Rowing Injuries

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ABSTRACT

The sport of rowing has gained considerable momentum in recent years. It appeals to many age groups and is an endurance activity with no sudden accelerations or ballistic impact forces. It is associated with several injuries that are so typical that they are easily recognized by the enthusiast and in many cases do not require imaging. These include wrist tenosynovitis, intersection syndrome, and rib fracture. Other injuries may be the result of strenuous training programs or faulty rowing technique and include low back injuries and patellar maltracking. The etiology, biomechanics, imaging, and treatment of rowing-related disorders are discussed

KEYWORDS: Rowing, biomechanics, injury, tenosynovitis, spondylolysis, rib fracture, epicondylitis, intersection, patellar tracking

WHO IS ROWING?

Rowing is an Olympic sport that has gained considerable momentum in recent years due in part to press interest in the now retired five time Olympic gold medalist Sir Stephen Redgrave. Up to the 1970s rowing was essentially a male-only sport, perhaps a result of its affiliation to the English public (private) school system. A noncontact sport that requires a combination of technical skill, strength, cardiovascular fitness, rhythm, and balance, it is not surprising that rowing now appeals to women in large numbers. In many clubs women rowers now outnumber men. Rowing became an Olympic sport for women in 1976. International rowing is contested in male and female categories. However, at the local and masters level, mixed boat races are also popular.

Since around the time of the Sydney Olympics, British junior rowing has developed in conjunction with grants from Henley Royal Regatta and the National Lottery. Children as young as 6 are introduced to rowing, taking part in organized games in boats. Until the age of 14, children are permitted to train and compete only in sculling boats, where they use two sculls (oars) each. This is a rule based on the somewhat empirical thought that swept oar rowing (one oar each) twists the back and may lead to developmental problems in the growing skeleton.

Rowing is also a sport that appeals greatly to older age groups; it is an endurance activity with no sudden accelerations or ballistic impact forces. There are age-based competitions up to the 80s, and there is literally no limit to the age one can race. The World FISA (Federation Internationale Sociétés d'Aviron) Masters Regatta attracts over 3000 competitors each year including hundreds of athletes over the age of 70.[1] At the highest levels of performance, rowing power declines linearly with increasing age.[2] This is explained physiologically by obligatory reductions in maximal cardiac output with age consequent to reductions in maximal heart rate that occur whether one trains regularly or not. In addition, after the age of 50, muscle mass loss reduces anaerobic capacity, which is also of importance in highly intense rowing performances lasting between 3 (masters competitions over 1000 m) and 7 minutes (standard 2000 m competitive distance). However, although aging

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clearly results in loss of performance capacity, when a wider spectrum of participants is examined, it is not uncommon to see athletes in their 50s performing at the same or similar levels as competitors in their 20s.[2] Masters rowers who continue to train regularly demonstrate impressive performances. Rowing is sometimes described as an exercise especially suited for the older person.[3] In a survey of over 1000 masters rowers commissioned by FISA, 13% of male and 41% of female rowers took up the sport after the age of 30 years.[4] It is worthwhile to note that those who compete in rowing in older age groups appear to have a much lower rate of cardiovascular disease (30%), diabetes (20%), and obesity (20%) compared with the average population of the same age group in the United States.[4]

WOBBLY BEGINNINGS: NOVICE INJURIES

Rowing is a cyclical movement like running or cycling. However, unlike cycling and running, the rowing stroke cycle is not an intuitive act. Moving the body while sitting in a narrow rowing shell, controlling the placement of a long oar, all in water that is inherently unstable, requires a period of learning (and frustration) of several weeks before aerobically strenuous activity may begin. During this period the boat tips in and out of balance often during the stroke and athletes have difficulty managing to apply power effectively and evenly through the entire stroke. Consequently, beginners are likely to be cold and at risk for limb and back strains due to sudden unexpected motion. Once the fundamentals of the stroke cycle are engrained, cohesion among a crew is the next challenge. Lack of accurate timing causes wobbles in the boat but also leads to the rowers who take the stroke on time being loaded with extra weight; a potential cause of injury. As the boat wobbles, the fingers of the hand holding the oar may be slammed against the saxboard (side) of the boat. These types of injury are rare in experienced rowers.

The ideal rower is tall with a medium build. Rowing is unique as endurance sports go in that, technical skill being equal, larger athletes are generally favored. For example, internationally competitive male rowers tend to average around 190 cm + and 90 to 100 kg (and perhaps 180 cm and 70 kg among elite females). This is quite large when compared with size of elite cyclists and runners (where 170 cm and 65 kg are more typical). Taller rowers have longer levers and a mechanical advantage. And, because heart size and maximal oxygen consumption scale with body size, large athletes also tend to have a greater *absolute* work capacity. Because body weight is supported, absolute work capacity and not power relative to body weight (cycling or cross-country skiing uphill) is advantageous in rowing. However, body weight does increase the draft of the boat. Power and endurance to weight ratios are critical. Imposed on this are timing and technique issues; a very powerful but uncoordinated rower is likely to be a hindrance. It is true to say that the Olympic champion is likely to be tall, medium built, well coordinated (at least in rowing), and blessed with enormous endurance capacity and a tremendous tolerance for both the rigors of training and the pain of intense racing.

TRAINING

There is evidence that experienced athletes learn how to recruit selectively their muscle groups that propel the boat while relaxing the muscles that do not.[5] The beginner uses muscle groups in a less coordinated and less efficient way. The adage "miles make champions" is very true (Steve Fairbairn, 1904).[6] Many miles rowing on the water induce not only physiological adaptations at the muscular level such as increased mitochondrial and capillary density but also neurological changes that help to automate and refine the coordination of contraction of the numerous involved muscles. The experienced rower does not think about the numerous independent muscular actions comprising a stroke cycle, as it becomes almost second nature. However, the art of coaching is to be able to detect and correct errors in this stroke pattern and timing to help the athlete become more efficient. As a result, rowers are thinking about technique for most of their training sessions as the coach tries to build up a model of the best action to create a muscle memory that moves the boat with smooth and flowing actions.

Muscular strength and muscular endurance are integrated in a rowing performance, but they have different physiological limitations. Therefore, most training regimes concentrate on these aspects of performance separately. An all-year sport, the cycle of rowing training typically starts in the autumn with muscle strength work in the gymnasium, endurance training on indoor rowing machines, and technique work on the water. In this out-of-competition period the athlete concentrates on low-intensity, long-duration exercises to stabilize technique and stimulate muscular adaptations associated with improved endurance. The winter period with dark nights and flooding limits activity on the water. In some climates it is impossible because of ice. The most popular indoor rowing machine was invented by rowing brothers who lived in cold and icy Vermont.

Weight Training

Strength training is primarily performed in the weights gymnasium. Exercises are designed to increase both maximal strength and strength endurance. A combination of heavy weights (3 to 5 repetitions at 80% to 90% of maximum) and endurance weights (30 to 40 repetitions at 40% to 50% of maximum) has been traditionally employed. Training of stabilizing muscles around the spine may be particularly important in protecting the rower from injury and ensuring a strong connecting link between the legs and arms. In recent years greater attention has been given to so-called core stability training for rowers. Exercises such as side bridges, or holding static position while lifting cross-lateral hand and foot off the ground from a starting press-up position, are employed to strengthen abdominal and spinal muscles that stabilize the pelvis and spinal column. Although free-weight training is preferred over machines, injuries are more common with free weights and the technique must itself be coached. The exercises are designed to strengthen the primary muscle groups used in rowing. These are principally the legs and low back. The upper limbs are used to complete the rowing stroke but most of the energy is expended in the initial leg drive and low back extension; the arm pull may be likened to the follow-through of a golf swing. A typical weight regime is centered on developing leg drive and back extension, with some supplementary upper body work and exercises for opposing muscles groups. The latter are intended to promote muscular balance. Injuries sustained in the weight room are relatively common and range from muscle strains and tears to trauma after losing control of a weight. Poor technique may also lead to back and rib injuries.

Body Circuits

During the off-season many clubs also organize a weekly body or "commando" strength circuit to build up aerobic fitness and to provide some variety in training. Exercises include sit-ups, press-ups, jumps, and a variety of other "body weight" exercises using minimal equipment. These highly intense sessions often take the form of interval bouts with 30 to 45 seconds of work separated by perhaps 15 to 20 seconds of rest as athletes move from station to station. Because loads are generally limited to body weight, injuries are rare and usually the result of slips or falls.

Running

Running medium distances (3 to 10 km) is used as a cardiovascular exercise. Rowers are rarely of a build suited to middle distance running, and strain injuries are moderately common. They include ankle sprains, internal derangement of the knee, stress fractures, and occasionally Achilles strains or tears. Because the rowing movement is essentially devoid of eccentric loading, the transition from a period of training consisting exclusively of rowing to other forms of training such as running where eccentric loading stress is high can quickly result in tendon strains.

Ergometer (Rowing Machine) Training

There are a variety of rowing machines available for indoor training. They all employ some frictional resistance such as a fan in air or water to create the load. They have electronic readouts that allow the athlete and coach to measure time, distance, work intensity, and stroke rating. Rowing ergometers tend to err on the side of heavy initial loading with an increased risk of back injury if the catch (beginning) of the stroke is overly emphasized. International crews train with the workload settings at low to medium partly to reduce the risk of back injury and more to better mimic the feel of a boat.

Training schedules vary from short repeated intervals to endurance sessions of an hour at a steady low intensity. There is anecdotal evidence that injuries are more common in the high-intensity repetitions, especially when poorly warmed up. However, there is also the view that as fatigue sets in during long sessions low back stability is impaired.[7,8] Some advise taking a 5-minute break every 30 minutes during ergometer training to reduce this risk. In general, injuries to indoor rowers are uncommon but more frequent than those seen on the water.

Water Work

Rowing on the water, river or lake, is the essence of the sport. In the winter, the exercises are of long endurance and involve concentration on stroke technique. Toward the end of the autumn, long-distance races against the clock are organized to break the monotony of training and provide some competition. These are typically 15 to 30 minutes in duration, but there are a few marathon events with times in excess of 4 hours.

In the spring, the intensity is gradually increased to increase lactic acid tolerance. Short interval sessions with recovery periods are used with more power and higher ratings. Rowers are used to training at a level where the aerobic activity is finely balanced with lactic acid accumulation. This means 20 to 40 minutes at pressures with the pulse rate at the individual lactic threshold. Repeated blood sampling can identify this intensity during exercise at progressive intensities. In the absence of such direct methods, the threshold intensity can be roughly approximated as that yielding a heart rate equal to 80% of 220 beats per minutes minus age in years. When the regatta season starts, this transition period is changed to high-intensity race practice, with fast starts and greater potential for muscle and back injury.

International races are contested over 2000 m on still water lakes often purpose built for rowing. The race lasts 6 to 8 minutes and takes place in multiple lanes (six to eight). The race tactics vary, but most crews aim to achieve maximum speed over the distance with little regard for the direct competition with the crew alongside.

Despite the intensity of rowing races, it is exceptionally rare for permanent injury to result. Although there have been episodic reports of acute deaths in rowers during competition or immediately after, these are usually attributable to undiagnosed cardiomyopathy or cardiac conduction anomalies.

Boats are steered by a coxswain (cox) or a member of the crew. In the coxless boat this may be achieved by a mechanism attached to the shoe of one of the rowers. Training or racing on a winding river, the steersman must look around at intervals and then twist the lower leg to control the rudder. Both these actions lead to a risk of injury by rotational stress to neck, back, and knee. Sculling boats may be steered by pulling harder on one scull (oar), which may also lead to a twisting force.

Collisions and crashes are fortunately rare, but if they do occur the athlete may be subjected to considerably trauma. The momentum of a fast-moving eight loaded with near a half-ton of rowers is considerable when unknowingly directed into a steel or concrete bridge support.

Because everyone is looking the wrong direction when rowing (except hopefully the coxswain in larger boats), boat-on-boat collisions are also a danger, particularly when training in high rowing traffic sections. Experienced rowers are not immune. The lower leg of great Canadian sculler Silken Laumenn was terribly mangled when a fast-moving German coxless pair crashed into her during training for a World Cup race in Germany 10 weeks before the 1992 Olympics. She looked down to see her gastrocnemius muscle dangling from her ankle and was lucky not to pass out and drown. Amazingly, 27 days and five operations later, she returned to her boat while still walking with crutches. Her bronze medal in the Olympics just weeks later ranks as one of the great comebacks in Olympic sport.

Immersion is common in inexperienced single scullers but rare at all other levels and especially in crew boats. In winter, hypothermia is a risk. However, drowning and death from rowing are exceptionally rare.

Training Schedules

Rowing demands large-volume training schedules to achieve any competitive success. For example, Olympic and World Champion single sculler Olav Tufte performs 1125 hours of effective training per year (all types). This works out to a 50-week average of 22.5 hours per week (personal communication). Although international athletes are occupied full-time with three sessions a day, the ambitious amateur also makes time for intense programs. A typical club athlete hoping to achieve success at local regattas and perhaps win a round or two at Henley Royal Regatta would train between six and nine times a week for 1 to 2 hours per session. Masters rowers (age over 27) average 8 to 9 hours training a week in their 30s with little change in the older age groups, the 70 years and over group still averaging 6 hours per week.[4] This high volume of training leads to problems with overtraining and fatigue states. Amenorrhea is common in female athletes. High calorie intake is required to maintain body weight. Anecdotal evidence has suggested that the ex-rower becomes overweight as a result of the habit of high caloric intake, but the opposite seems to be the case from an investigation of ex-college rowers, who were less obese than controls.[9] Repetitive strain injuries are very common. “Rower’s wrist” or “teno” (tenosynovitis) is so common that most rowers have suffered a bout and know the simple measure to deal with it.

Lightweight Events

To allow the smaller person to compete internationally, a lightweight category has been introduced. The weight limits are 72.5 kg for men and 59 kg for women. The crew should average less than 70 kg for men and 57 kg for women. To meet these weight restrictions, athletes who are naturally heavier diet intensely. Unfortunately, the naturally heavier athlete is invariably taller and therefore has an advantage. The dieting strategies of “natural middle weights” chronically fighting to maintain lightweight status lead to risk of osteoporosis in women and a variety of dietary deficiencies in both sexes.

THE ROWING STROKE

Some technical details and terms are necessary to understand the mechanics of injury.

Catch

The stroke begins with the catch (Fig. 1). This is when the blade(s) of the oar or scull is placed in the water. The athlete is fully compressed at the front of the sliding seat track (front stops) with the ankles maximally dorsiflexed, the knees flexed to around 90 degrees, and the hips fully flexed. The low back should be held extended, but poor technique often leads to lower lumbar flexion. This not only places the spine at risk but also lowers the hand position and thereby leads to waving the ends of the oars in the air. This slumped position is often a result of the athlete trying to lengthen the stroke. Paradoxically, because the hand tends to dip and send the oar blade skyward, it results in missing the first connection with the water and has the opposite effect. At the moment of the catch the arms are held outstretched with locked elbows and extended shoulders.

Figure 1 The catch. Two double sculls. The blades have been placed in the water and the leg drive is about to take hold.

Figure 3 The finish. The blades are extracted from the water. This is a technically demanding movement.

Drive

Once the blades are in the water, the drive starts by pushing the legs to extension while first maintaining body angle, then leaning backward still holding the lumbar spine extended. This is the power phase of the stroke and should be smooth and progressive. Because boat (Fig. 2) speed is lowest near the beginning of the catch, this phase is associated with the highest muscular forces as the boat is reaccelerated each stroke cycle.

Draw

The athlete should be extended and leaning a little past the vertical (shoulders slightly behind hips) before any upper limb contraction occurs. The power phase is completed with the hands and arms being drawn to the chest. The goal of the rower is to hold pressure on the oar through the entire stroke. However, toward the end of the stroke, the boat accelerates to near its highest speed and the loading decreases.

Finish

The hands are lowered to extract the blades from the water and then pushed away from the body until the elbows are locked (Fig. 3). At the same time a twisting of the hand and wrist feathers (flattens) the blade position so that it is parallel to the water.

Figure 2 The drive. Later in the power section of the stroke the legs are flat, the back extends, and the arms begin to finish the stroke.

Recovery

With arms fully outstretched after oar extraction at the finish of the stroke, the upper body rotates over the hips so that the shoulders are in front of the hips, while keeping the legs fully extended and the low back in extension (Fig. 4). Only then are the knees and legs allowed to flex, drawing the body forward along the slide. As this body action takes place, the kinetic energy stored by part of the extension action is transferred to the boat. Strangely, the highest boat velocity is recorded at this moment when the oars are out of the water. Technically this is the most complex and demanding part of the stroke, and it is here that races are won and lost. During the recovery phase the hands pass over the sides of the boat at the oar or scull describing an arc. If the boat wobbles during rough conditions, the fingers

Figure 4 The recovery. The arms are extended and the body leans forward, transferring kinetic energy to the hull and reaching the maximum boat speed for that stroke.

may be trapped against the side of the boat. In sculling, the hands and arms move apart evenly with external rotation of the shoulders. In swept oar rowing (one oar) the whole body rotates to follow the handle of the oar; the outer arm is fully extended and stretched compared with the inner side. The drive phases for sculling and rowing are therefore taken with different body positions. Although sculling is a straight and symmetric action, upper body (considerable) and lower body (minor) asymmetries are necessary to achieve proper body and oar position at the catch in swept oar rowing.

In sculling, the handles of the oars (sculls) overlap so that one hand must pass above the other midway through the recovery. It is common for the fingers of the upper hand or the rubberized cover of the handles to scrape the dorsum of the lower hand. Consequently, experienced scullers keep the fingernails well trimmed during rowing season.

SPECIFIC INJURIES

Spine

Not surprisingly, low back problems are common among rowers. The prevalence is said to be less than that of the nonrowing population.[10,11] This may reflect a lower rate of reporting among an enthusiastic population not keen on curtailing their sport.

There has been debate as to whether changes in equipment have placed extra load on the rower's spine.[12,13] Oars and sculls are now made from synthetic polymers with embedded carbon fiber. They are much stiffer than their wooden predecessors. The blade at the end of the oar provides connection with the water. The shapes have changed from thin "needles" through spoon-shaped "Macon" style to the current asymmetric cleaver shape blade. Each change has given a firmer connection with the water and potentially more load on the rower in the early phase of the stroke. Before the newer oars were available, conventional coaching wisdom was to take the catch powerfully to get the boat up to speed quickly. This old technique applied to a modern carbon fiber–reinforced blade creates a heavy acute load on the spine. Coaches now suggest that the initial catch should be comparatively "light and delicate" with a rapid but steady acceleration of the oar handle. It is probable that there was a flurry of equipment-related back injuries before coaching ideas changed but that the frequency has settled since. There are no hard data on this matter and these conclusions are therefore speculative. In some countries, age limits have been imposed on the use of cleaver blades in an effort to limit overloading of the back in young rowers.

Rowers who habitually row on one side of the swept oar boat may suffer back pain related to asymmetric development,[5,14] but muscle weakness is not a factor.[15] Other technical factors that may contribute to the exacerbation of back pain are the previously described slumped catch position[16,17] and strains that occur during weight training. There may be a relationship between pelvic tilt and back pain in rowers, but the evidence is not conclusive.[18]

Back pain in the rower may be due to several disorders including disc degeneration, annular tears, facet disease, spondylolysis, sacroiliac joint dysfunction, and nonspecific muscular pain.

ANNULAR TEARS, DISC AND FACET DEGENERATION

Annular tears are seen as areas of increased signal within the posterior annulus of the intervertebral disc on T2-weighted or fat-saturated images. Several types are recognized according to whether they are linear or rounded and whether their orientation is radial or transverse. An intensely bright, rounded high signal focus surrounded entirely by low signal annulus is called a focal high signal zone (HSZ). Some authors have shown that the HSZ has a strong association with low back pain[19] although others disagree.[20] Differences in the precise definition of the HSZ may account for much of the disagreement, which is reduced when strict criteria are used. Disc degeneration diagnosed on the basis of loss of signal on T2-weighted images is common in the asymptomatic population and of itself not a useful indicator of pain. The association with increased edema in the adjacent vertebral bodies is a sensitive but nonspecific indicator of the disc being the pain generator,[21] although it is also seen in asymptomatic individuals.[22] The correlation between pain and radiological facet arthrosis is also poor. The only reliable method of diagnosing facet syndrome is ablation of pain following intra-articular injection of local anesthetic. Painful annular tears have been treated with radiofrequency intradiscal electrothermal annuloplasty and facet syndrome by intra-articular corticosteroids or medial branch radiofrequency neurolysis.

SPONDYLOLYSIS

The pars interarticularis is a small isthmus of bone that connects the superior to the inferior articular process of the posterior elements of the vertebral body. At its upper extent it is connected to the vertebral body by the pedicle. Sports that involve hyperextension and hyperextension rotation, particularly in the immature skeleton, are most associated with stress fractures of the pars, which are termed spondylolysis. Spondylolysis involves L5 in 80% of cases, decreasing in prevalence as the spine is ascended.[23] Eighty percent of pars fractures are bilateral; an association with unilateral pars and side of the boat has not been studied, although unilateralism has been identified in other sports. For example, unilateral defects are more common in the nonbowling arm of cricketing fast bowlers. Spondylolisthesis occurs in

~35% of lyses and more commonly in women than in men.

The association between spondylolysis and rowing is debated. Soler and Calderron studied 3152 high-level Spanish athletes to determine the prevalence of spondylolysis in different sports and found similar rates in rowing and gymnastics (both 17%), second only to throwing sports (27%) in prevalence.[23] Spondylolysis was more common in rowing (17%) than the average among all athletes in this study (8%) and the general population (~5%). Differences among studies[24] on the prevalence of pars defects in rowers may reflect the imaging methods used.

The imaging goal in spondylolysis is to address the important clinical questions. These are (1) whether the patient has a spondylolysis; (2) whether it is acute or long standing; (3) if acute, whether it is showing signs of healing; and (4) whether it is definitely the cause of pain. The imaging techniques available include conventional radiographs, computed tomography (CT), skeletal scintigraphy, magnetic resonance imaging (MRI), and pars blockade. Each of these addresses a different component of the clinical questions, and several techniques in combination may be required to provide a complete answer.

Conventional radiographs coupled with oblique views if necessary are now largely replaced by cross-sectional techniques (Fig. 5). Radiographs carry a significant radiation dose, are insensitive to other causes of low pain in this group of patients, and obtaining good visualization of the pars, especially at L5, requires a skilled technician.

Figure 5 Oblique plain film showing classical ''Scotty dog.'' The pars is the neck of the dog and lies just below the ear (arrow). The neck at L5 is broken, indicating a pars fracture (arrowhead).

In the authors' view, the examination should begin with MRI. There are several reasons for this choice. MRI does not involve ionizing radiation and provides the best overview of potential causes of low back pain in the athlete. Sagittal T1-weighted images with no more than 4 mm slice thickness are the mainstay of diagnosis. High-signal marrow crossing the isthmus of the pars interarticularis on T1-weighted images carries a high negative predictive value (Fig. 6). Several pitfalls and variations occur, the principal one being loss of corticomedullary differentiation at the waist of the pars. Usually, the marrow signal tapers to a point where it may be effaced by cortical thickening, only to reappear, also as a point, which expands into the inferior articular process. This tapering is easily distinguished from the blunt interruption that occurs when there is a fracture of the pars (Fig. 6). In some patients with thin pars, careful review at a workstation, placing a cursor on areas of high-signal marrow, and following them on successive sections can be helpful. One of the more difficult pitfalls occurs in the presence of hematopoietic (red) marrow, particularly when the pars are thin, as might occur in younger athletes. In this scenario, differentiation between the normal and the abnormal is more difficult because of the loss of contrast between the fatty marrow and cortex.

T1-weighted images are supported by fat-suppressed images also obtained in the sagittal plane. Diffuse marrow edema in the region of the pars is a measure of the acuteness of the lesion. Increased signal

Figure 6 Spondylolysis at L5. Note the intact isthmus at L4 crossed by normal marrow signal on T1-weighted sagittal image (arrowhead). Compare with the interrupted isthmus at L5 (arrow).

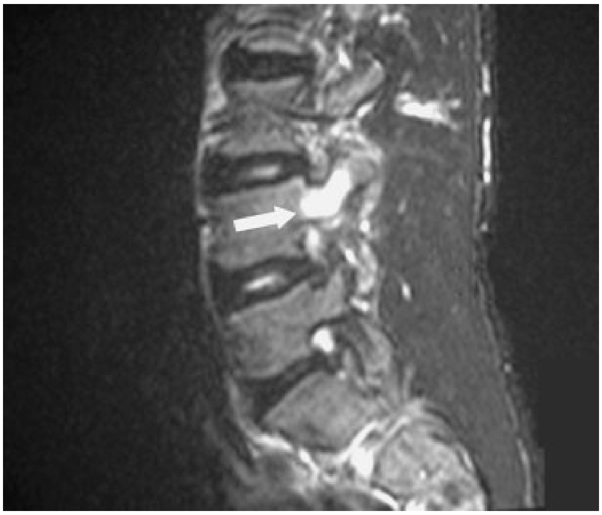


Figure 7 Sagittal fat-suppressed short inversion time inversion recovery (STIR) image of pars with edema at the isthmus and extending into the pedicle (arrow) consistent with stress response.

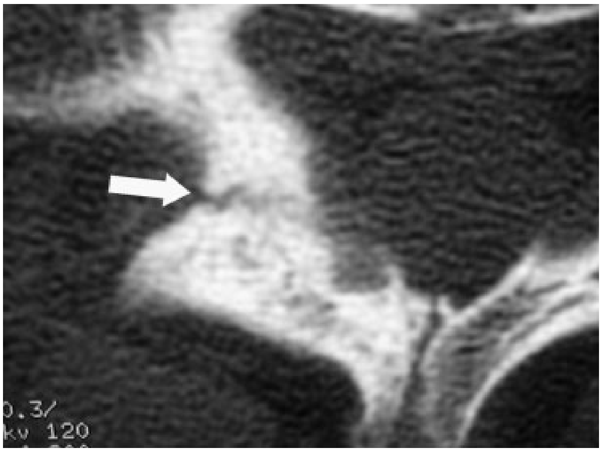


Figure 8 CT through established pars fracture (arrow).

on fat-suppressed imaging may be seen in the absence of a defect, and this indicates the presence of an earlier phase of injury termed stress response (Fig. 7). MRI can therefore differentiate between the normal, acute, or chronic fracture and prefracture or stress response in the majority of cases. It is likely that edema on MRI correlates with new bone and hence healing on CT, but this has not been firmly established.

CT provides the best depiction of the bone anatomy of the pars itself. In the past, the gantry was angled along the long axis of the pars (the so-called reverse gantry, as it is opposite to the tilt used to look for a disc herniation). On newer helical or multislice equipment, this is not necessary and high-resolution imaging in the axial plane supported by sagittal reconstructions depicts pars anatomy clearly (Fig. 8). There have been few formal studies comparing CT with MRI and particular concern exists in the area of stress response. Medullary sclerosis not associated with fracture probably indicates stress response (Fig. 9), but it is likely that this represents a later stage in the evolution of the disease process. In patients with relatively thin pars it can be difficult to decide whether the degree of medullary sclerosis on CT is normal or abnormal. Comparison with the contralateral side can help, but the range of normal has not been established. An estimation of the chronicity of the lesion is also possible on CT based on the degree of medullary sclerosis (Figs. 8, 9), cortical margination of the fracture, cortical thickening, and new bone formation. Serial CT may be superior to MRI in following fracture healing given its superior resolution of the bone interfaces. Healing is more common in unilateral than bilateral spondylolysis, but there is a poor correlation between healing and return to sport.[25]

Increased uptake on skeletal scintigraphy provides a good measure of activity around the fracture site,[26] although planar imaging needs to be combined with single photon emission computed tomography (SPECT) to differentiate disease of the pars from abnormalities in the adjacent facet joints and vertebral bodies[27–30] (Fig. 10). Proponents argue that SPECT helps to distinguish the significant (painful) spondylolysis from the insignificant (painless) one and that intervention is not indicated if there is no increased activity on the scintigram. There is no evidence to show that it can differentiate between established fracture and prefracture state or stress response. Both scintigraphy and CT carry a significant radiation dose.

SIJ DYSFUNCTION

The prevalence of sacroiliac pain in the U.S. national rowing team was 54% in a study by Timm using clinical symptoms and palpation.[31] Sacroiliac joint dysfunction was prevalent in both sweep rowers (66%) and scullers (34%) and did not vary with the handedness of sweep rowers.[31]

OSTEOPOROSIS

Although not usually regarded as an injury per se, osteoporosis is an important issue for lightweight female athletes. Although eating disorders among athletes are rare,[32] heavy training regimens coupled with dietary

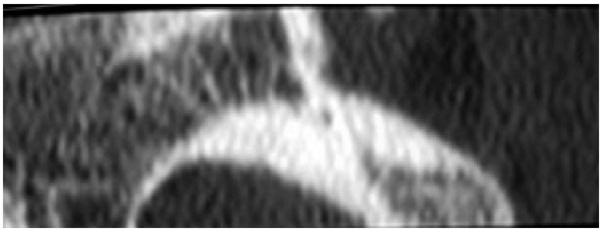
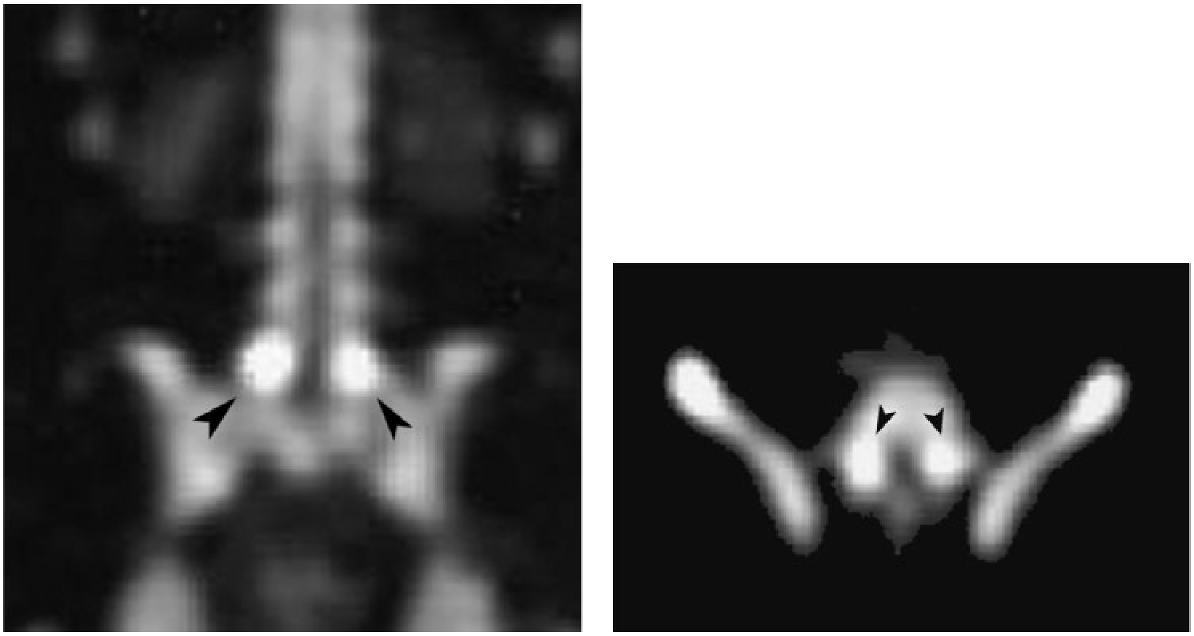


Figure 9 Medullary sclerosis without fracture indicating stress response. There was an established pars fracture on the contralateral side.



A B

Figure 10 (A) Coronal SPECT image showing hot spots in the region of both pars (arrowheads). (B) Corresponding axial image locating activity to the region of the pars (arrowheads).

control to reach designated weight levels for competition predispose women athletes to amenorrhea, which in turn reduces trabecular bone mineral density (BMD). There is some evidence that rowing may confer some protection against vertebral osteoporosis. Several studies have shown a protective effect of exercise on BMD at the site of maximal muscle exertion.[33] Huddleston et al showed increased BMD in the wrists of tennis players,[34] and Williams et al showed similar increases in the os calcis of runners.[35] In a study of 26 elite female rowers, half of whom had amenorrhea, significant differences in BMD as measured by CT densitometry were detected between the amenorrheic and eumenorrheic athletes.[36] In the same study, rowers were found to have higher spinal BMD than a cohort of sub-3 hours marathon runners and professional ballet dancers, implying a protective effect of back exercise.[36] Menstrual state, whether or not associated with absolute weight, was the main determinant of spinal BMD. Later studies using dual-energy x-ray absorptiometry[37] have confirmed these results and shown no associated increase in femoral neck BMD.

Rib Injury

Stress fractures of the rib are a specific rowing-related injury. They occur in up to one in eight rowers and account for the most time lost from on-water training and competition.[38] It is an injury that is more common in sweep rowers than scullers[39–41] and women are more often affected than men.[42] The posterolateral angle of the fifth to ninth ribs on the side of the outside arm is the most typical location.[42] It is likely that the outside arm in the rowing stroke places extra load on the chest wall as the rower pulls to oar through its arc. The scapula and rhomboids are relatively fixed and with the arms fully extended a bending force is created at the junction of the serratus anterior and internal oblique attachments leading to stress fracture.

The diagnosis is clinical and rarely requires imaging, although imaging does allow a differentiation between stress and overt fracture, nonunion (Fig. 11), and other local causes of focal pain such as stress fracture of the neck of the rib[43] and internal oblique[44] and serratus anterior[45] avulsion.

Rowers can alleviate the symptoms by changing to the opposite side of the boat, where the other arm takes the load. Stress fractures of the ribs have also been observed in throwing sports,[46] golf,[47] canoeing,[48] and swimming.[49] Cricketers may develop enthesitis or internal oblique strains in the same location, but the mechanism is a little different.

Shoulder

Shoulder injuries are rare in rowers. The joint is not subjected to particular load. However any condition that affects this joint limits the stroke action. We have seen two cases of a sculler with a ganglion arising from the glenohumeral joint that was compressing the suprascapular nerve and leading to infraspinatus muscle atrophy. The suprascapular nerve arises from the trunk formed by the fifth and sixth cervical nerves, with some contribution from the fourth. It is most commonly a purely motor nerve, although in 15% of normal individuals it can receive a sensory branch from the upper lateral arm, termed the deltoid patch.[50] It runs beneath the trapezius

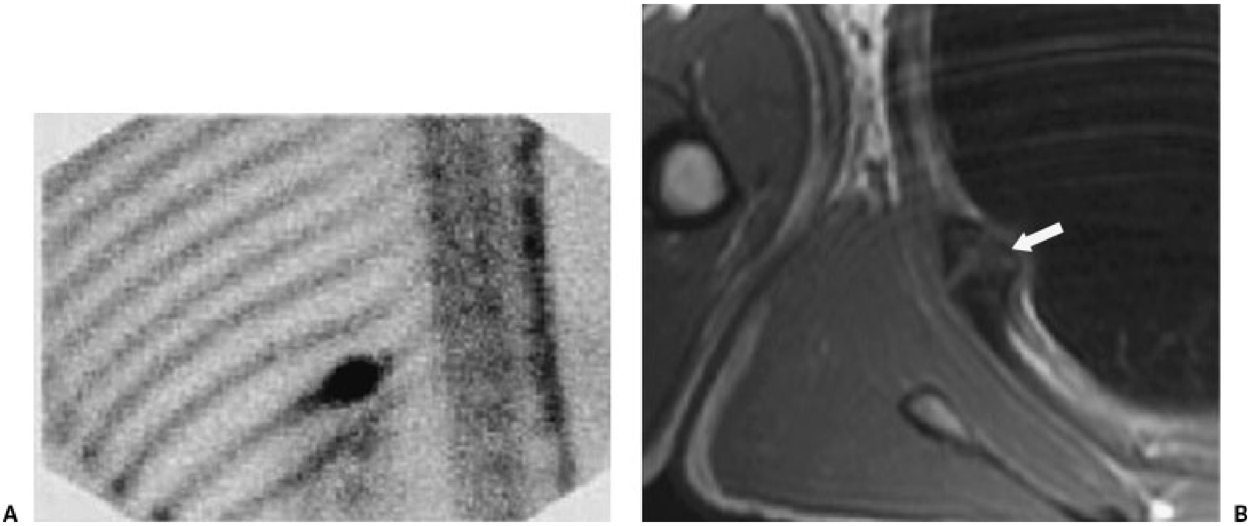


Figure 11 (A) Skeletal scintigram with focus of increased uptake in rib fracture. (B) Axial T1-weighted MR showing nonunion of rib fracture (arrow). The patient complained of grating and pain on scapular motion.

and omohyoid muscles before entering the supraspinatus fossa through the suprascapular notch. A variety of different notch shapes have been described, with U and V configurations of varying depth.[51] Probably more important than the configuration of the notch is the relationship between the nerve and spinoglenoid ligament in the spinoglenoid notch. In this location it is relatively fixed and susceptible to compression or traction. Just below this it divides into two motor branches to the infraspinatus muscle. One of the most common radiologically identified causes of infraspinatus dysfunction and atrophy is compression due to a paralabral cyst arising from the posterosuperior labrum (Fig. 12). It should be recognized, however, that infraspinatus atrophy is most often due to traction or other compressive etiology for which there is usually no discernible radiological cause. Indeed, it is the most frequently injured peripheral branch of the brachial plexus in athletes, although most commonly seen in volleyball, throwing sports such as baseball, tennis, weight lifters, and swimmers.

Elbow

Enthesitis at the common flexor origin is the most frequent problem that rowers experience in the elbow.

Figure 12 (A) Axial T2-weighted spin echo image of moderate-sized paralabral cyst. Note the small neck extending back toward the posterosuperior labrum (arrow). The infraspinatus muscle is atrophic. (B) Ultrasound in a different patient demonstrating the paralabral ganglion.

The hands grip the handle of the scull or oar throughout the stroke and subject the flexor muscle group to repetitive strain. This is more common on the outside arm of swept oar rowers and may be asymmetric in scullers, perhaps because of the slightly different actions as one scull passes above the other in the stoke cycle. The common flexor tendon lies on the medial aspect of the elbow joint and arises from the medial epicondyle. It is shorter and thicker than the common extensor tendon. Medial epicondylitis is more commonly known as "golfer's elbow" although it is more frequently reported in tennis players, when it is also referred to as medial tennis elbow. Medial epicondylitis most frequently involves pronator teres, flexor carpi radialis, and palmaris longus if it is present. It is thought to arise from microtears of the tendinous attachments to the underlying epicondyle, associated with changes in the adjacent fibrocartilage enthesis, bone, and collateral ligament. Histologically, as in many other overuse syndromes, an inflammatory response is lacking. Fibrovascular and fibrocartilage proliferation, mucoid, collagen, and hyaline cartilage degeneration and fibrosis[52] predominate; hence, the term epicondalgia is probably more appropriate. Similar histological findings have also been reported in elderly cadavers.[53]

Plain films may show calcification in up to 20% of cases,[54] but cross-sectional imaging with MRI and ultrasound remain the mainstay of diagnosis (Fig. 13). On MRI, fat-suppressed images with coronal and axial acquisition planes are the most useful. The ulnar collateral ligament may also be involved, although this is more common in throwing sports. Other findings described in epicondylitis include bone spurring and joint effusion. Ulnar neuropathy is not uncommonly associated with medial epicondylitis and may mimic it symptomatically.

The sonographic findings in both medial and lateral epicondylitis are similar. The normal common tendon origins are reflective with a smooth transition from tendinous to myotendinous elements. Under normal circumstances, little blood flow is evident within the common origins (Fig. 14). The ulnar collateral ligament can be identified as a separate, thin reflective striated band, typical of ligaments elsewhere in the body. It is more often injured at its humeral origin than its insertion into the coronoid process. Stress ultrasound can demonstrate ligament injury not obvious on static scanning and may be an advantage over MRI.[55] There are few studies that compare ultrasound versus MRI in the diagnosis of epicondylitis, but those that exist suggest that MRI is more accurate.[56] However, studies comparing operative findings with ultrasound or MRI suggest that they are of similar diagnostic accuracy.[57,58]

Epicondylitis can be divided into mild, moderate, and severe based on the degree of degeneration and tearing. Mild findings are limited to degeneration only with thinning and loss of the normal low signal within the extensor origin. Moderate disease is diagnosed when tearing does not extend through the entire tendon and severe as full-thickness involvement with fluid separation from the underlying epicondyle. Means of treatment include altering the size of the grip of the oar or scull and changing training regimes. More severe disease may require surgery, but disease of this extent is rare in rowing.

Figure 13 Common flexor origin tear on coronal fat suppressed STIR image (arrow).

Wrist

Tenosynovitis is the most common rowing-specific injury. Tendinopathy can involve either the flexor or extensor compartments. Creaking or grating in the carpal tunnel with pain and swelling is common in flexor tenosynovitis. The mechanism appears to be the repeated rotation of the oar twice each stroke to achieve squaring and feathering of the oar as training on a rowing machine rarely causes tenosynovitis.

There are four groups of tendons on the flexor aspect of the distal wrist. The largest group comprises the tendons contained within the carpal tunnel, along with the median nerve. In addition to the main flexor tendons, there is one tendon group on the ulnar side of the carpus and two on the radial. The ulnar side tendon is the flexor carpi ulnaris, which overlies the ulnar nerve at the wrist. The more ulnar of the two tendon groups on the radial aspect of the carpal tunnel is the flexor pollicis longus tendon, which inserts at the base of the distal phalanx of the thumb. It has its own synovial sheath but does pass through the flexor retinaculum. The final

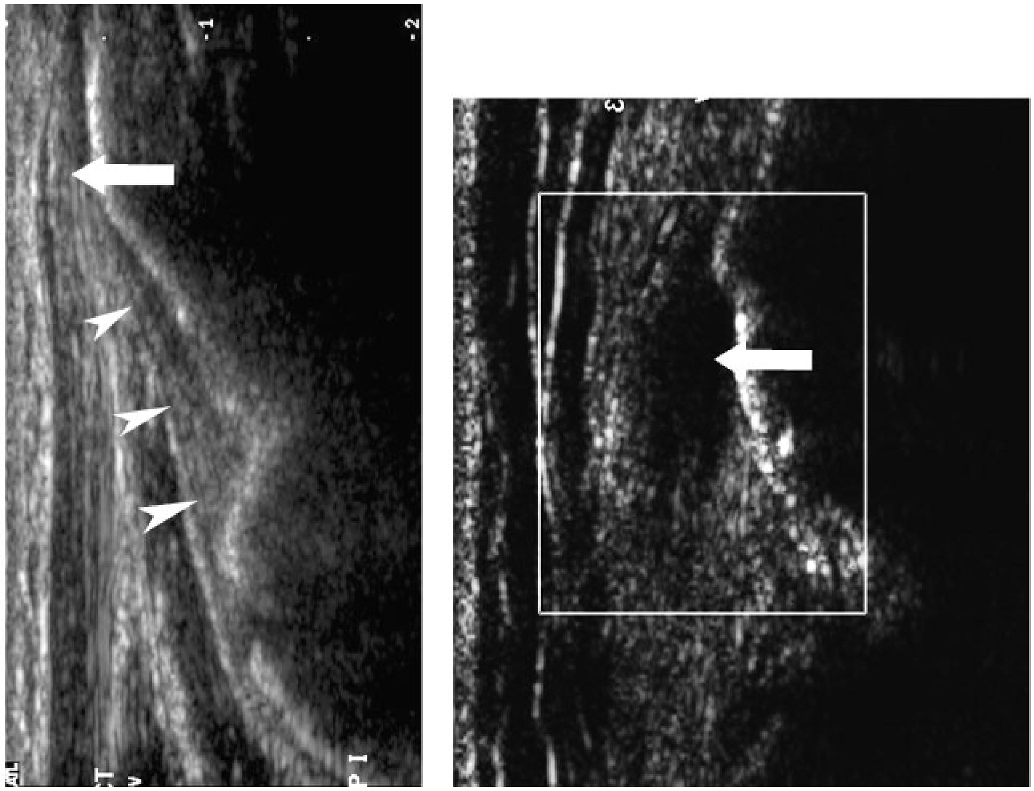


Figure 14 (A) Normal coronal ultrasound of the common flexor origin. Note the generally reflective appearance to the common tendon (arrow) and the distinct band of the ulnar collateral ligament (arrowheads). (B) Loss of reflectivity (arrow) and increased Doppler signal in extensor carpi radialis brevis.

flexor tendon is flexor carpi radialis. The tendons most frequently involved in flexor tenosynovitis are the flexor digitorum superficialis and profundus.

On MRI, the axial plane is the most efficient for diagnosis. Normal tendons return low signal intensity on both T1- and T2-weighted images. Signal intensity of T1- or short TE-weighted images show more variation than T2, most frequently due to the magic angle phenomenon. Correlation with T2, preferably with fat suppression, enables a more confident diagnosis of tendon disease. A small quantity of fluid may be identified within the sheath in the asymptomatic population. Overuse results in increase in fluid within the sheath. As a general rule, if the quantity of fluid exceeds the cross-sectional area of the tendon, it may be regarded as abnormal. In some cases, such as the tendon sheath of flexor hallucis longus, considerably more fluid is frequently not associated with symptoms. In other cases, such as tenosynovitis of extensor compartment 1 of the wrist (Fig. 15), the process is more sclerosing and much less fluid may still be significant.

Tendinopathy most commonly results in an increase in tendon size. Findings on MRI are therefore a combination of tendon thickening without internal signal derangement and fluid within the tendon sheath, ranging from a small quantity to a markedly distended sheath.

Tenosynovitis on ultrasound is characterized by an increase in tendon sheath fluid and thickening and increased vascularity of the synovial lining (Fig. 16). Loss of the normal reflectivity within the tendon indicates associated tendinopathy. This may be diffuse but is more commonly focal or associated with longitudinal splits.

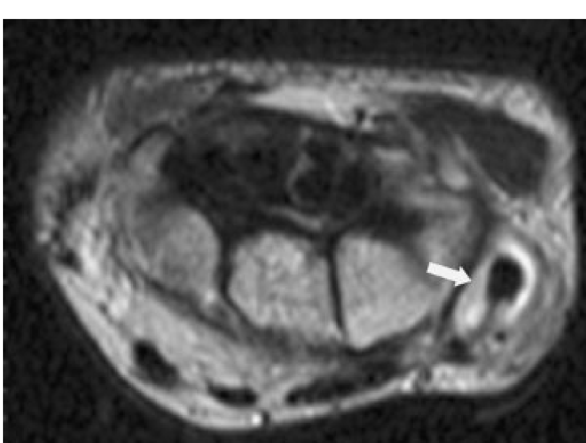
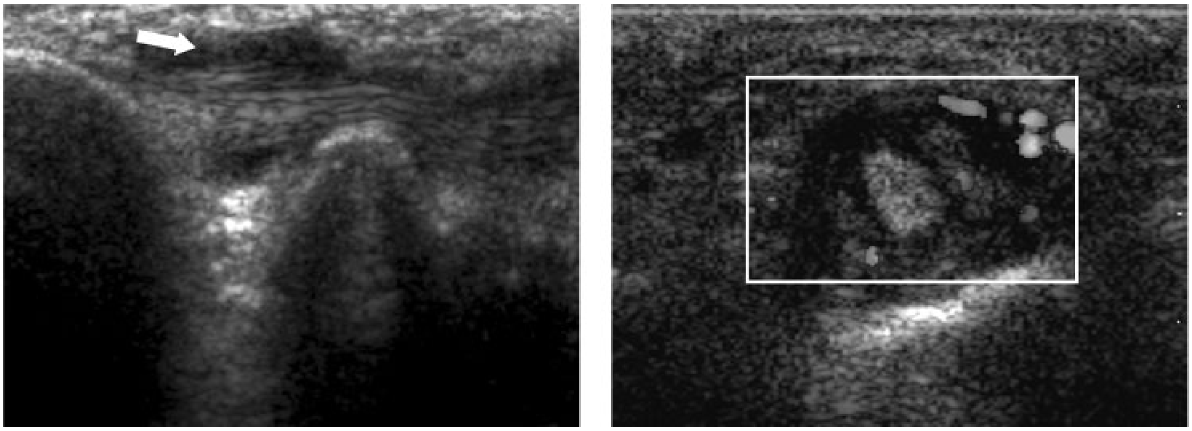


Figure 15 MRI of extensor compartment 1 of the wrist illustrating tendinopathy. There is increased fluid within the sheath on axial T2-weighted image (arrow).



A B

Figure 16 (A) Tenosynovitis with increased fluid within the tendon sheath (arrow). (B) Markedly increased vascularity within the inflamed tendon sheath synovium.

Tendinopathy may also involve the extensor compartment. There are six separate extensor compartments numbered 1 to 6 from the radial aspect of the wrist. Extensor compartment 1 contains two tendons, extensor pollicis brevis and abductor pollicis longus. The two tendons together form the palmar boundary of the anatomical snuff box. Extensor compartment 2 comprises two tendons, the extensor carpi radialis longus and brevis. The brevis tendon is the more ulnar of the two, inserting into the base of the third metacarpal whereas the longus inserts into the base of the second. They form the dorsal aspect of the anatomical snuff box. The second extensor compartment is separated from the third extensor compartment by Lister's tubercle, which is a prominent anatomical landmark on the dorsal aspect of the radius. The third compartment comprises the extensor pollicis longus as the sole tendon. It passes through its own retinaculum, where it forms the dorsal aspect of the anatomical snuff box. It is easily recognized by the sharp radial deviation that it takes around Lister's tubercle as it heads toward its insertion in the base of the distal phalanx of the thumb. It is one of the more common extensor tendon ruptures in patients with rheumatoid arthritis because of this relationship with Lister's tubercle but is rarely involved by tenosynovitis. The fourth compartment comprises five tendons, four of which are extensor tendons to the four fingers while the fifth, which lies deep to the other four, is the extensor indices. The fifth compartment is the extensor digiti minimi, which inserts in the extensor apparatus of the little finger. This may be a paired tendon or become a paired tendon as it moves distally. It is joined by the extensor digitorum tendon to the little finger just proximal to the metacarpal phalangeal joint. The sixth compartment is most easily identified lying within the groove on the medial aspect of the distal ulna. It contains the extensor carpi ulnaris tendon, which inserts in the base of the fifth metacarpal.

The first and sixth compartments are the most frequently involved by extensor tenosynovitis in the general population. In rowers, a distinct syndrome occurs where the first and second extensor compartments cross each other in the forearm.

INTERSECTION SYNDROME (OARSMAN'S WRIST)

The intersection syndrome is characterized by the presence of pain and swelling $\sim$4 to 8 cm proximal to the radial styloid on the radial aspect of the forearm. The condition was first described in 1841 by Velpeau. Since that time it has been variously referred to as peritendinitis crepitans, subcutaneous perimyositis, squeaker's wrist, bugaboo forearm,[59] oarsman's wrist, and abductor pollicis longus syndrome.[60] The occurrence of symptoms where the first extensor compartment tendons crosses over the second extensor compartment tendons led to the more commonly used term "intersection syndrome."[61]

The etiology is disputed. One hypothesis proposes a simple friction phenomenon due to the anatomical crossover and the proximity to the musculotendinous junctions. Grundberg and Reagan suggest that the syndrome may result from tightness of the tendon sheath of the extensor carpi radialis longus and extensor carpi radialis brevis tendons, causing swelling and tenderness proximally.[62] As in tendinopathy elsewhere, inflammatory cells are sparse pathologically. Besides rowing, there is an association with other sports such as canoeing, racket sports, horseback riding, and skiing,[59] where it is said to be common among helicopter skiing because of pole planting activity in deep powder. Clinical examination of the right upper extremity reveals an area of swelling, tenderness, and crepitus exaggerated by ulnar deviation of the hand in the classical location.[63,64]

MR and ultrasound findings are similar to those for tendinopathy elsewhere but in the characteristic location (Figs. 17, 18). Enhancement has been reported

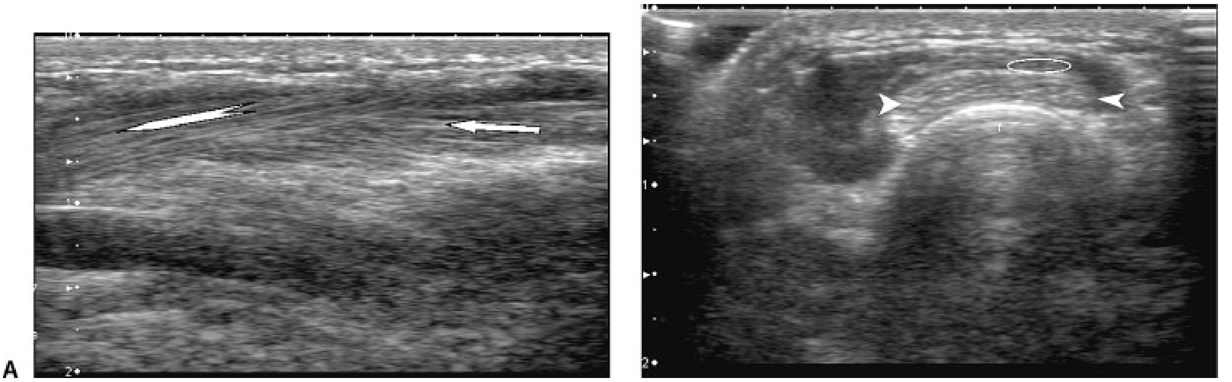


Figure 17 Normal US anatomy of crossover point (A) Long axis with extensor compartment 1 (line arrow) crosses compartment 2 (headed arrow). (B) Transverse section with compartment 1 tendon (oval) overlying compartment 2 (arrowheads), which in turn overlies radius (r).

at the interface between the two tendon compartments, but gadolinium is not routinely administered in our practice. Indeed, in most cases the syndrome is an obvious clinical diagnosis and imaging is not necessary.

The principal differential is de Quervain's tenosynovitis (Fig. 19). This is a stenosing tendinopathy of the first dorsal extensor compartment. The distinction is largely made clinically based on the location of the point of maximal tenderness, which is more distal at the level of the radial styloid. Finkelstein's test confirms the diagnosis, with pain on resisted abduction of the thumb. On MRI, tendon thickening, minimal edema, and occasionally secondary changes within the adjacent radial styloid are typical. The latter can occasionally be detected on conventional radiographs.

On ultrasound, the only finding may be thickening of the tendon sheath (Fig. 20), although tendon sheath fluid and internal signal changes within the tendon may also be apparent.

Treatment includes reducing the rowing element of training, but this will not be a popular suggestion with the athlete. Change in the size of the oar or scull handle may help, and rowing with the oar square all the time may assist. The latter is a common training exercise and benefits the whole crew. It is, however, difficult to carry out in rough water or with the less experienced and therefore unstable crew. Rest, ice packs, and anti-inflammatory drugs are used with varied success. Teaching the rower to rotate the oar by rolling the fingers

Figure 18 Edema and fluid at the musculotendinous junction of the extensor compartment 1 as it crosses compartment 2 (arrow). (Image courtesy of Dr Andrew Grainger.)

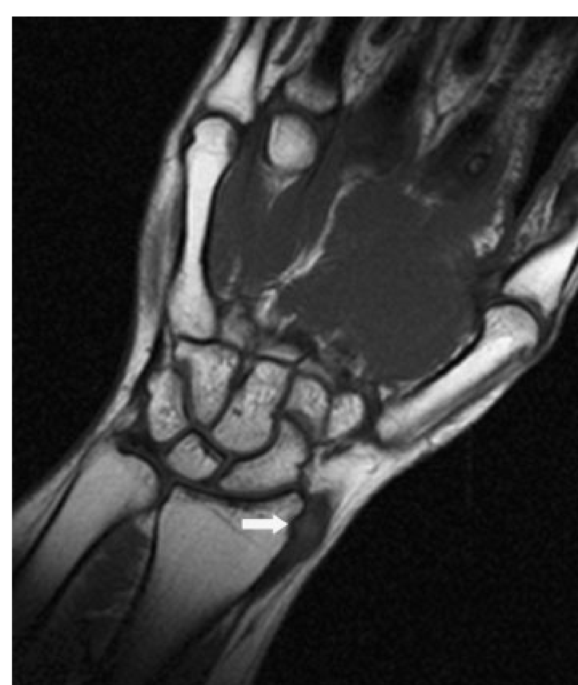


Figure 19 Coronal T1-weighted MR image of a patient with stenosing tenosynovitis. Note the thickened tendon and minor scalloping of the underlying radius (arrow). The latter can occasionally allow a conventional radiographic diagnosis.

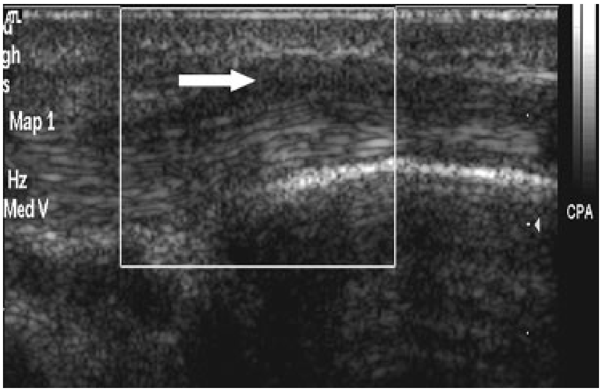


Figure 20 Thickening of the tenosynovium without synovial fluid (arrow) typical of sclerosing tenosynovitis.

rather than twisting the wrist will help and should also improve technique.

Fingers

Impact between the oar handle and the side of the boat (saxboard) is common in unstable crews or rough water conditions. There is little that can be done to avoid this injury, although it is rarely disabling. Fractures are exceptional.

Knee

Knee injuries most commonly occur during circuit training and running. These are discussed in other sections. It has been reported that maltracking may be a problem in female rowers, possibly made worse by the fixed footwear in the boat. Maltracking may contribute to or exacerbate other causes of anterior knee pain.

Maltracking is difficult to assess on plain films, as most significant tracking abnormalities occur between 0 and 30 degrees of flexion and skyline views in this position are not easy to obtain.[65,66] It is best assessed using a true kinematic cross-sectional imaging technique. In the author's institution, MRI is most often used although techniques using CT have also been reported.[67,68] True kinematic studies require that the images be obtained during active extension, preferably against a resistance to load the quadriceps. Equipment manufacturers have developed a variety of motion restraining devices, but the principle of these devices is relatively constant. They allow a range of motion between ~40 degrees and full extension with free and unconstrained patellar movement.[69] Advantages of a dedicated restraining device include its ability to reduce lateral or rotary motion of the femur during extension. Although these movements do not obscure patellar maltracking, the relatively fixed position of the femur makes diagnosis easier. Disadvantages include inadvertent fixation of the patella by the device, which may obscure abnormal movement. This was a particular problem with older devices, which examined the patient in the supine position.

Manufactured devices are not always necessary; the authors use an inflatable ball to provide the necessary resistance to extension to invoke active quad contraction. This technique is more fully described elsewhere[70,71] but used a rapid gradient-echo sequence T1-weighted "Turboflash" (TR 11 milliseconds, TE 4.2 milliseconds, flip angle 15 degrees, slice thickness 5 mm, interslice gap 0 mm, matrix 80 $\times$ 128, one excitation, field of view 480 mm) using a body coil. This pulse sequence provides six axial images and one sagittal image every 7 seconds and is repeated 15 times, with the first sequence commencing just prior to movement, aiming to reach full knee extension toward the end of the study (at ~2 minutes). Once an adequate set of images has been obtained, the axial image that best shows the midportion of the patella from each of the 15 acquisitions is selected and viewed as a cine loop (Fig. 21).

Patellar tracking can be assessed by using various measurements including lateral patellar angle, congruence angle, lateral patellar deviation, and tilt. The principal difficulty with angle and distance measurement is their application to a method where the interosseus relationships change during the examination. As the knee extends, the patella rides up the femoral notch. This makes relating measurements on the patella to a fixed point of the femur difficult. The alternative is to assess visually the tracking study on a cine loop facility (Fig. 21). Normally, the patella remains centrally positioned within the femoral groove as the knee extends. Various patterns of maltracking have been described. The most common of these is lateral subluxation, which can be graded into 1, minor perceptible lateral deviation or tilt; 2, obvious lateral deviation or tilt; and 3, gross

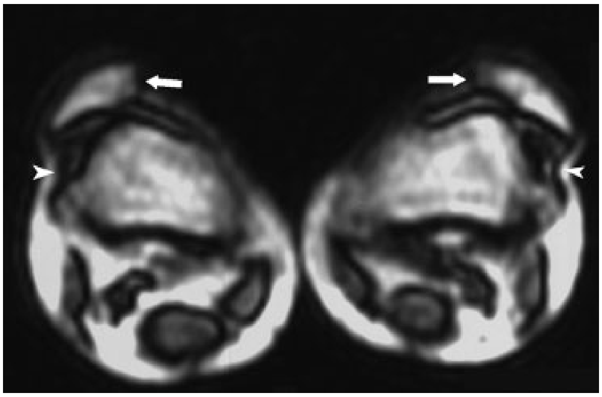


Figure 21 One frame from an axial fast gradient echo image obtained during a tracking study. Note the lateral deviation of the patellae (arrow) and lax lateral retinacula (arrowheads). Although the spatial resolution is poor because of the fast acquisition, a series of images during active extension can be viewed as a cine loop to demonstrate maltracking.

Figure 22 Lateral condylar impingement. Note the increased signal in the peripatellar tendon tissues (arrow).

patellar subluxation. As it subluxes, there is also a tendency for the patella to tilt laterally, presumably due to a rotatory force induced by quadriceps contraction. Grade 1 subluxation is seen in ~30% of asymptomatic individuals and therefore should probably be regarded as a variation of normal.

Maltracking may predispose to chondromalacia and superior Hoffa's impingement (Fig. 22). These have to be distinguished from other causes of anterior knee pain including patellar tendinopathy, patellofemoral osteochondral disease, and other diseases of Hoffa's fat pad.

Ankle

A particular problem in the older rower is lack of flexibility of the ankle related to degenerative arthropathy. Modern boats have purpose-made track shoes built into the foot plate. These are laced or closed by Velcro straps. An inclining plate fixes them to the keel and sides of the boat whereby force is transmitted to the hull. The heels of the shoes lift off, but they are retrained by cords so that if the boat capsizes rowers can still extract their feet to clear the upturned craft. At the catch of the stroke the heels elevate from the foot plate but much of the compression is achieved by flexing the joint.

Muscle Injury

Strains and sprains are common in land training, especially when using heavy weights. Muscle injury in the boat is exceptionally rare.

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