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Alterations in function after rotator cuff tears in an animal model

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Abstract

Rotator cuff tears are a common problem presenting with loss of shoulder function, such as reduced range of motion and inability to perform daily activities. Unfortunately, most animal models of shoulder injuries do not examine shoulder function as a result of rotator cuff injury. This study examined the effect of rotator cuff tears on shoulder function in an animal model. Forty-eight Sprague-Dawley rats were divided into uninjured control, supraspinatus tendon detachment, supraspinatus+infraspinatus tendon detachment, or supraspinatus+subscapularis tendon detachment groups. Functional assessment was determined with ambulatory parameters (paw and stride measures) and range of motion prior to tendon detachment and at various time points after tendon detachment. We found that measures of shoulder function were significantly altered with rotator cuff tendon tears. The addition of a second tendon detachment had additional detrimental effects on animal shoulder function. These findings are consistent with alterations in shoulder function observed clinically with rotator cuff injuries.

Introduction

Rotator cuff tears are a common problem presenting with impairment of shoulder function, such as reduced range of motion and inability to perform daily activities. Clinically, rating systems are used to evaluate the effect of tears on shoulder function and may help guide treatment options [7]. Studies suggest a correlation between rotator cuff tear size and decreased shoulder function after rotator cuff repair, specifically during arm motions and activities of daily living [5,7]. Additionally, patients with a recurrent tear have decreased functional scores compared to those with intact rotator cuffs [5,7].

Functional deficits due to injuries, such as Achilles tendon rupture, have been studied in animal models using various ambulation parameters [13]. Using a functional index to evaluate the recovery of Achilles tendon injuries quantitatively in rats, studies have shown alterations in function between animals with transected and transected and repaired Achilles tendons up to 15 days post-injury [2,13]. In addition, the effect of immobilization on the healing the Achilles tendon has also been investigated using these ambulatory parameters [12]. Animals had a decrease in paw parameters (length and width) at least 3 days after immobilization.

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Although in common use clinically, most animal models of shoulder injuries do not examine shoulder function resulting from rotator cuff injury. This is necessary to provide parallel measures in humans and animal models. Once established, these measures could be used to evaluate potential treatments for human rotator cuff disorders in the animal model. Further, animal models could then be used to identify and examine the potential mechanisms behind functional deficits, which cannot be done in the clinical setting. Therefore, the objective of this study was to examine measures of shoulder function after various rotator cuff tears in an animal model. Our hypotheses were that 1) a supraspinatus tendon tear (1 tendon tear) would result in decreased shoulder function, and 2) a supraspinatus tendon tear with an infraspinatus or subscapularis tendon tear (2 tendon tear) would result in additional decreases in shoulder function.

Material and Methods

Forty-eight, mature, adult Sprague-Dawley rats (400-450 g) were used in this Institutional Animal Care and Use Committee approved study. Twelve animals served as uninjured controls, while thirty-six were divided among the tendon detachment groups (supraspinatus detachment, supraspinatus+infraspinatus detachment, and supraspinatus+subscapularis detachment). In the tendon detachment groups, a unilateral surgery was performed to detach the prescribed rotator cuff tendon(s) sharply from the bony insertion similar to that described previously [6]. Briefly, with the arm in external rotation, a 2 cm skin incision was made followed by blunt dissection down to the rotator cuff musculature. The rotator cuff was exposed and the tendons were visualized at their insertion on the humerus. The tendons were identified as the subscapularis, the most anterior and broadest tendon, the supraspinatus, which passes under the bony arch created by the acromion, coracoid, and clavicle, the infraspinatus, posterior to the other tendons with a similar insertion as the supraspinatus, and the teres minor, inferior to the infraspinatus with a similar insertion. Suture was passed under the acromion to apply upward traction for further exposure, and the supraspinatus was separated from the other tendons before sharp detachment at its insertion on the greater tuberosity. A marking suture with long tails was placed at the end of the tendon to facilitate retrieval at the time of dissection. In the two-tendon detachment groups, the other tendon was detached in the same manner with a sharp dissection from the insertion site and a marking suture. Any remaining fibrocartilage at the insertion was left intact, and the detached tendons were allowed to retract freely without attempt at repair, creating a gap of ~4 mm from their insertion sites. The overlying muscle and skin were closed, and the rats were allowed unrestricted cage activity.

For quantitative ambulatory assessment, ambulatory parameters were determined prior to tendon detachment (pre-surgery) and 1, 3, 5, 7, 10, 14, 21, 28, 42, and 56 days after tendon detachment. Animals were tested in a confined walkway 4.25 inches wide by 24 inches long, with a small bath of water at the beginning and dark shelter at the end [8,13]. A digital video camera (720 × 480 resolution, 30 frames/sec) was placed perpendicular to the walkway and was used to capture images from above of the animals walking. Two 4.25 inches wide by 11 inches long pieces of paper soaked in bromophenol blue were placed on the floor of the walkway and were recorded footprints. The paper was made by briefly soaking it, two sheets at a time, in a 0.5% solution of the anhydrous sulfone form of bromophenol blue in absolute acetone [10]. Animals were placed in the water bath, so that their paws become wet before they were allowed to walk through the confined walkway. Since bromophenol blue turns blue when reacting with water, blue footprints were left when the animal walks through the corridor. Papers were coded for animal number, date, and trial. Each animal performed two walking trials per time point to assure consistent walking data. Each paper trial was then scanned, and subsequent measurements of ambulation were performed with a custom MATLAB program and UTHSCSA ImageTool. Paw widths and lengths, intermediate toe spreads (distance between the 2nd and 3rd toes on the front paws), paw offsets, stride widths (distance between

front paws: LF-RF), and stride lengths (distance between opposite paw strikes: RF-LF) were measured as described previously (Figures 1 and 2) [1,4,8,9,12,13]. The video from each trial was processed using MotionDV Studio and UTHSCSA ImageTool. Walking speed was calculated using the amount of time it took the animal to move through a 239 mm central portion of the tunnel.

Additionally, range of motion was measured prior to and 1, 3, 7, 14, 21, 28, 42, and 56 days after tendon detachment [14]. Briefly, after completion of the ambulation assay, animals were anesthetized, and the forearm was placed in a custom designed fixture which constrained rotation about the long axis of the humerus. Data from three cycles of internal and external rotation to a torque of 15 N-mm was collected. Total range of motion (ROM) was calculated as the difference between the average internal and external rotations.

Uninjured control animals exhibited a difference in functional parameters between time points. Therefore, data from each animal was compared to the original pre-injury data, and the change (difference) with time was calculated. Change (difference) from pre-injury was compared between groups at each time point using one-way ANOVAs with Bonferroni corrections to test the specific stated hypotheses. Significance was set at $p < 0.05$ and trends at $p < 0.1$.

Results

Uninjured data

Measured values for stride and paw parameters, walking speed, and total range of motion are given in Table I.

Supraspinatus tendon detachment

Stride length between the right and left front paws (left paw would be used to push off) was decreased early and late (Figure 3). Negative values indicate the parameter was decreased from pre-injury levels. Injured paw width and total ROM was generally decreased for the entire study (Table II). There were no changes in stride width, offset of the paws, injured paw length, injured paw ITS, or animal walking speed.

Supraspinatus+infraspinatus tendon detachment

Both stride length and injured paw width were decreased up to 56 days after injury (Figures 3, Table II). Stride width between the front paws was generally decreased early (Figure 4). An increase in the offset of the injured front and rear paws occurred 1 day after injury (Table II). Right paw offset was increased up to 10 days after injury (Figure 5). Injured paw length was generally decreased early and late (Table II). ITS of the injured paw was generally decreased from day 3 to day 56 (Figure 6). Walking speed was decreased up to 10 days after injury (Table II). Total ROM was generally decreased throughout the study (Table II).

Supraspinatus+subscapularis tendon detachment

Stride length between the right and left front paws (left paw would be used to push off) was decreased up to 14 days post-injury (Figure 3). Stride width between the front paws was generally decreased early (Figure 4). The offset between the right paws was increased up to 14 days after tendon detachment (Figure 5). Injured paw width and length were decreased up to 56 days after injury (Table II). Injured paw ITS was decreased up to 14 days after injury (Figure 6). Walking speed was decreased 1 day after injury (Table II). Total ROM was generally decreased up to 56 days after tendon detachment (Table II). There were no changes in left paw offset.

Discussion

This study demonstrated functional changes in a rat rotator cuff model. Ambulatory parameters and total range of motion, representing measures of shoulder function, were significantly altered with rotator cuff tears. The addition of a second torn tendon (infraspinatus or subscapularis) had additional detrimental effects on animal shoulder function compared to uninjured controls.

In the two tendon detachment groups, alterations in stride width between the front paws and in offset of the right paws demonstrated compensation for the injury via a tripod effect (Figure 7A and B). This suggests that the right front paw was moving medially, to stabilize the animal. It is also possible that the animal chose to bear as little weight as possible on the injured limb initially after surgery. With time, as the animal gained strength in the injured arm and did not need compensation for the injury, the right front paw returned to its original location.

Interestingly, some measurements remained altered throughout the study, while others were transient. Many of the permanent changes were likely present because the required motion used for those actions could no longer be performed, and therefore, these were the most important changes in our study. For transient parameters, pain, either in addition to or instead of function, may be the limiting factor initially, though this was not evaluated in the current study.

Based on similarities to the human shoulder anatomy and a rotation of the scapula in the animal model, rat forward arm elevation is similar to human arm abduction. Therefore, when the animal reaches for a stride, it is expected that they are primarily using the supraspinatus tendon with the deltoid, infraspinatus, and other muscles serving a secondary role, which explains the decrease in stride lengths. In the injury scenario, the animal cannot initially lift the arm as high and, during walking, may not bear full weight on the injured limb, suggesting that strength in that limb may be reduced. With an intact infraspinatus, the supraspinatus and subscapularis group can eventually compensate for the loss of the supraspinatus and abduct the arm near the end of the study. However, a permanent decrease in stride length was observed in the supraspinatus+infraspinatus tendon detachment group, where there was no further compensation for the injury.

Also in support of our hypotheses, paw parameters of the injured limb were decreased with injury. There was a permanent decrease in injured paw width in all groups. Additionally, there were decreases in injured paw length and ITS in the two tendon tear groups. It is possible that the animal was contracting the injured paw during walking and not placing as much force on it compared to normal. This provides further evidence that larger tears have additional decreases in function.

Animal walking speed was not decreased after an isolated supraspinatus tendon tear and was decreased only 1 day after injury with the addition of a subscapularis tear. Animals continued to ambulate at normal speeds for most of the study, further suggesting that the parameter changes were due to the inability to perform certain motions. The decrease in speed after the addition of an infraspinatus tear suggests that this type of tear may be more painful or that the functional deficiencies associated with it, such as decreased stride length, limited the animal's speed. This was confirmed as there was a moderate correlation ($0.8 < r < 0.9$) between animal walking speed and stride length.

The findings in this study are consistent with the alterations in shoulder function observed with rotator cuff and other shoulder injuries in the human. Clinically, there is a decrease in function associated with rotator cuff tears, which is further decreased with increasing tear size [5,7]. Rotator cuff tears may affect the ability to abduct the arm, cause decreases in range of motion

due to shoulder stiffness, and decrease shoulder strength. Overall, many patients with a rotator cuff tear cannot lift a weight to shoulder level, wash the back of the opposite shoulder, or work at their regular full-time jobs [3,11]. Ambulation can be considered an activity of daily living for the rat and can be used to investigate the functional deficiency after rotator cuff tears. Alterations in stride length after injury may represent an inability to abduct the arm but may also suggest decreased strength or ability to push off with the injured limb. This model also shows decreases in range of motion after rotator cuff tears.

Although many of the parameters measured are somewhat variable, the methods used are reliable and consistent. Images were scanned at a high resolution (2550×3300), and the measurement system was calibrated using a known length before each trial. The relatively large standard deviations with time and injury may be due to biologic variability or differing compensatory abilities and/or strategies among animals. This may be comparable to humans, where similar rotator cuff tears may require repair due a functional loss in one individual but may be asymptomatic in another. We are confident that this method will be useful for future studies, but due to variation, all parameters measured may not be sensitive enough to detect changes associated with all shoulder injuries. Based on a comparison of the supraspinatus tendon tear group, the injury in which we expected the least change in function, stride length and range of motion have been identified as parameters potentially sensitive to small changes in function. One day after injury, stride length RF-LF and range of motion decreased to 83% and 73% of the pre-injury values, respectively. These parameters represent the largest alterations in function one day after injury in the one tendon detachment group. Additionally, the standard deviations for these measurements were under 16% of each mean, particularly low for biological samples.

While no animal model fully parallels the human condition, understanding the functional alterations present after injury in a model can provide baseline data to which future shoulder injuries and treatment modalities can be compared. Many of the parameters measured in this study have parallels to those tested clinically and are potentially useful in future studies using this method. Stride length can be indicative of the ability to abduct the arm. Paw parameters, such as width and length, may serve as a measure of the general strength of the shoulder. Finally, range of motion is the most clinically applicable measurement. These measurements are a direct comparison to those performed in humans and indicate the ability to rotate the arm internally and externally. Combining this method with other measurements, such as force or strength data, could provide a rating system to assess shoulder disorders similar to that used clinically. A successful treatment in the animal model, which improves function, would be a logical treatment to evaluate in the human.

There are some potential limitations to this study. First, the rotator cuff tendons in this model were detached acutely by surgical methods rather than the gradual progression of degeneration associated with chronic tendon tears. Therefore, many functional alterations occurred immediately after surgery, instead of small changes over time. Further, the contribution of pain to functional deficit was not fully examined. While pain may play a role in the limited functional parameters seen in this animal model, it also limits arm function clinically. Additionally, while it may be present immediately after the surgical procedure, any residual pain subsides within days as animals voluntarily use their limbs to walk and eat immediately after surgery. A sham surgery could be performed to help determine if the functional differences in the early time points were due in some part to pain. In addition, a longer time point could be examined in this model to help determine if some of the functional parameters continue to be altered permanently. While we were interested in the differences between the 2 tendon tear groups, we did not have sufficient animal numbers for statistical power with that type of analysis. Functional analysis on additional animals would allow comparison between the 2 tendon tears.

Finally, although the results of this study are consistent with the human condition, the cause of the functional differences is still unknown.

Therefore, future studies can begin to examine the root of the functional differences, whether it is pain, mechanical deficiency, or a combination of both and whether particular parameters, such as stride length and range of motion, can be used to distinguish between the two. Studies can also assess the forces on each paw during ambulation along with additional gait parameters. Finally, studies could investigate the functional recovery associated with potential treatment modalities.

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Figure 1.
Actual (A) and schematic (B) print used for paw parameter measurements

Figure 2.
Ambulatory parameters measured: Stride lengths (front to front) and stride widths (between front paws).

Figure 3.

Stride length RF-LF, where the injured limb is used to “push off”, is decreased after tendon detachment. Values on graph are relative to control. * = significant from control, # = trend from control.

Figure 4.

Stride width is decreased early after tendon detachment in the two tendon tear groups. Values on graph are relative to control. * = significant from control, # = trend from control.

Figure 5.

Offset of the right (uninjured side) paws is increased early in the two tendon tear groups. The paws are moving medially. Values on graph are relative to control. * = significant from control, # = trend from control.

Figure 6.

ITS of injured paw is decreased in the two tendon tear groups. Values on graph are relative to control. * = significant from control, # = trend from control.

Figure 7.

Schematic of “tripod” effect. A – pre-injury paw position. B – After tendon detachment, the right front, or uninjured paw, moves more medially to help compensate for the injury and stabilize during ambulation. The grey paw represents pre-injury paw position.

Table 1
Measured values from uninjured animals. (mean ± standard deviation)

	Stride length RF-LF (mm)	Stride width (mm)	Offset between left paws (mm)	Offset between right paws (mm)	Paw width (mm)	Paw length (mm)	Intermediate toe spread (mm)	Walking speed (mm/sec)	Total range of motion (°)
Uninjured	69.31±7.85	28.27±6.36	4.18±4.06	6.61±2.61	20.18±1.22	12.43±1.08	8.02±0.84	214.57±58.37	237.9±17.6

Table 2

Differences in offset between left paws, paw parameters, walking speed, and range of motion from pre-injury. (mean $\pm$ standard deviation)
* = significant compared to control, # = trend from control

	Time post-detachment (days)									
	1	3	5	7	10	14	21	28	42	56
up										
roll	-0.63±4.69	-0.84±5.75	-0.90±6.70	0.69±4.85	-0.38±4.98	1.71±4.48	-1.35±5.20	0.63±8.46	2.18±5.24	0.99±6.26
detachment	-0.62±5.38	-0.90±5.35	-0.02±3.86	0.52±3.26	0.83±4.09	2.01±6.02	1.82±4.13	1.42±4.85	2.51±4.10	2.38±4.65
tra detachment	6.41±4.20*	2.34±6.71	-1.06±4.97	1.10±4.93	1.80±4.56	2.81±6.08	1.10±7.51	0.69±7.07	0.90±4.24	1.25±6.57
cap detachment	2.8±2.83	-2.97±3.59	-3.16±4.43	-3.19±4.82	-1.72±5.78	-2.25±5.21	-2.75±4.47	-1.15±5.83	-1.17±5.17	-1.53±5.58
roll	6.89±1.15	0.45±0.61	0.78±1.01	1.22±1.32	1.09±1.13	1.12±1.06	1.06±0.92	0.76±1.35	1.06±1.33	1.06±1.28
detachment	-0.9±1.21*	-0.21±1.01	-0.90±0.90*	-0.06±1.19#	-0.24±0.91*	-0.05±0.64*	0.14±0.93#	-0.28±1.27	0.13±0.66#	-0.30±1.08*
tra detachment	-0.7±1.06*	-1.29±1.68*	-0.83±1.11*	-0.72±0.65*	-0.39±0.94*	-0.74±1.13*	-0.45±1.15*	-0.63±0.95*	-0.09±0.78#	-0.41±0.79*
cap detachment	-3.6±1.07*	-3.04±1.42*	-3.07±1.42*	-2.88±1.68*	-1.86±1.25*	-1.09±1.38*	-0.58±1.41*	-0.43±0.85#	-0.44±1.06*	-0.52±1.06*
roll	6.72±1.35	0.21±0.89	0.18±0.93	0.08±1.31	0.40±0.85	0.31±1.40	0.32±1.03	0.32±1.26	0.59±1.27	-0.14±1.21
detachment	6.09±0.88	-0.11±0.55	0.11±0.86	0.20±0.86	0.06±1.09	-0.44±0.70	-0.04±0.86	-0.01±0.81	-0.20±0.92	0.09±0.84
tra detachment	-0.21±0.44#	-0.81±0.74*	-0.20±0.58	-0.16±0.63	0.19±0.73	-0.08±0.69	-0.67±0.59*	-0.69±0.77#	-0.34±0.80*	-0.14±0.88
cap detachment	-0.91±0.92*	-1.23±1.22*	-1.35±0.90*	-1.75±0.89*	-1.22±0.61*	-1.20±0.84*	-1.04±1.22*	-0.79±0.90#	-0.87±0.87*	-1.20±0.50*
roll	3.540±62.97	-0.82±77.98	37.24±67.41	88.50±75.53	98.24±91.53	102.88±84.76	106.52±89.29	68.40±96.80	98.12±84.52	70.24±93.62
detachment	1.20±39.68	12.65±54.54	22.47±60.08	49.60±56.40	19.17±81.94#	65.92±62.03	83.18±72.21	79.32±79.97	95.87±70.74	91.94±70.83
tra detachment	-3.92±51.31*	-31.50±64.62	-27.32±60.25#	6.08±65.50*	21.40±58.72#	46.16±59.82	61.38±70.73	54.47±71.48	53.97±61.45	71.28±66.06
cap detachment	-4.34±64.20*	-27.08±53.46	37.15±75.32	37.93±61.11	89.53±50.08	130.68±57.28	118.98±66.23	150.17±57.00#	134.22±90.44	136.73±85.03
roll	-1.40±28.36	-1.68±40.27	-	-1.87±39.00	-	1.63±33.47	0.73±42.12	-0.18±30.88	1.84±39.14	-1.23±32.51
detachment	-6.49±16.54*	-56.69±25.21*	-	-20.77±29.48	-	-32.78±27.25*	-40.48±17.18*	-29.40±18.96*	-35.51±25.10*	-55.67±24.55*
tra detachment	-3.85±27.63*	-44.63±31.32*	-	-38.88±31.64*	-	-33.58±34.54#	-30.45±33.95	-34.95±42.69#	-34.87±34.03#	-48.69±28.30*
cap detachment	-103.74±27.15*	-63.76±34.71*	-	-69.77±27.30*	-	-50.49±43.38*	-41.64±48.19#	-21.35±20.39	-45.25±50.39#	-43.14±41.34*