuff repair: a prospective, randomized, blinded, controlled study. *Am J Orthop.* 1996;25:214-20.
32. Gimbel JA, Van Kleunen JP, Mehta S, Perry SM, Williams GR, Soslowky LJ. Supraspinatus tendon organizational and mechanical properties in a chronic rotator cuff tear animal model. *J Biomech.* 2004;37:739-49.
33. Favata M. Scarless healing in the fetus: implications and strategies for post-natal tendon repair. PhD dissertation. University of Pennsylvania, Philadelphia. 2006.
34. Silva MJ, Thomopoulos S, Kusano N, Zaegel MA, Harwood FL, Matsuzaki H, Havlioglu N, Dovan TT, Amiel D, Gelberman RH. Early healing of flexor tendon insertion site injuries: tunnel repair is mechanically and histologically inferior to surface repair in a canine model. *J Orthop Res.* 2006;24:990-1000.
35. Hashimoto T, Nobuhara K, Hamada T. Pathologic evidence of degeneration as a primary cause of rotator cuff tear. *Clin Orthop Relat Res.* 2003;415:111-20.