Shoulder pain in elite swimmers: primarily due to swim-volume-induced supraspinatus tendinopathy

Mya Lay Sein,1 Judie Walton,1 James Linklater,2 Richard Appleyard,1 Brent Kirkbride,2 Donald Kuah,2 George A C Murrell1

ABSTRACT
Background/hypothesis: Shoulder pain in elite swimmers is common, and its pathogenesis is uncertain. Hypothesis/study design: The authors used a cross-sectional study design to test Jobe’s hypothesis that repetitive forceful swimming leads to shoulder laxity, which in turn leads to impingement pain. Methods: Eighty young elite swimmers (13–25 years of age) completed questionnaires on their swimming training, pain and shoulder function. They were given a standardised clinical shoulder examination, and tested for glenohumeral joint laxity using a non-invasive electronic laxometer. 52/80 swimmers also attended for shoulder MRI. Results: 73/80 (91%) swimmers reported shoulder pain. Most (84%) had a positive impingement sign, and 69% of those examined with MRI had supraspinatus tendinopathy. The impingement sign and MRI-determined supraspinatus tendinopathy correlated strongly (r=0.49, p<0.00001). Increased tendon thickness correlated with supraspinatus tendinopathy (r=0.37, p<0.01). Laxity correlated weakly with impingement pain (r=0.23, p<0.05) and was not associated with supraspinatus tendinopathy (r=0.14, p=0.32). The number of hours swim/week (r=0.39, p<0.005) and weekly mileage (r=0.34, p=0.01) both correlated significantly with supraspinatus tendinopathy. Swimming stroke preference did not. Conclusions: These data indicate: (1) supraspinatus tendinopathy is the major cause of shoulder pain in elite swimmers; (2) this tendinopathy is induced by large amounts of swimming training; and (3) shoulder laxity per se has only a minor association with shoulder impingement in elite swimmers. These findings are consistent with animal and tissue culture findings which support an alternate hypothesis: the intensity and duration of load to tendon fibres and cells cause tendinopathy, impingement and shoulder pain.

INTRODUCTION
Millions of people participate in and enjoy aquatic sports, mostly swimming for fitness or competition. Sports injury surveys confirm that recreational swimmers have a low injury potential because of the buoyant effect of water.1 However, as in any competitive sport, injury and pain can affect the elite swimmer. Swimming training involves repetitive overhead movement. In all the main swimming strokes (freestyle, backstroke, breaststroke and butterfly), the swimmer uses large moment arm forces to reach forward to drag the water. Where the training is intense, these factors may all contribute to shoulder injury and pain.2–5 Competitive swimmers begin their careers as early as age seven, and most of them train and take part in year-round competitions. Competitive swimmers typically complete 2500 or more shoulder revolutions per day.6 The condition of ‘swimmer’s shoulder’ was first described by Kennedy and Hawkins7 in 1974 as a ‘common, painful syndrome of repeated shoulder impingement in swimmers’. Many studies have reported shoulder pain in elite swimmers.3, 7–16 The prevalence of shoulder pain in swimmers was 5% in a study published in 19747 and has increased in recent publications: 42% in 1980,16 68% in 1987,15 73% in 1993,5 40–69% in 19947,15 and 5–65% in 1996.10

Proposed causes of swimmer’s shoulder
A clear consensus is lacking as to the cause(s) of shoulder pain in swimmers. Suggestions have been made that swimmer’s shoulder represents a part of the impingement syndrome complex, rotator cuff tendonitis, biceps tendonitis and shoulder instability.15 19–21 Other pathological shoulder conditions, such as labral tears and acromioclavicular joint disruption, have also been observed in swimmers.22–24

As swimmers engage in repetitive overhead motion, it is possible that swimmer’s shoulder may involve glenohumeral joint laxity and the ‘instability complex’ described by Jobe et al.25–26 Jobe et al25 hypothesised that repetitive and forceful overhead activity causes a gradual stretching out of the anteroinferior capsuloligamentous structures leading to mild laxity, instability and impingement. Figure 1 summarises their hypothesis.

This hypothesis has been quoted extensively and has been used to design protocols to treat swimmers and other overhead athletes with shoulder pain. However, on review of the literature, there is little information that supports or refutes this hypothesis.

Laxity measurement
The normal range of glenohumeral joint laxity is unknown.27 Excessive translation of the humeral head on the glenoid is normally prevented during athletic activities by static stabilisers of the glenohumeral joint, especially the glenoid labrum and capsular ligaments. Repetitive stretch injury or traumatic injury to the capsular ligaments may adversely affect static stabilisation and increase the risk of instability to the joint. Instability has been defined as a symptom secondary to increased laxity.28
Many clinical tests have been described for assessing shoulder laxity and instability. However, most of these tests are subjective, do not provide a continuous scale of numeric values and have poor inter- and intraobserver reliability. Originally described the sulcus sign test as a test for multidirectional instability. A sulcus sign is a palpable and visible dimple created beneath the acromion when applying an inferior force, pulling downward on the subject’s arm while in a sitting position. Tzannes and Murrell studied multidirectional instability which was defined as the presence of grade 2 or greater laxity in more than one direction, in a symptomatic shoulder, on examination under anaesthesia. They confirmed that the sulcus sign is a good indicator of multidirectional instability.

However, when performing this test, the inferior force applied is not standardised, and assessment of the dimple size is subjective. With this manual assessment, interobserver reliability is only fair (intraclass correlation coefficient (ICC)=0.60). Electronic quantification of translation in the knee joint, using the KT-1000, is well established. However, there have been few attempts to quantify shoulder laxity with instrumentation. Jørgensen and Bak have applied the use of a Donjoy laxometer to test the laxity of shoulders in elite swimmers. Sauers et al developed an instrumented arthrometer to assess glenohumeral joint laxity anteriorly and posteriorly at four force levels. As noted by Tibone et al, it has been very difficult to find a clinical device that provides an easy-to-use, objective, accurate, non-invasive and reproducible measurement of shoulder laxity. We recently described an instrumental shoulder laxometer with these features that can measure inferior translation of the glenohumeral joint.

In the present study, we used this laxometer to test the laxity of shoulders in elite swimmers.

**Supraspinatus tendinopathy**

Supraspinatus tendinopathy (ie, supraspinatus tendinosis or tendinitis) is another candidate cause of swimmer’s shoulder. The supraspinatus is the major rotator cuff muscle responsible for securing the humeral head in the glenoid, and its tendon is susceptible to tendinopathy in swimming and other overhead sports. The normal tendon appears yellow-white. When magnified, quiescent rows of tenocytes (tendon cells of fibroblast origin) can be seen interspersed among the compact parallel bundles of collagen fibres which in turn comprise collagen fibrils. In supraspinatus tendinopathy, the tendon usually changes from yellow-white to grey, becoming dull and oedematous, often with the bursa appearing inflamed. Microscopically, the tissue appears disrupted. Although there is little evidence of inflammatory cells, the tissue appears hypercellular with fibroblastic cells in varying states of cell health.

The aim of this study, therefore, was to investigate the pathogenesis of swimmer’s shoulder. To do this, we examined (1) which clinical sign best predicts shoulder pain in swimmers; (2) which anatomical structure(s) is/are associated with this shoulder pain; (3) whether repetitive swimming movements are associated with increased shoulder laxity; (4) whether increased laxity is associated with impingement pain; and (5) the extent, if any, to which training characteristics are associated with supraspinatus tendinopathy, laxity or both in elite swimmers.

**METHODS**

**Swimmer recruitment**

Under ethics approval, 86 elite swimmers were recruited from four competitive swimming clubs. All swimmers met the following inclusion criteria: (1) aged between 13 and 25 years; (2) having trained with a coach for a minimum of 2.5 years; and (3) swimming for at least 6 h/week. Exclusion criteria were: (1) previous surgery on the involved shoulder; (2) previous fracture of the shoulder; and (3) inability or unwillingness to participate in the MRI and clinical shoulder examination. Six elite swimmers were excluded from the study. Two were older than the age inclusion criterion, one had a dislocated shoulder, one inadvertently enrolled twice, and two failed to sign the consent form, leaving a total of 80 swimmers for the study.

**Swimming training**

Each study participant completed a standardised self-administered swimming training questionnaire, which requested the following information: number of years with coaching; hours per week in swimming training; level of competition (international, national, state or club level); weekly swimming distance; personal best in highest ranked event; and percentage of time in training spent in each stroke over the previous 3 months.

**Shoulder pain and function**

Descriptive characteristics were obtained for each swimmer using a standardised Shoulder Service Questionnaire, which is a modification of a validated questionnaire. Items pertaining to the subject included age, gender, birth date, occupation, arm dominance (right, left or ambidextrous) and an overview of general health. Clinical parameters of the shoulder condition included affected shoulder (right or left), date of injury onset, mechanism of onset (whether traumatic or insidious), presence of an insurance claim, level of activity at work and highest exercise level before shoulder problem. All items contained in the Shoulder Service Questionnaire were scored on a five-point rating scale (0–4) except for the current level of activity, which was scored on a four-point rating scale (1–4). This questionnaire was designed to indicate the frequency and severity of the shoulder pain (with activity, at night and at rest), stiffness of the shoulder, difficulty in reaching behind the back, difficulty with activities above the head, overall shoulder status (very bad, bad, fair, good), current level of activity (none, light activity, moderate activity and strenuous labour) and highest level of sport at the time of examination (none, hobby sport, club sport, state sport, national and international sport).

**Clinical examination**

Clinical shoulder examinations were performed on all 80 subjects. For the analysis, data from one shoulder of each subject were included. The shoulder chosen was the affected shoulder if symptomatic or the dominant shoulder if asymptomatic. For the analysis, data from one shoulder of each subject were included. The shoulder chosen was the affected shoulder if symptomatic or the dominant shoulder if asymptomatic. Each athlete was given a systematic clinical shoulder examination which included 23 clinical tests. The results of each of these tests were recorded on a standardised Examiner’s Form. The validity, reliability and clinical usefulness of the majority of these tests have been previously described.

**Laxometer**

We used a non-invasive electronic device for testing inferior translation of the humeral head in humans which has been shown to have excellent reliability and validity, that is, patients with shoulder instability have higher laxity readings. All subjects in this study were tested with the laxometer for inferior translation of their glenohumeral joint.
Magnetic resonance imaging
Fifty-three swimmers were available for MRI. One was unable to tolerate more than two pulse sequences and was excluded from the MRI study, leaving 52 swimmers for this aspect of the study.

MRI was used in a systematic fashion by a single examiner trained in musculoskeletal MRI (JL) using a standardised form to determine the minimum thickness of the supraspinatus tendon and to assess for acromion shape, tendinopathy, tears, acromioclavicular joint arthritis and other pathological conditions in the shoulder. Minimum tendon thickness was measured immediately medial to the insertion of the supraspinatus tendon into the greater tuberosity of the humerus, 1 cm posterior to the biceps tendon.

The swimmers’ shoulders were examined with a 1.5 T MRI system (Signa; GE Medical Systems, Milwaukee, Wisconsin) and system software 9.1 (slew rate, 77 T/m/s, 35-mm T gradient amplitude), with the use of a high-resolution, non-arthrographic technique with a four-channel phased-array shoulder coil (Medical Advances, Milwaukee, Wisconsin). Oblique coronal proton-density and fat-suppressed T2, sagittal T2 and axial proton-density sequencing were performed (table 1).

Magnetic resonance imaging

| MRI-assessed supraspinatus tendinopathy |

Supraspinatus tendinopathy was graded using a modified four-point scale from 0 to 3.46 For grade 0 (normal), the tendon showed complete homogeneous low intensity on all pulse sequences. For grade 1 (mild tendinopathy) there was a mild focal increase in tendon signal on proton density (PD) and fat-suppressed T2 sequences not equal to that of fluid. Grade 2 (moderate tendinopathy) represented a moderate focal increase in tendon signal on PD and fat-suppressed T2 sequences not equal to that of fluid. For grade 3 (marked tendinopathy), the tendon showed a marked generalised increase in tendon signal without frank fluid signal intensity. The grading of MRI-determined supraspinatus tendinopathy is very reliable (ICC=0.75) when assessed by a single well-trained observer.46

Statistical analyses
Statistical tests were carried out using SigmaStat software (Systat Software, Point Richmond, California). Multiple logistic regression analysis was performed with supraspinatus tendinopathy as the dependent variable and training regime parameters as independent variables. Statistical analyses that compared laxity with training and symptoms were based on data from all 80 swimmers, whereas the MRI analyses were based on a subset of 52 swimmers.

Table 1
| MRI shoulder protocol |

<table>
<thead>
<tr>
<th>Swimmer’s position</th>
<th>Oblique coronal PD</th>
<th>Coronal fat-suppressed sagittal T2</th>
<th>Sagittal T2</th>
<th>Axial PD</th>
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The swimmers underwent an MRI of a single shoulder scanned, either the dominant shoulder if asymptomatic or the affected shoulder if symptomatic. Oblique coronal proton density (PD) and fat-suppressed T2, sagittal T2, and axial PD sequencing was performed on a Signa 1.5 T superconducting magnet, Hi Speed MRI unit (General Electric Medical Systems, Milwaukee, Wisconsin), using system software 9.1, slew rate 77 T/m/s, 33-mm T gradient amplitude, utilising a high-resolution, non-arthrographic technique with a four-channel phased array shoulder coil (Medical Advances, Milwaukee, Wisconsin).

RESULTS

Demographics of the swimmers
The age range of the swimmers in this study was 13–25 years. The mean (±SD) age was 15.9 (±2.7) years, and the median age was 16 years. Forty-two (53%) of the elite swimmers were male, and 38 (47%) were female. Of the total participants, 13/80 represented their country at an international level, 41/80 swam at the national level, 24/80 were at the state level, and 2/80 swimmers were at the club level. With regards to the swimmers’ main event, 55% specialised in freestyle, including two open water swimmers, 19% specialised in butterfly stroke, 24% specialised in backstroke, 18% specialised in breaststroke, and 5% were individual medley swimmers. Table 2 shows the percentage of training time spent in each of the four strokes.

Shoulder pain and function
Of the total study group of 80 swimmers, 43 (54%) reported unilateral shoulder pain (affecting 28 right shoulders and 15 left shoulders), and 30 (37%) others reported bilateral shoulder pain. The remaining seven swimmers (9%) stated they had no shoulder pain. Sixty-four swimmers (80%) reported they had pain during activity, and of these, 25 had activity pain monthly, 22 had it weekly, 14 had it daily, and three stated they always had shoulder pain during activity. Fifty-six out of 80 (70%) swimmers specified that they had shoulder pain with activity above their head. Twenty-two (28%) swimmers had shoulder pain at night. Of this group, 14 swimmers had
night pain monthly, six had it weekly, one had pain every night, and another stated she had pain continuously throughout the night. Twenty-two (28%) swimmers rated the level of their night pain as mild to moderate. Twenty-four out of 80 (30%) swimmers reported they had extreme pain monthly, while nine had it weekly. The same proportion of swimmers indicated they had mild to moderate shoulder pain, even while resting. Fifty-four out of 80 (68%) swimmers indicated they had shoulder stiffness. Of these, 42 (52%) had difficulty reaching behind their back, and 43 (54%) had difficulty with activities above their head. Four (5%) of the 80 swimmers had severe to very severe difficulty with overhead activities, whereas the remainder had mild to moderate difficulty.

Of the total study group, 41/80 (51%) self-assessed the overall condition of their shoulder as fair (4) on a scale of 1–5 (very bad to good). Ten out of 80 (12.5%) reported their shoulder to be in poor condition (3), and five out of 80 (6%) in bad condition (2). None of the swimmers permanently discontinued swimming because of their shoulder problem. Eighty-nine per cent had sought treatment for their shoulder pain: 16/80 (20%) with chiropractic therapy, 47/80 (59%) with physiotherapy and 9/80 (11%) with acupuncture, while 8/80 (10%) had no treatment for their pain.

Clinical examination of the shoulder
Details regarding the clinical examination findings in swimmers are shown in table 3. The most common positive findings were a positive impingement sign (90%) and signs related to the biceps and A-C joint: biceps tenderness (45%), Paxinos sign (34%), O’Brien sign (25%) and A-C joint tenderness (10%).

Glenohumeral joint laxity in swimmers
Glenohumeral joint laxity was manually assessed during the clinical examination for a sulcus sign. None of the swimmers had a grade 3+ sulcus sign. In 11 (14%) of swimmers, the sulcus sign was assessed as grade 2+, and in 41 (51%) as grade 1+. Forty-nine (61%) swimmers had grade 1+, and eight (10%) had grade 2+. The clinical examination findings are shown in table 3. The most common positive findings were a positive impingement sign (90%) and signs related to the biceps and A-C joint: biceps tenderness (45%), Paxinos sign (34%), O’Brien sign (25%) and A-C joint tenderness (10%).
Sheath effusion. Tears of the supraspinatus tendon were found in three swimmers: two were reported as having a delaminated intrasubstance tear, and one had a partial 3 mm articular side tear. Two had subscapularis tendinopathy, and one had infraspinatus tendon thickening, but no change was reported for the teres minor tendon.

Labral tears were detected in 10/52 swimmers whose shoulders were imaged. Eight swimmers had superior labrum anterior posterior (SLAP) lesions. One had a SLAP lesion and Bankart lesion, and another had a Bankart lesion alone. Mucoid changes in labrum were noted in five swimmers’ shoulders, and two were noted to have a paralabral cyst. Five sublabrum-foramens and one Buford complex were also observed.

The acromion shape was assessed as type I in 20/52 (38%) swimmers, type II in 29/52 (56%) and type III in 3/52 (6%). Thickness of the subacromial bursa was reported in 33/52 (63%) swimmers, and thickness of the subscapularis bursa affected 3/52 (6%) others. Minimal to moderate increase in subacromial and subdeltoid fluid was observed in 21/52 (40%) swimmers’ shoulders, while 7/52 (13%) of the swimmers had acromioclavicular

MRI findings in elite swimmers

**Supraspinatus tendinopathy**

Thirty-six (25 male, 11 female) or 69% of the 52 swimmers that were imaged by MRI showed evidence of supraspinatus tendinopathy. Of those with tendinopathy, 27/36 (75%) had their tendinopathy assessed as grade 1, 8/26 (22%) as grade 2 and 1/36 (3%) as grade 3 (figure 6). Of the imaged population, 4/4 (100%) swimmers at the international level exhibited supraspinatus tendinopathy, 24/27 (89%) swimmers at the national level and 8/20 (40%) swimmers at the state level, and 0/1 (0%) swimmers at the club level had supraspinatus tendinopathy (figure 7). This condition was found in 13/24 (54%) of swimmers aged between 13 and 14 years, 10/13 (77%) between 15 and 16 years, 8/8 (100%) between 17 and 18 years and 5/7 (71%) between 19 and 22 years of age. This study found no association between preferred swimming stroke and supraspinatus tendinopathy.

**Other MRI findings**

For all swimmers, MRI-determined minimum supraspinatus tendon thickness ranged from 6 to 10 mm, with a median value of 8 mm. Twenty-seven per cent of the swimmers had thickened supraspinatus tendons. There was no relationship between tendon thickening and the swimmers’ ages.

The biceps tendon was normal in 46 imaged shoulders. The biceps anchor was reported to be unstable in three swimmers’ shoulders, and three other shoulders were found to have biceps sheath effusion. Tears of the supraspinatus tendon were found in three swimmers: two were reported as having a delaminated intrasubstance tear, and one had a partial 3 mm articular side tear. Two had subscapularis tendinopathy, and one had infraspinatus tendon thickening, but no change was reported for the teres minor tendon.

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**Table 3 Clinical examination results**

<table>
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<th>Negative</th>
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</tr>
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<td>8 (15%)</td>
</tr>
<tr>
<td>Impingement (ER)</td>
<td>19 (37%)</td>
<td>33 (64%)</td>
</tr>
<tr>
<td>Paxinos sign</td>
<td>23 (44%)</td>
<td>29 (56%)</td>
</tr>
<tr>
<td>O’Brien’s sign</td>
<td>16 (31%)</td>
<td>36 (69%)</td>
</tr>
<tr>
<td>Apprehension sign</td>
<td>23 (44%)</td>
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<tr>
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</tr>
<tr>
<td>Ab ER lag</td>
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</tr>
<tr>
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<tr>
<td>Scoliosis</td>
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<td>50 (96%)</td>
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</table>

ER, external rotation; IR, internal rotation.

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**Figure 6 MRI-determined supraspinatus tendinosis in elite swimmers.**

**Figure 7 Relationship between competition level and supraspinatus tendinosis in elite swimmers ($r_s=0.56$, $p<0.00005$, using Spearman rank order correlation).**
Statistical correlations

Laxity correlated modestly with impingement ($r_s=0.28; p<0.05$) but lacked significant association with supraspinatus tendinopathy. There were significant relationships between laxity and extreme pain ($p<0.05$), and between impingement during external rotation and shoulder pain ($r_s=0.25; p<0.05$). The correlation between laxity and pain during activity approached ($r_s=-0.30, p<0.05$), or between supraspinatus tendinopathy and the number of hours swum/week ($r_s=0.36, p<0.01$). Swimmers who swam more than 15 h/week were more likely to have supraspinatus tendinopathy than those who swam fewer hours ($r_s=0.48, p<0.0005$). All swimmers who swam more than 20 h/week had supraspinatus tendinopathy (figure 8). Elite swimmers who trained for more than 15 h/week were twice as likely to have tendinopathy as those who trained for less time ($r_s=0.48, p<0.0001$).

There was also a significant association between supraspinatus tendinopathy and the number of kilometres swum per week ($r_s=0.33, p<0.05$). The swimmers who swam more than 35 km/week were more likely to have supraspinatus tendinopathy than those who swam fewer kilometres ($r_s=0.37, p<0.01$). Importantly, all swimmers who swam more than 60 km/week exhibited supraspinatus tendinopathy (figure 9). Athletes who swam more than 55 km/week ($r_s=0.37, p<0.01$) were four times more likely to have tendinopathy than those who swam fewer kilometres.

Stepwise multiple regression analysis was used to determine the relationship between supraspinatus tendinopathy and the significant independent variables of swimming training: the number of hours swum per week and the weekly mileage.

The level of competition was omitted, since this is not a variable that the swimmers could voluntarily change. This analysis showed that the dependent variable ‘supraspinatus tendinopathy’ could be predicted from the independent variable ‘hours swum per week’ ($r^2=0.131, p<0.01$). Multiple logistic regression analysis showed that supraspinatus tendinopathy could be correctly predicted in 85% of elite swimmers either from the number of hours swum per week alone or in combination with the swimmer’s weekly mileage. In essence, swimmers who train more than 15 h/week and swim a weekly distance of more than 35 km are at increased risk for supraspinatus tendinopathy.

Stepwise multiple regression analysis showed that the dependent variable ‘pain during activity’ in the elite swimmers could be predicted from a linear combination of two

![Figure 8](http://bjsm.bmj.com/)  

**Figure 8** Relationship between hours swum per week and supraspinatus tendinosis in elite swimmers ($r_s=0.39, p<0.005$, using Spearman rank order correlation).

There was a highly significant association between supraspinatus tendinopathy and competition level (figure 7). Athletes at higher levels of competition were more likely to have supraspinatus tendinopathy than those at lower levels of competition ($r_s=0.56, p<0.0001$).

A significant association was also found between supraspinatus tendinopathy and the number of hours swum/week ($r_s=0.36, p<0.01$). Swimmers who swam more than 15 h/week were more likely to have supraspinatus tendinopathy than those who swam fewer hours, ($r_s=0.48, p<0.0005$). All swimmers who swam more than 20 h/week had supraspinatus tendinopathy (figure 8). Elite swimmers who trained for more than 15 h/week were twice as likely to have tendinopathy as those who trained for less time ($r_s=0.48, p<0.0001$).

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Stepwise multiple regression analysis showed that the dependent variable ‘pain during activity’ in the elite swimmers could be predicted from a linear combination of two


Our results concur with the findings of Borsa et al.\textsuperscript{48} that repetitive swimming does not increase shoulder joint laxity in elite swimmers. These data also oppose the hypothesis that cumulative swimming time (weekly mileage×4 weeks×number of years coached) in the form of swimming training leads to glenohumeral joint laxity in swimmers. Hence, we doubt that laxity is a major contributor to swimmer’s shoulder.

On the other hand, our results showed a modest yet significant correlation between glenohumeral joint laxity and either impingement pain ($r=0.23$, $p<0.05$) or extreme pain ($r=0.26$, $p<0.05$). Similarly, McMaster et al.\textsuperscript{44} found a statistically significant correlation between a clinical score of glenohumeral joint laxity and the presence of interfering shoulder pain in senior national and elite swimmers.

An alternate interpretation of swimmer’s shoulder

We found a high incidence of MRI-assessed symptomatic supraspinatus tendinopathy in elite swimmers. The incidence of tendinopathy was related to the time spent in training (hours swim per week) and the distance swim per week. Elite swimmers who trained for more than 15 h/week were twice as likely to have tendinopathy as those who trained for less time. Similarly, elite athletes who swim more than 35 km/week were four times more likely to have tendinopathy as those who swim fewer kilometres. The level of competition also correlated with supraspinatus tendinopathy, with a higher proportion of swimmers at the higher competition level having supraspinatus tendinopathy than swimmers at lower competitive levels.

An association between the extent of training and shoulder pain has been identified by Pollard\textsuperscript{49} when evaluating the prevalence of shoulder pain in elite British swimmers. Specifically, he found a correlation between the number of kilometres the athletes swim per week and shoulder pain ($p<0.001$). A study involving German triathletes also noted a significant relationship between the number of weekly training hours and incidence of muscle and tendon injuries ($p<0.05$).\textsuperscript{50} Thus, shoulders of the elite swimmer are, in the long-term, susceptible to the continuous overloaded associated with excessive activity.\textsuperscript{51, 52} Our study indicates that supraspinatus tendinopathy in swimmers is related to the amount and duration of load on supraspinatus tendons. The high incidence of biceps tenderness and A-C joint pain suggest that these areas may also be subject to overload stress in elite swimmers.

Despite some evidence to the contrary by others,\textsuperscript{16, 49} these data indicated that specific swimming strokes have little effect in predisposing elite swimmers to shoulder pain. In our view, the following diagram more accurately describes what generally happens to cause shoulder pain in elite swimmers.

In this model, repetitive movement causes tendinopathy with an associated increase in tendon thickness. Tendinopathy leads to pain when the thickened tendon and associated bursa are repeatedly squashed under the bony arch of the acromion during swimming as in impingement testing.

Our results showed that intensive training increases tendon thickness, a feature that is significantly associated with supraspinatus tendinopathy. Other human and animal studies have also shown that prolonged mechanical loading increases tendon thickness and alters its mechanical properties.\textsuperscript{21, 53–57} For example, the cross-sectional area of the supraspinatus tendon was larger than normal in rats exercised for 4 weeks and continued to increase in size up to 16 weeks, its elasticity amounted to only 52–61% of the control (non-exercised)
value, and less stress was required to rupture it. Following this overuse protocol, more substance of lesser quality was present in the injured tendons. In another study with exercised rats, the cross-sectional area of the Achilles tendon was increased at 4 months of running training. In horses, 18 months of training increased the cross-sectional area of the Achilles tendon, whereas 5 months of training did not. Also, a guinea fowl study showed that 8–12 weeks of mechanical loading was sufficient to increase tendon stiffness.

A possible cellular mechanism for swimmer’s shoulder
Experimental studies suggest a mechanistic basis that may explain the supraspinatus tendinopathy we observed in the swimmers’ shoulders. For evaluating supraspinatus tendinopathy, the running rat model has been particularly informative. Supraspinatus tendon overuse was modelled by subjecting the rats to repetitive exercise, consisting of treadmill running at 17 m/min at a 10° decline for 1 h/day over 5 days/week. This protocol results in approximately 7500 strides/day.

In running rats, the supraspinatus tendon can be damaged by overuse and intrinsic factors, overuse and extrinsic factors, or overuse alone. Specifically, extrinsic factors such as the coracoacromial arch can cause repetitive mechanical impingement of the rotator cuff. Intrinsic factors originate within the tendon as from tendon overload or tendon thickening. In combination, overuse plus extrinsic compression dramatically increased the incidence of significant injury in the rat supraspinatus tendon.

Normally, the spindle-shaped tendon cells or tenocytes lie in rows surrounded by parallel bundles of collagen fibrils. Early microscopic change in rat supraspinatus tendons after running for 12 weeks is characterised by tenocyte rounding and proliferation. The cell machinery of the tenocytes is diverted from their differentiated task of maintaining the collagen fibrils and the extracellular matrix to mitosis. Under these conditions, the matrix accumulates water, glycosaminoglycans and other ground substance while collagen frays and becomes disorganised, and the tendon thickens. Loss of tendon biomechanical integrity occurs early, coinciding with tendon thickening. The structural changes are accompanied by decreased elasticity in the tendon and decreased load for its rupture.

Mixed findings have been reported with regard to apoptosis and cellular inflammation in the tendons of rats that ran on a treadmill for 1 h/day over 1–3 months. Excessive apoptosis was induced in isolated rat tibialis anterior tendons loaded with a high (20%) strain for 6 h. Apoptotic rates were 20 times higher than in control tendons. The biochemical basis for this apoptosis effect was examined using canine patellar tendon cells in tissue culture. The amount of stress applied directly to the tendon cells showed a positive relationship with the induction of a stress-activated protein kinase (c-Jun N-terminal kinase or JNK) within the cells. Cyclic strain (analogous to that in swimming movements) results in immediate activation of JNK, peaking at 30 min. This activation is regulated by a magnitude-dependent but not frequency-dependent, calcium-dependent mechanotransduction pathway. Whereas transient JNK activation is associated with normal cell metabolism, persistent JNK activation can initiate apoptosis.

In our study, the number of strokes per day calculated to be made by elite athletes who swim more than 15 h/week was similar to the number of strides per day made by the running rat model. At this activity level, significant change can occur in the thickness of the tendon and in supraspinatus tendinopathy.

In the swimmers and the running rats, overuse activity can affect factors that are intrinsic (eg, tendon thickening) and extrinsic (eg, tendon impingement by the acromial arch). A weakness in our hypothesis is that we did not test whether scheduled rests can prevent or reverse supraspinatus tendinopathy in athletes. Soslowsky has shown this condition to be reversible in the running rat model (personal communication). Although biopsies of the athletes’ tendons were not available to determine whether apoptosis occurs in human tendon cells stressed by overexercise, other studies in our laboratory based on discarded human tendon tissue obtained during surgery found that JNK is expressed, cells proliferate, collagen fibrils become disorganised, and apoptosis occurs in human rotator cuff tissue exposed to oxidative stress.

In summary, these animal, ex vivo and in vitro findings help to explain our results in the elite athletes (figure 10). Both the swimming human and running rat systems showed significant associations between the amount of exercise (mileage/time) and the development of tendinopathy, supporting the hypothesis that tendinopathy relates to the amount (mileage and hours) of load on the tenocytes that normally secrete pro-collagen and maintain the collagen fibrils. Under conditions of excessive stress, the homeostatic equilibrium may be lost, ultimately resulting in increased apoptosis, fraying and disorganisation of the collagen fibrils, water accumulation, tendon deterioration and pain. These changes could thus lead to the presence of incipient tears evident in some of the swimmers’ tendons.

Acknowledgements: The authors would like to thank the swimmers and their families, for participating in this study, and the South East Sydney and Illawara Area Health Service, for their support.

Funding: This work was internally funded by the South East Sydney and Illawara Area Health Service.

Patient consent: Obtained

Ethics approval: The South East Sydney and Illawara Area Health Service

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