

Rowing Injuries: An Updated Review

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Abstract Although traditionally seen as a sport for elite schools and colleges, rowing is a founding Olympic event and is increasingly enjoyed by people of all ages and abilities. The sport's rapidly changing demographics shows significant growth in masters (age 27 years and above) and para-rowing populations. It has further expanded beyond its traditional flatwater format to include the discipline of open-water or coastal rowing, and an increased focus on indoor rowing. Rowing-specific injury research has

similarly increased over the last decade since our last review, revealing areas of improved understanding in pre-participation screening, training load, emerging concepts surrounding back and rib injury, and relative energy deficiency in sport. Through a better understanding of the nature of the sport and mechanisms of injury, physicians and other healthcare providers will be better equipped to treat and prevent injuries in rowers.

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Key Points

The largest risk factor for rowing injury remains rapid increases in training frequency, intensity and/or volume.

Appropriate loading in the boat and on the rowing ergometer can reduce risk of overuse injuries.

While the recent increase in rowing injury research is encouraging, there remains a significant demand for well-designed prospective studies.

1 Introduction

Rowing consists of three main disciplines: flatwater (e.g., traditional Olympic and collegiate style racing), open water (coastal rowing), and indoor. Classifications exist across disciplines for age, weight, and ability. Internationally, age categories start at Under-19 (athletes aged 18 years and younger). Under-23 and senior categories are followed by a series of masters categories ranging from “A” (age 27+ years) to “K” (age 85+ years). In most situations, a

single weight class division exists for men and women with lightweight women competing below 57–59 kg and men 70–72.5 kg. Domestically, especially within high school racing, age and weight classifications may differ. Para-rowing, for athletes with a physical disability, is further divided into three Paralympic classifications based on extent of actual ability: Legs, Trunk and Arms (LTA); Trunk and Arms (TA); and Arms and Shoulders (AS).

Rowers use two oars each (sculling) or one oar with rotation to port (right) or starboard (left) (sweep rowing). Sculling boats include the single, double, and quadruple sculls. Sweep rowing is done in crews of two (called a pair), four, and eight athletes. A coxswain, who steers and faces forward, is always employed in an eight, sometimes in fours, and rarely in pairs. In boats with no coxswain (called “coxless” or “straight”), steering is controlled by one rower turning his/her foot to move the rudder mechanism.

Race distances may vary, but the standard Olympic racing distance is 2000, and 1000 m for masters and para-rowers. Rowing is primarily an aerobic activity with the anaerobic system contributing approximately 10–30 % [1–3]. Lactate levels of 28 mmol/L have been reported and are among the highest of any sport [4] while maximum oxygen uptake values can exceed 70 mL/kg/min for Olympic rowers.

This review covers all currently known injuries in all aspects of rowing as a whole, including different types of rowing (e.g., coastal and para-rowing), for the first time. Furthermore, new key messages have emerged in recent years including those regarding training load, energy deficiency, and our knowledge base around rib stress and back injury. We therefore believe an updated review from that of our previous review over a decade ago [1] is now warranted.

1.1 The Rowing Shell or Boat

Boats used in rowing competitions are generally narrow and relatively long. Traditionally made of wood, modern materials such as carbon fiber add lightness and stiffness. With the exception of some para-rowing events, boats almost universally employ sliding seats that run on wheels along tracks within the shell. The sliding seat allows for inclusion of the powerful lower body muscle groups during the “stroke”. The rower compresses and extends in a repeated cycle, reproducing with each stroke the force necessary to propel the boat through the water. The rower’s feet are placed into shoes secured to the boat. Each oar inserts into an oarlock mounted on a “rigger” extending from the boat. The oar comprises the blade, shaft, and handle. Boats and oars are largely adjustable, allowing load changes for different rower sizes and abilities.

Pontoons, usually affixed below the rigger, can be used for added stability, especially in some para-rowing events where they may be required for safety. Certain para-rowing shells are mandated to be further specialized with the inclusion of Velcro® straps to secure athletes to the boat for the dual purpose of safety because of limited ability and of setting an equal limitation on athletes within the same para-rowing sport class.

1.2 The Rowing Ergometer

Rowing ergometers are widely used for training, testing, and crew selection [5], as well as for general fitness purposes. A range of ergometers are commercially available, each with different biomechanical loading patterns [6]. There are two main types: stationary and dynamic. Using the stationary ergometer, the rower moves back and forth via a sliding seat. In contrast, dynamic ergometers seek to mimic the boat’s movement, achieved by enabling the flywheel and/or footrest to move as well. Alternatively, a stationary ergometer can be placed on “slides” for a similar effect. Stationary ergometers exhibit increased magnitudes of peak force production [7–12], yet the dynamic ergometer has a similar total power output via an earlier rise in force [8–11], sometimes in combination with an increased cadence (strokes/min) [7, 8, 10]. Dynamic ergometer rowing imitates on-water rowing more closely, and recently has been shown to be a better predictor of on-water performance [13], while imposing less loading per stroke. A prospective investigation of injury incidence in elite rowers found that the risk of overuse injury in general was associated with time spent on the ergometer [14], possibly explained in part by the observed greater lumbar spine flexion, longer stroke length, and higher force at the catch with a flexed spine [15–17]. Future research could therefore investigate the effect on injury rates using dynamic ergometers.

1.3 Phases of the Rowing Stroke

The rowing stroke is a repeated movement through two phases: “drive” and “recovery” (Figs. 1, 2). The drive begins in the “catch” position with the rower’s arms in full extension and legs and trunk in full flexion. As the blade of the oar enters the water, force is applied against the foot stretchers through knee extension and contraction of the gluteal muscles, which further serve to extend the trunk. Flexion of the arms completes the drive and the blade is removed from the water as the rower arrives at the “finish” or “release” position.

The recovery begins at the release. Once extracted from the water, the oar is rotated so that the blade is “feathered” (parallel to water). In reverse order to the drive, arms



Fig. 1 Sculling: catch (a) and finish (b) position (credit: V. Nolte)



Fig. 2 Sweep rowing: recovery (a) and drive (b) phases (credit: S. Di Ciacca)

extend, followed by the trunk moving forward in a flexed position and knees rising up to the chest as legs return to full flexion. Oar handle is rotated again so the blade is “squared” (perpendicular to water) in preparation for entry at the catch.

2 Approach to Injury

Evaluation of rowing injuries consists of an assessment of changes in the training process (intensity, volume, or frequency) along with equipment, technique, and biomechanical issues (muscle imbalances, alignment, and length of extremities), or deficiencies in strength [17–19]. The transitional period between dry land and on-water training generally results in higher rates of injury [20], and up to 50 % of injuries in elite rowers have been related to land-based training, including ergometer training and weight training [20, 21].

Furthermore, recent evidence suggests that completely removing an injured athlete from training is predictive of

injury recurrence, as he or she must play ‘catch-up’ upon return to sport. Maintaining a normal training load whilst avoiding both aggravating factors and complete prolonged rest is therefore important [22].

3 Back

3.1 Non-Specific Low Back Pain

Injuries to the lumbar spine account for 2–53 % of all reported injuries in rowing [23, 24], making it the most frequently injured region, with an incidence between 1.5 and 3.7/1000 h of rowing and associated training. Of studies reporting a 12-month incidence, 32–53 % of rowers will experience rowing-related low back pain (LBP) in that time period [14, 25, 26]. Point prevalence in adolescent rowers has been reported as high as 65 % (male individuals) and 53 % (female individuals) [27]. Much epidemiological research to date has concentrated on elite/international or college rowers, lacking prospective injury

surveillance. Further investigation in a diverse cohort is needed to understand possible causation.

3.1.1 Mechanism of Injury

The majority of low back injuries are chronic and associated with training volume and kinematics. The strongest predictors of LBP in rowing are a previous history of LBP [25, 27] and the volume of ergometer training, particularly sessions exceeding 30 min on static ergometers [14, 25, 27]. The number of total training hours and years rowing also contribute [26]. Factors less strongly associated are a history of rowing before age 16 years, time of season (peaking in winter months), and an improper weight lifting or core stability training technique.

End range (or ‘hyper’) flexion and twisting forces are exacerbated at the catch, with estimated compressive loads placed on the spine reaching 4.6 times the rower’s mass [28]. Fatigue, coupled with high-volume, high-intensity training, compounds this effect by impairing muscle fiber contractibility and proprioception resulting in spinal creep [15, 29] and altered kinematics [15, 30]. Such high-magnitude cyclic load can also cause inflammation in lumbar ligaments [31].

Several studies have emphasized the importance of a full hip range of motion (ROM) [32–35] to reduce stress on the spine. Rowers must achieve considerable anterior rotation of the pelvis at the catch position [36–39] to reduce lumbar flexion. Novice rowers and those with a history of back injury tend to use high levels of lumbar flexion with limited pelvic rotation, deteriorating further with increasing work intensity [40].

Breathing patterns may be linked to both prevention and development of LBP in rowers. Manning et al. [41] examined the effects of inspiring vs. expiring during the drive. Expiring increased intra-abdominal pressure, which may exert a protective effect by offsetting high levels of shear force and compression observed in the lumbar spine. One case study of a recreational rower, however, documented a possible exacerbation of an existing diaphragmatic hernia during the drive as a result of increased intra-abdominal pressure [42].

Research examining muscle activity and injury in rowing is limited and inconclusive. No difference exists in overall trunk strength between rowers and controls, although rowers exhibit higher electromyography activity in their trunk extensors [43], which increases throughout a 2000-m ergometer test [38]. Spinal extensor muscle activity dominates the stroke [44], something important to consider in both training and rehabilitation.

It should be noted that studies examining both kinematics and muscle activity have generally been examined on a static ergometer with only one study examining

kinematics on the water [15]. This is likely to pose limitations to the confident translation of findings from a laboratory to a dynamic water (boat) setting and thus research should be interpreted with caution. There is a great need for more water-based research.

3.1.2 Assessment

Observation of the rower’s technique on the ergometer and in the boat can be particularly helpful for elucidating problematic movement patterns. Muscle asymmetry is common and possibly unrelated to a sweep rower’s preferred side [45]. McGregor et al. [34] and Ng [46] showed that rowers with current or previous LBP present with lower lumbar stiffness and compensate at the pelvis, upper lumbar, or lower thoracic spine to achieve catch length. However, full hip flexion with vertical shins, a relatively anteriorly rotated pelvis, and a smoothly flexed spine (with flexion spread throughout as in an extended ‘c’ shape) should be observed (Fig. 3). At the finish, the pelvis rotates posteriorly, the hips and the ‘c’ shape of the spine extend (although never reaching neutral). Previous guidance to maintain a very straight spine has now been replaced by advice to allow some flexion. Curvature of the spine is necessary for its load-bearing function, which performs best with load distributed evenly through the vertebrae [47].

3.1.3 Management

Achieving proper hip ROM and training lumbar extensor endurance is crucial to maintaining healthy levels of flexion. Lumbar extensor fatigue leads to impaired awareness of excessive flexion, which is associated with injury [49, 50].

Modern rehabilitation emphasizes co-contraction of the trunk muscles, particularly using protocols such as Pilates-type exercise. Research shows, however, that during peak force generation, such co-contraction does not exist and extensor muscles dominate [44]. Traditional ‘core stability’ protocols emphasizing co-contraction and isometric trunk training are not supported by evidence; dynamic endurance-based training is preferable [50]. Nevertheless, limited isometric trunk activity may be effective in pain management during the early acute phase of LBP. Teitz et al. [25] further recommend that the ergometer be used with reduced load setting.

Rehabilitation (and injury prevention) should focus on correcting any underlying hip ROM and/or strength and flexibility deficiencies. Spinal position sense can be compromised following injury, and must be considered [50].

Interestingly, a study of college rowers with pre-existing back pain showed that they were no more likely to miss



Fig. 3 Various lumbar curves of successful Olympic rowers, with the ‘c’ shape at the catch position (far left). Reproduced from Kleshnev V et al. [48] with permission

training than their teammates, and when practice was missed, it was for a shorter duration. These rowers were also less likely to have career-ending LBP [51].

While most approaches to rowing LBP are either pathology or impairment based, recent studies have recognized its psychological effects, incorporating behavioral therapies into management [46]. There is strong evidence that understanding cognitive and social components of LBP is key to its management.

3.2 Specific Low Back Injuries

3.2.1 Disc, Ligament, Muscle, and Facet Joint

3.2.1.1 Mechanism of Injury The annulus and nucleus work together to sustain compressive loads [52]. High anterior compressive force occurs with high ranges of lumbar flexion [53]. Repeated cyclical loading and spinal flexion in rowers may cause disc bulging [54], herniation [55], and facet joint capsule strain [56]. Compression forces observed in rowers’ lumbar spine are comparable to those in repeated lifting, which can cause the fracture of vertebral end plates [57].

The mechanism of injury remains unknown, but is likely cumulative loading combined with other factors such as biomechanics, genetic predisposition, lifestyle, and work activities. Chronic repetitive loading of this type leads to impairment of sensorimotor control mechanisms and decreased reflexive action of multifidus and longissimus muscles.

3.2.1.2 Assessment Assessment, especially with disc herniation, includes a comprehensive neurological examination including sensation, strength, reflexes, and bowel and bladder function. More than one structure is frequently compromised. The multifaceted aspects of back pain should be considered at all times: ROM of the spine may be limited because of muscle spasm, pain, or fear avoidance behavior. Some athletes experience pain with flexion of the spine and relief with extension, while in others, the opposite is true. With pain on extension, spondylolysis or facet problems should be considered in the differential. While imaging may assist in management (Fig. 4), the risk of false positives is high and, without a baseline evaluation (prior to injury), it is very difficult to establish if the finding is the true source of pain [58].



Fig. 4 Disc herniation (credit: M. Sechser)

3.2.1.3 Management In rare cases of significant nerve damage, progressive pain and disability, or treatment non-response, surgery may be warranted, but the high failure rate should be recognized. First-line therapy is always conservative, including physiotherapy (using exercise), non-steroidal anti-inflammatory drugs (NSAIDs), and analgesia. The impairment rather than the suspected pathology should be the focus of management, and a combined biopsychosocial approach is optimal.

3.2.2 Spondylolysis/Spondylolisthesis

3.2.2.1 Mechanism of Injury Spondylolysis is a stress fracture (or cortical rupture) at the pars interarticularis and is usually preceded by a stress reaction at the same site. In some cases, and when there is a bilateral stress fracture, it can lead to a spondylolisthesis, or forward displacement of one vertebra relative to another. Severity is expressed in degrees ranging from a 25 % slip (Type I) to a complete vertebral displacement (Type IV).

Spondylolysis has a slightly higher prevalence in rowers compared with the general population at 17 % in adult rowers [59] vs. 11.5 % [60]. The risk is higher in

adolescent rowers with 22.7 % presenting with a stress reaction and 4.5 % with spondylolysis compared with 0 % for both in non-rowing controls [61]. The risk of development of spondylolysis increases in sports with lumbar extension and rotation. Non-traumatic spondylolysis and/or a stress reaction at the pars interarticularis may be a significant cause of pain. As rowers never actually extend their lumbar spine (it is always in relative flexion), it is unclear what the mechanism of this injury is, although there may be an association with weight training [62].

3.2.2.2 Assessment General clinical findings may include tightness of hip flexors and hamstrings, weakness of the abdominals and gluteal muscles, and an excessive lordotic posture [63], although rowers may present without the latter findings. Palpation of the lumbar spinous process [64] and step deformity [65] may help diagnose spondylolisthesis. Classic spine radiographs, including lateral obliques (where the “Scottie dog” sign may be seen) are frequently equivocal. While bone scintigraphy, computed tomography (CT), and magnetic resonance imaging (MRI) are all used in diagnosis [66], the fact that the majority of these injuries occur in younger rowers has led to increased use of MRI for this condition to avoid ionizing radiation. A nuclear medicine single-photon emission CT (SPECT) scan combined with a limited-view CT scan when the SPECT scan is positive remains the gold standard, however, and may also identify other causes of LBP [67]. Young athletes with bilateral pars defects or spondylolisthesis should have routine standing lateral radiographs every 6–12 months until skeletal maturity is reached, to monitor for slip progression.

3.2.2.3 Management Conservative treatment including initial rest followed by physiotherapy is usually successful, leading to a return to sport 5–7 months after diagnosis. Routine bracing is not generally recommended [66], and only a small percentage of patients require surgical intervention.

3.3 Chest

3.3.1 Rib Stress Injury

3.3.1.1 Mechanism of Injury Stress fractures result from an imbalance between microdamage caused by continuous mechanical loading of the bone and its ability to remodel and repair itself [68]. The term rib stress injury (RSI) has recently been proposed to cover the spectrum of rib overuse injuries [69, 70]. Incidence has been estimated to be close to 9 % [6] with ribs 5–9 most frequently involved. In the absence of direct loading during rowing, injuries are likely the result of repeated high-force muscular contractions [6, 68].

Very few studies have explicitly quantified thoracic muscle firing patterns during rowing to investigate rib loading [71–73]. Further studies with other primary aims have done so, which still provide relevant information regarding neuromuscular activity [10, 44, 74–76]. Three distinct theories have been advanced as to the mechanism of RSI. All three theories are based on expert opinion and mechanistic studies and thus represent a very low level of evidence:

1. Opposing stress forces induced by serratus anterior (SA) and obliquus externus abdominis (OEA) muscles at the end of the drive phase are hypothesized to generate shear forces at the bony attachments on the ribs [3]. These muscles do not reach high levels of neuromuscular activity simultaneously, however, and quantification of co-contraction of SA and OEA in rowers with previous RSF vs. uninjured matched controls found no difference between the groups [72]. Furthermore, conflicting data surrounding SA firing patterns exist, with peak activation observed at different points of the rowing stroke [10, 71–73]. Variation may result from different neuromuscular strategies in individual rowers, with female rowers potentially more likely to show increased activity during the drive [10].
2. OEA muscles may induce detrimental rib loading (compression of the ribcage) at the end of the drive phase, when resisting layback and assisting in the often forceful expiration accompanying the finish of the stroke [71]. The timing of peak activity of the abdominal muscles [10, 44, 71, 72, 74, 75] lends more support to this theory, although it is unlikely that the forces induced by the abdominals alone can reach a detrimental magnitude.
3. Combined forces arising from transmission of force to the oar handle and the contraction of the shoulder retractors (i.e., latissimus dorsi and trapezius muscles) have been suggested to result in ribcage compression [68] and consistently exhibit peak activation during the drive [10, 44, 72, 74, 76]. Peak handle forces during this phase have reached close to 900 N or above 1000 N in elite male rowers during submaximal high-intensity and race-pace ergometer rowing, respectively [10, 11]. In one study, peak neuromuscular activities of latissimus dorsi and trapezius muscles as well as peak ergometer handle forces were all found to occur in the second quartile of the drive phase, lending support to this suggested mechanism of injury [10]. Furthermore, one study in a single rower investigated the actual bending force applied to a rib during ergometer rowing [77], and here too it appeared to be closely related to handle force production.

3.3.1.2 Assessment The recent Great Britain Rowing Team *Rib stress injury guidelines for diagnosis and management* [69, 70] provides an excellent overview of the hallmark “clinical markers” of RSI in rowers (Fig. 5): generalized pain in the rib area, which persists with activity and gradually becomes more specific, progressing to a more severe presentation as pain worsens with deep breathing or rolling over in bed. On examination, point tenderness and a positive rib spring as well as reproduction of pain during movements such as press-ups and initiation of sit-ups are important markers. Emphasis should be placed on early clinical diagnosis, allowing adequate measures to be taken immediately (described below), potentially followed by verification by ultrasound, bone scan, or MRI. Differential diagnoses such as costochondritis, intercostal muscle strain, and especially bone malignancy exemplified by the case of Ewing’s sarcoma should be investigated appropriately and are further discussed elsewhere [69, 78, 79]. Finally, an attempt to grade RSI severity as mild, moderate, or severe could be used to provide rowers and coaches with a rough estimate on time to return to full activity [69, 70].

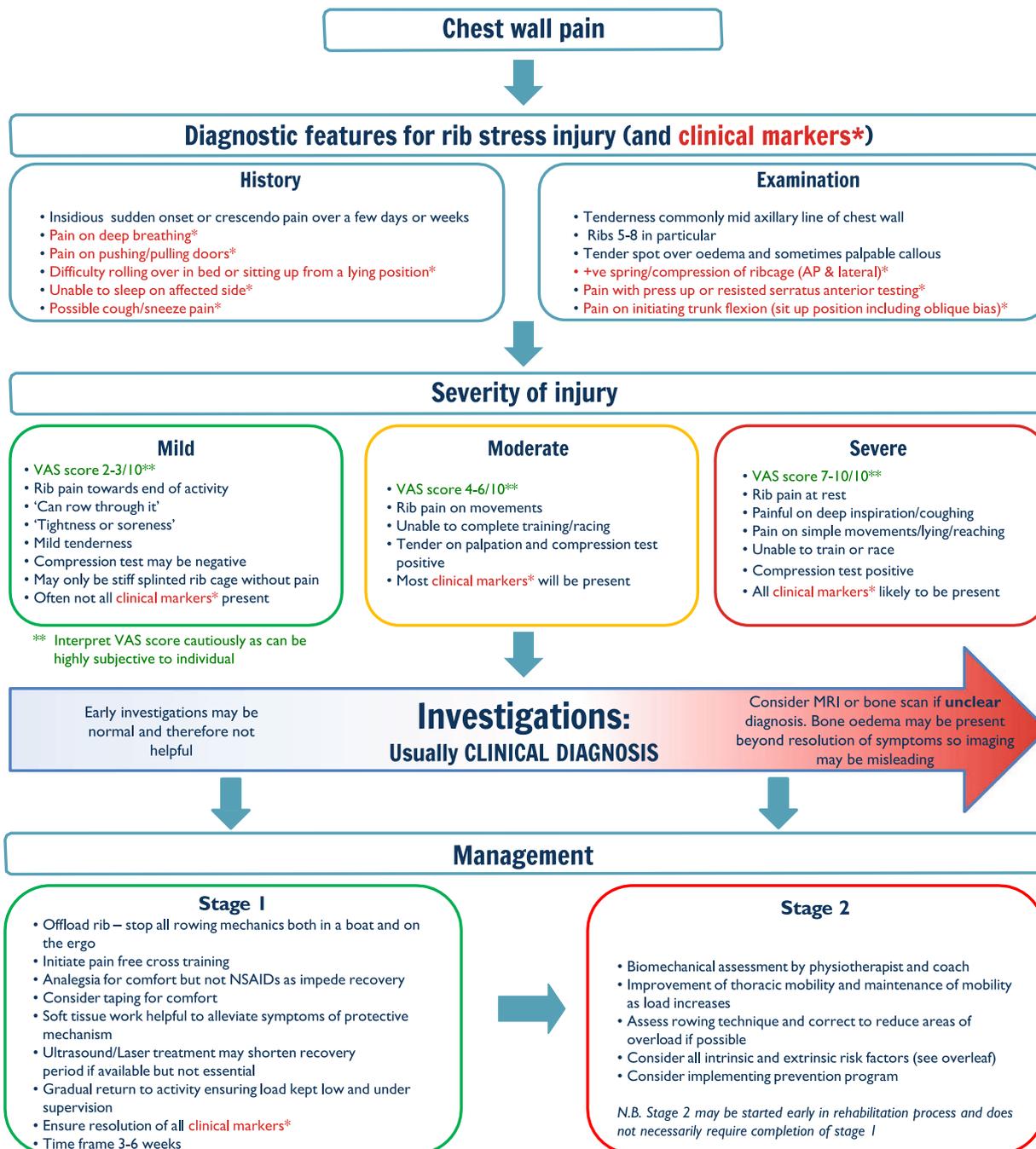
3.3.1.3 Management As recently summarized [80], management of RSI over the past 20 years has changed very little: a symptom-dependent approach of initial rest followed by a graded return to rowing over a period of approximately 3–6 weeks [81, 82]. Evans and Redgrave [69, 70] have further provided a more structured approach. In short, the key elements of RSI management center on avoiding painful activities. In the case of a severe RSI, an initial period of complete rest may be necessary, as exercise-induced deep breathing may be painful even during isolated lower extremity exercise. NSAIDs should be avoided, as they can theoretically impair bone healing when taken for prolonged periods [83]. Taping, soft-tissue treatment, and thoracic spine mobilization can manage symptoms. These recommendations are based on case reports and case series. No clinically controlled studies are reported that can provide a higher level of evidence regarding RSI management [69, 70].

A very important part of RSI management is identification and modification of risk factors to prevent future injury [69, 70, 80]. Although transitional periods between land and water, changes in training volume, intensity, and/or technique, lack of core stability, concurrent shoulder or low back problems, and ‘hatchet’ blade shape were suggested as potential risk factors in the past [3, 6, 69, 70, 81], the lack of prospective studies investigating potential risk factors led to the conclusion in a recent systematic review that there is no solid evidence regarding any risk factors for RSI [84]. Consequently, management can be based on risk factors for bone stress injuries in general such as low energy availability (EA), calcium and/or vitamin D deficits,

Rib Stress Injury: Guidelines for Diagnosis and Management



Definition: Rib stress injury is the development of pain due to bone oedema caused by overload along the bone shaft



See overleaf for intrinsic and extrinsic risk factors for rib stress injury

The GB Rowing Team is the High Performance Arm of British Rowing

Fig. 5 Great Britain Rowing Team Rib Stress Injury Guidelines for Diagnosis and Management. Reproduced from Evans and Redgrave [70], with permission

Rib Stress Injury: Risk Factors to Consider



Intrinsic factors

- Poor trunk/strength/endurance
- Poor trunk mobility/flexibility
- Concurrent shoulder pathology/injury
- Low back injury
- Previous rib injury
- Lightweight rower
- Female
- Reduced bone density
- Weight loss
- Relative Energy Deficiency in Sport (RED-S)

Extrinsic factors

- Rowing or erg at high load/low rate or over geared
- Rowing against strong wind/current
- Rapid increases in training load/volume/intensity
- Long steady state rowing
- Change from sweep to sculling and vice versa
- Change from rowing to ergo or vice versa
- Change from large to small boat
- Rigging over geared or too much height

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Fig. 5 continued

and menstrual disorders [69, 70, 80]. Training on dynamic rather than stationary ergometers could theoretically lower the incidence of RSI as well.

3.4 Shoulder

3.4.1 Mechanism of Injury

Shoulder pain in rowers generally results from compromised shoulder girdle positioning and stabilization, often owing to weakness in the scapulothoracic area and overuse of muscles in the neck and anterior thorax [85]. The upper extremity is the third most common location of injury in rowers [73]. One study on various types of athletes reported a significant correlation of shoulder pain prevalence with years of practice, days of practice per week, and level of sport. It noted that rowers had the longest-lasting shoulder pain, from 1 year to a lifetime [86].

Changes in shoulder girdle positioning include an anteriorly placed glenohumeral head, a tight posterior shoulder capsule, tight latissimus dorsi, and weak rotator cuff muscles [87]. This decentralized glenohumeral joint [88] may lead to impingement and instability [89]. In the sweep rower, this position is exaggerated in the outside arm.

3.4.2 Assessment

Evaluation of the neck, shoulder girdle, thoracic spine, and rib cage is crucial when an athlete presents with non-specific shoulder pain. History should include previous traumatic injuries, weight-training programs, generalized joint/ligamentous laxity, and rowing technique. Routine X-rays will demonstrate bony pathology and underlying osteoarthritis, while other tests such as diagnostic ultrasound and/or MRI may be necessary to look further at the surrounding soft tissues. Clavicular stress fractures should be ruled out as this has been noted in a case study of a lightweight rower [90].

3.4.3 Management

While conservative treatment including ice and analgesia may prove adequate for acute symptomatology, long-term management involves correcting muscle imbalances including strengthening scapulothoracic stabilizers, stretching the neck muscles, postural realignment, and technique modification [79, 91].

3.5 Knee

3.5.1 Mechanism of Injury

Knee pain is common in rowers [14, 18, 73, 92, 93]. As rowing is non-weight bearing, rowers typically do not

sustain traumatic ligamentous or meniscal damage, but may experience instead bouts of generalized patellofemoral pain syndrome (PFPS), tendinopathy, or iliotibial band friction syndrome (ITBS) [18, 73, 93, 94]. Although not as well studied in rowers, these conditions are known to elicit inflammatory responses and eventually retropatellar and/or lateral knee pain [95, 96].

During the rowing stroke, the knee moves through its full ROM, including deep knee flexion, placing high compressive forces between the posterior surface of the patella and the femur [18, 96]. Abnormal tracking of the patella often leads to imbalance of forces around the joint, increasing wear of the hyaline cartilage on the undersurface of the patella, and resulting in PFPS. These athletes may have a “knock-kneed” appearance through the drive phase because of a genu valgum dysfunction or adductor moment of the femur [96]. Additionally, female rowers may be predisposed to patellar tracking problems because of anatomical considerations (wider Q angle); while equipment limitations such as the foot stretcher angle or placement may compound the problem [18].

Rowers with an increased abduction moment or “bow legs” may develop ITBS [95], irritation due to the increase in compression of the iliotibial band friction over the lateral femoral condyle. Unilateral iliotibial band friction symptoms should always prompt further examination for leg length discrepancy or pelvic malalignment [18, 95]. Non-rowing-specific activities, such as weight training, running, and cycling [69, 93, 97] often contribute, which may perpetuate the inflammatory reaction and prolong the injury.

3.5.2 Assessment

Assessment of generalized knee pain should include a history of previous injury (such as patellofemoral dislocation or subluxation), locking, swelling, or giving way. Patellofemoral pain is generally dull, localized to the retropatellar area, and worse with going up or down stairs or sitting with the knee bent for prolonged periods of time (positive “theater” sign). Lateral tracking of the patella may be evident with knee flexion, and malalignment such as genu valgum (“knock-kneed”) or genu recurvatum (hyperextension of the knees), along with excessive foot pronation or internal tibial torsion, may increase the abnormal mechanical forces on the joint. Examination of the patella often reveals lateral patellar tenderness [96].

ITBS pain is characterized by lateral knee pain, particularly as the knee moves past 30° of knee flexion (i.e., up/down stairs). Clinical examination usually reveals a tight iliotibial band. Palpation over the lateral femoral condyle, with or without active knee ROM, will typically elicit a painful response. It is not unusual for the athlete to

experience crepitus in the joint and mild swelling with either injury, but a large knee effusion or significant locking or catching should suggest other diagnoses such as meniscal pathology.

3.5.3 Management

Treatment for anterior knee pain has been well documented in the literature with numerous high-quality studies, but there is a paucity of rowing-specific studies. Generally, treatment consists of strengthening hip musculature to normalize the adduction/abduction moment of the femur and thus diminish any functional genu valgus/varus during deep knee bending. Hamstring flexibility and strength should be assessed. Strengthening the quadriceps muscles, correcting any imbalance between vastus lateralis and medialis, will also improve patellar tracking [96]. Often, taping the patella can help in the short term [98]. Both clinically and practically, bracing is not advised because of potential ROM limitation. Modifying the position of the shoes in the boat with or without heel wedging may prove effective, along with standard conservative treatment of ice and NSAIDs. Although rare, one case report describes bilateral atraumatic meniscal tears likely owing to repetitive low-energy loading in an adolescent female rower; a diagnosis that should be considered in rowers with PFPS, who do not respond to conservative treatment [99].

3.6 Hip

3.6.1 Mechanism of Injury

Anterior hip/groin pain may signify femoral acetabular impingement (FAI) or labral tears, which have only recently become more commonly reported in rowers and athletes in general owing to advances in diagnostic criteria and imaging [100, 101]. Currently, there are a limited number of quality studies to corroborate what has been seen clinically for years. It is suspected, however, to be a result of repetitive full flexion combined with a possible anatomical variation of femoral head neck junction (Cam deformity) and acetabulum (pincer deformity). This sequence can result in increased mechanical stress on the anterior chondrolabral junction of the hip.

3.6.2 Assessment

A thorough history usually reveals a chronic presentation that progresses as the volume and intensity increase. The athlete commonly reports isolated groin pain, brought on with flexion and internal rotation of the affected hip (positive anterior impingement sign) [101]. Thorough radiological assessment (radiographs, MRI, CT, and motion

analysis) may reveal anatomical differences in the affected hip that will define appropriate treatment.

3.6.3 Management

Non-surgical protocols decrease pain and improve function, but symptoms typically return with resumption of the aggravating activity. A number of clinical studies have described the success rate and return to sport after FAI arthroscopic surgery. The results vary from 70 to 96 % in higher-level athletes, although rowers were not studied [102–104]. Success rates may largely depend on adherence of the athlete and medical team to a comprehensive rehabilitation protocol with slow advancement, to prevent continued irritation or re-injury [102, 105].

3.7 Forearm and Wrist

3.7.1 Mechanism of Injury

Forearm and wrist injuries can usually be traced back to poor technique or fatigue, through excessive wrist motion during the action of feathering the oar (turning the oar so that it moves parallel to the water on the recovery), or a tight grip. Injuries include exertional compartment syndrome (ECS), lateral epicondylitis, De Quervain's tenosynovitis, and intersection syndrome [79].

De Quervain's tenosynovitis involves the first dorsal compartment of the wrist, while intersection syndrome, also known as "Oarsman's Wrist", involves the second dorsal compartment muscle bellies of extensor carpi radialis longus and brevis [106]. Hypertrophy of the muscle bellies of abductor pollicis longus and extensor pollicis brevis or "Sculler's Thumb" [107] may occur as a result of improper mechanics of the thumb to feather the oar, compressing the underlying radial extensor tendons, and leading to swelling over the dorsal aspect of the forearm. Improper initiation of the drive phase with the elbow and not the shoulder girdle can lead to ECS of the forearm (often the volar compartment) [108]. Wrongly sized handle grips, poor rigging, and wet or cold conditions can all exacerbate the problem [79].

3.7.2 Assessment

The most important first step is to establish the site of injury (Fig. 6). Pain with intersection syndrome is felt at the dorsal wrist and is exacerbated with extension [92]. "Sculler's Thumb" may be observed as swelling over the dorsal aspect of the forearm [107]. Lateral epicondylitis is characterized by pain over the lateral aspect of the elbow, especially with resisted wrist extension [18]. If ECS is suspected, intercompartmental pressure is measured at rest

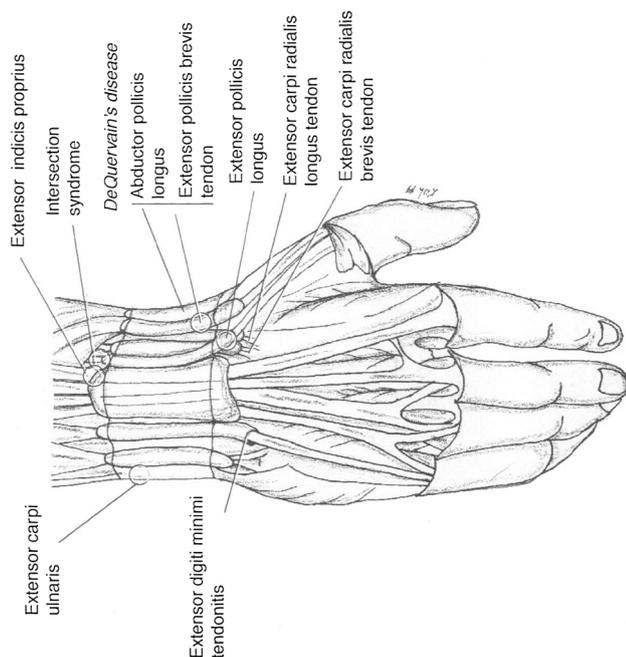


Fig. 6 Extensor compartments of the wrist. Reprinted from Lebrun CM [109], with permission from Elsevier

and immediately after the exacerbating activity. Diagnosis is confirmed, if pressure remains elevated for a prolonged period of time post-exercise.

3.7.3 Management

Conservative treatment involves ice, stretching, deep tissue massage, myofascial release, acupuncture, NSAIDs, and bracing or taping. Relative rest should be promoted. Failing this, cortisone injection is often very successful with a rapid resolution of symptoms, but must be reported if the athlete is subject to doping control [92]. Immobilization and surgical intervention are usually only required in severe or recalcitrant cases.

Training on the ergometer or rowing “on the square” where no feathering is involved can aid in the short term, provided the grip remains relaxed. A cold weather strategy involves the use of fleece “pogies”, which cover the outside of the hands while still allowing the hand to grasp the oar handle [79].

3.8 Energy Availability, Body Composition Issues, and Disordered Eating

3.8.1 Mechanism of Injury

Weight categories for competition increase the potential for body composition and disordered eating (DE) problems [110, 111]. Lightweight rowers employ different methods

to shed weight prior to a competitive event, including “sweat runs”, saunas, laxatives, and/or diuretics. These can negatively impact plasma and blood volume, stroke volume, cardiac output, endocrine function, and thermoregulation [112, 113]. Most research is older, with small sample sizes—larger scale prospective studies are needed.

Dieting and/or DE habits can occur in all rowers and can result in energy deficiency, whether purposeful or inadvertent. The term Female Athlete Triad has been used for many years to describe the inter-related conditions of low EA, menstrual dysfunction, and altered bone mineral density (BMD) in female athletes, each falling on a continuum from health to disease [114]. A recent meta-analysis has investigated DE and low EA in male athletes [115]. There are parallels to the Female Athlete Triad [116] with hypogonadotropic hypogonadism replacing the functional hypothalamic amenorrhea [117].

Small studies from the 1990s have reported that sub-clinical eating disorders exist in lightweight male rowers [118], and both fasting and energy intake influence bone turnover in this population [119]. Moreover, as there are additional concomitant negative effects on endothelial function and subsequent cardiovascular health [120, 121], an updated Consensus Statement by the International Olympic Committee has further expanded the terminology to the more inclusive term of Relative Energy Deficiency in Sport (RED-S) [122]. This includes both male and female athletes and emphasizes the musculoskeletal, hormonal, cardiovascular, gastrointestinal, electrolyte, and performance sequelae. Future epidemiological research should elucidate the breadth and depth of these problems in rowers. Several small retrospective studies have reported association of low BMD with rib pain in both female [123] and male rowers [124]. A case report of a male para-rower with a RSI suggests that athletes with disabilities may also have issues with EA and BMD [125].

3.8.2 Assessment

History of stress fracture or increases in frequency, volume, and intensity of training, use of medication or hormonal therapy, and nutritional habits, such as desire to lose weight, diet, and weight history can be helpful [126]. A newly developed simple tool for clinicians—the RED-S Clinical Assessment Tool, or RED-S CAT—is easily available online, in multiple languages [127].

In female individuals, questioning regarding screening of gynecological function, including menstrual history, length, and frequency of periods is crucial. There are a variety of different screening tools for ED and DE. The 25-item Low Energy Availability in Females Questionnaire (LEAF-Q) has been shown to have acceptable sensitivity (78 %) and specificity (90 %) [128] for correctly

classifying current EA and/or reproductive function and/or bone health. A recent consensus statement from the Female Athlete Triad Coalition contains helpful algorithms for determining risk levels and the need for further investigations [129].

3.8.3 Management

An older study comparing performance effects of 6–8 and 16–17 week periods of weight reduction among elite lightweight rowers found the longer period to be optimal and associated with improvements in nearly all physical performance parameters measured (maximum oxygen uptake, respiratory anaerobic threshold, upper body peak power, and knee flexor and extensor strength) [130]. In contrast, the shorter period of weight loss resulted in a reduction in every performance parameter. Notably, in many cases, weight loss is attempted in far shorter periods of time. A maximum weekly body weight-loss rate of 0.7 % in association with strength training has also been shown to help athletes gain lean body mass and increase strength and power-related performance [113].

Management strategies for the Female Athlete Triad [126, 131] and RED-S are outlined in review articles and the most recent consensus statements of the Female Athlete Triad Coalition [129] and the International Olympic Committee [122, 127]. In addition to ensuring adequate EA for both female and male rowers, dietary recommendations should include vitamin D 600 IU daily for men and women aged 19–50 years for bone health, and calcium 1300 mg per day to account for growth in adolescents and young adults aged 9–18 years [132].

4 Special Populations

4.1 Junior Rowers

Junior rowers (age under 19 years) compete at the same race distance and train with similar frequency and duration as elite senior rowers, yet data related to injuries are scarce.

A survey of competitors at the 2007 Junior and Senior World Championships found that junior rowers have a higher annual aggregate injury rate than senior rowers (2.1 vs. 1.75 injuries per 1000 training sessions) [93, 94]. This is partly owing to a lack of rowing experience, inappropriate training, and a significantly higher incidence of traumatic low back injuries among sweep rowers who changed rowing side during the season. Training volume was significantly associated with injury, with those averaging more than seven training sessions/week during a rowing season at higher risk [94]. These two studies [93, 94] do carry some limitations. They are retrospective studies that

rely on the accuracy of the reporting athlete, and it is possible that the incidence of severe rowing injury was underreported (as those rowers may not recover and compete at the international level). Thus, the data can be interpreted only as indicative of the subgroup of elite level rowers sampled at the World Rowing Championships. The studies are also limited by the assumption that the injury information received was medically valid and accurate. Although physicians interviewed the participating athletes, the results have to be considered self-reported and thus subjective.

Young rowers have not completed growth and maturation; thus they have open physal plates (including end-plates of vertebral bodies), comprising cartilage tissue that in some rowers cannot withstand supraphysiological stresses placed by too frequent and/or too intense training [133]. Carsen et al. found that an asphericity of the femoral head-neck junction (Cam deformity) was only observed after femoral head growth plate (i.e., epiphysis) was closed, consistent with the theory that this is a developmental phenomenon [134]. Activity level was higher in subjects with this deformity, which has been recognized in young adults as an important source of pain and cause of cartilage and labral damage predisposing them to degenerative arthritis. Boykin et al. presented a review of 18 young rowers (21 hips) with labral tears [100]. The Cam deformity was present in 15 hips. Only 10 of the rowers (56 %) returned to rowing following arthroscopic treatment [135]. The study by Boykin et al. has limitations regarding its retrospective review design, small number of participants, lack of control group, and lack of validated outcome instruments. Additionally, the study has been questioned in relation to the understanding of movements in the hip joint during the rowing stroke, objective measurement of FAI morphology, and most importantly, inconsistency in operative technique, postoperative rehabilitation process, and the definition of a desired return to the sport of rowing [128, 135]. However, as the disturbance of growth and maturation can have serious implications for sporting careers (and life), training in this population must be adjusted accordingly.

Open physal plates elongate bones faster than soft tissue, causing stress on muscle attachment points (also often made of cartilage at this age) and joints. Adoption of proper and regular stretching programs, performed after each practice or race, may reduce injury risk [94]. Limb elongation causes proprioception problems and, in addition to weakening the muscles, makes young rowers more prone to different acute injuries. Complex cross-training should be avoided in this group.

Although the most common injury site in juniors is the low back followed by the knee and the forearm/wrist, female rowers report fewer traumatic injuries, but more

overuse and chest injuries than male rowers. All stress fractures reported among elite level junior rowers in the 2007 study were in female individuals [94]. Maximizing EA and optimizing vitamin D and calcium intake is therefore essential. Of note, the World Rowing Federation, or FISA (Fédération Internationale des Sociétés d’Aviron), contrary to some national rowing federations, does not recognize lightweight junior categories.

4.2 Para-Rowers

Para-rowing (formerly called adaptive rowing) is rowing or sculling for those with a physical disability [136]. To ensure an equitable playing field, rowers with similar levels of physical function and disability are classified into one of three different sport classes for competition (Table 1).

Para-rowers participate at World Rowing Cups and the World Rowing Championships, although race distance is half the distance of able-bodied rowers [137]. The major reason for this decision by FISA was to avoid prolonged racing times as crews, particularly AS and TA classes, use boats with fixed seats in wider and heavier hulls. Rowing technique also differs significantly from able-bodied and LTA class rowing (Fig. 7). Finally, AS rowers are required to use stabilizing pontoons (optional for TA rowers) on their boats to prevent possible boat capsize, further reducing boat speed.

Para-rowing made its debut at the 2008 Paralympic Games in Beijing and injury data in this population are still lacking [138]. It is currently limited to personal experiences, anecdotal stories, a manual published by British Rowing [138], a literature review [137] and a single case report of rib stress fracture [125]. In addition to risks shared by all rowers, para-rowers face specific challenges during training and competition, as areas of the body experiencing higher force transmission are altered [137].

Para-rowers’ specific areas of weakness, loss of ROM and/or motor control, influence injury presentation. For example, a para-rower with less ability of one leg to contribute to the force production of the leg drive will experience increasingly imbalanced forces through his/her pelvis and lumbar spine, possibly contributing to low back injuries. Para-rowers with limb loss requiring use of prosthetics present with specific considerations: phantom limb pain, stump swelling, and skin breakdown of the residual limb. The latter may result in extended time away from rowing and wearing of the prosthesis until the skin heals. Daily monitoring must be performed to prevent such skin conditions.

The limited parts of the body used during TA and even more during AS rowing result in repetitive generation and transfer of forces in isolation, which may be further compounded by increased stroke rate, boat weight, and duration of race. Equipment adaptation may also contribute. For instance, the chest strap, introduced because of safety reasons to stabilize the trunk of adaptive rowers in the AS class, created additional pressure on the thorax and was identified as a new etiologic factor for RSF [125]. Healing of RSF in para-rowers can be facilitated by application of a chest orthosis that distributes loading at the catch position across a wide area of padding. All straps used in para-rowing should be single-point release, with no mechanical buckles, so they can be undone in a quick-release fashion in case of boat capsizing.

Finally, some para-rowers from the TA class and the majority from the AS class have sustained a spinal cord injury [138]. Special attention is required when designing exercise programs for these athletes. Specific risks of exercise include autonomic hyperreflexia, bone fracture and/or joint dislocations following trivial or imperceptible trauma due to bone demineralization and muscle spasticity, thermal dysregulation, and skin problems (i.e., pressure sores). Exposure to water from sweating, waves, and

Table 1 International competitive para-rowing sport class and boat class description. Reproduced from Smoljanovic et al. [137] with permission from the *Croatian Medical Journal* (120)

Para-rowing sport class	Description	Boat class
Arms and shoulders (AS)	Rowers with minimal/no leg and trunk function, inability to use a sliding seat and perform backward lean via hip flexion and extension (body swing)	Rowers compete in single sculls (1×)
Trunk and arms (TA)	Rowers with functional use of trunk movement to create body swing, however, are unable to use the sliding seat to propel the boat because of significantly weakened function or mobility of the lower limbs	Rowers compete in mixed ^a double sculls (2×)
Legs trunk and arms (LTA)	Rowers with a verifiable and permanent disability (meeting a set minimal disability) who have rowing specific functional use of their legs, trunk, and arms, using the sliding seat to propel the boat	Rowers compete in mixed coxed fours boats (4+) and mixed double sculls (2×) ^b

^a Mixed means that crews are composed of an equal number of female and male rowers

^b A new event added to the program of World Rowing Cups and World Rowing Championships in 2013

Fig. 7 Upper two panels rowers from Trunk and Arms (TA) class: **a** the catch position and **b** the finish position of rowing stroke. Adaptive rowers in the TA class have to use a strap placed over their extended knees to prevent any movement of their legs during rowing (the rower in stroke is unable to extend his knees beyond this position). In the TA class, the spine and pelvis act together as a somewhat rigid lever, and rowers will use body swing and arm pull to generate and transfer force during the stroke. Lower panels rower from Arms and Shoulders (AS) class: **c** immediately after the catch phase (i.e., early drive phase) and **d** the finish phase of rowing stroke. In the AS class, only the upper extremities and the upper thorax will generate and transfer force to the oar. The chest strap is usually the main conjunction for transition of the force between the oars to the boat shell and high pressure of the strap to the rib cage is inevitable. Reproduced from Smoljanovic et al. [138] with permission from British Rowing



backsplash during rowing complete the triad of pressure, shear forces, and moisture, which may result in pressure sore formation [137]. Prevention of pressure sores is vital to the wheelchair-bound athlete and includes adequate cushioning and padding for the buttocks, frequent pressure relief, good nutrition and hygiene, and clothing that absorbs moisture. An athlete with a pressure sore should not be allowed to compete until healed, as infected pressure sores can be life threatening. Rescue services operating at rowing venues must therefore be adequately trained to handle issues specific to para-rowing.

4.3 Masters Rowers

Beyond simple enjoyment, rowing confers several health benefits to older participants [139]. Regular rowing has been linked to the slowing of several aging processes through correction of serum cholesterol levels [140] and the prevention of muscle wasting [141] and osteoporosis [142]. A particularly low-impact sport [143], rowing is among the few suitable following total hip replacement [144, 145]. Masters rowers range from recreational to highly competitive.

4.3.1 Mechanism of Injury

Although masters outnumber younger groups of rowers, no published study mentioning injuries among them [92, 139, 143] presents the incidence of injuries in this group (as those are general review articles). Rowing-specific studies and case reports of different medical problems among masters [42, 146–149] provide a basis for predicting similar problems and rationales for prevention.

4.3.2 Assessment

Older individuals should be medically evaluated before beginning rowing because of its strenuous nature [139], and competitive masters are strongly recommended to undergo pre-competition health screening [156]. History of aortic aneurysm and/or previous cardiovascular surgeries, such as repair of an abdominal aortic aneurysm, is a clear contraindication for participation as rowing can cause significant complications [146, 147, 149].

4.3.3 Management

All prospective masters rowers should begin with general conditioning addressing lower extremity and abdominal strengthening, flexibility, and aerobic conditioning. A sound understanding of both technique and on-water safety is essential to avoid potential injury and life-threatening situations [148]. Older individuals should be encouraged to row, but must be made aware of possible injury.

5 Miscellaneous

5.1 Dermatologic Issues

Abrasions, common in rowing, are usually not significant, but should be monitored closely for signs of infection. These include blisters due to excessive friction with oar handles, “sculler’s knuckles” from banging handles together because of inclement weather or inexperience [79], and slide or track “bites” over the calf muscles (Fig. 8) and on the buttocks as a result of improperly fitted seats [20, 150].

Hand blisters tend to occur during transition periods from land to water or with changes in equipment, humidity, or intensity of training [79]. It is important to ensure that handles are properly scrubbed, present blisters kept clean and pliable, and grip material intact. Open blisters in contact with handles shared among team members can increase exposure to infection and even hand warts [151].



Fig. 8 Slide bites (a) and blisters (b) (credit: C. Lebrun)

5.2 Environmental Exposure

Rowers are subject to varying weather conditions. Exposure to the environment cannot be avoided, but can be controlled to a certain degree. Hydration status should be closely monitored in warmer months, as excess sweating can lead to dehydration and electrolyte loss [79]. Sun protection is also very important.

During the colder months, layering is advised with wind barrier fabric if necessary [79]. In general, a coach boat should be in proximity whenever possible, and waves and weather patterns monitored closely. Flipping, or tipping the boat as it is sometimes referred to, can be dangerous because of athlete immersion in potentially frigid waters [152]. Inflatable personal flotation devices are often a requirement and should be stored in the boat in an easily accessible location.

5.3 Travel

As rowing is practiced worldwide and events take place across the globe, it is important to take into account the usual precautions when traveling to foreign areas for camps or regattas.

The FISA Sports Medicine Commission advises the FISA Council and member delegations on all medical aspects related to rowing. One aspect is to work with local, regional, and international public health organizations to help ensure environmental and infectious disease risk at regattas is minimized. These recommendations are then made available to all athletes through the FISA website [153, 154].

5.4 Preparticipation Physical Examination

The Preparticipation Physical Examination is a powerful tool for screening and injury prevention [155], and can present an opportunity to assess changes to pre-existing issues, identify risk factors for new injuries, and review preventative strategies. FISA now mandates pre-competition screening to identify athletes at risk to advise them accordingly [156]. Screening consists of three parts. The first part is completing a medical questionnaire. The second part is a physical examination followed by 12-lead resting electrocardiogram (ECG). Select cases with a positive personal history, family history of potentially inherited cardiac disease, or a positive physical or ECG result will require further evaluation by an age-appropriate cardiac specialist.

Furthermore, although endurance exercise is key in preventing and controlling cardiovascular disease, it is becoming increasingly evident that prolonged endurance training may predispose masters athletes to a higher risk of atrial flutter or fibrillation [157]. The actual cause at this stage is not clear, but may be related to atrial dilation or enlargement. For these reasons, regular cardiac screening including a resting ECG for masters athletes is recommended.

6 Conclusion

This review covers injuries in all aspects and types of rowing (e.g., coastal and para-rowing), for the first time. While the largest risk factor for injury remains rapid increases in training frequency, intensity and/or volume, key concepts have emerged in the last decade in the following areas:

Rehabilitation:

- Complete cessation of training is predictive of injury recurrence, and should be discouraged.

Back:

- Full hip range of motion and neutral spinal curvature are indicated for prevention of back injury.
- Dynamic endurance-based training is preferable to static ‘core stability’.
- For treatment of back injury, a combined biopsychosocial approach is optimal, focusing on impairment rather than suspected pathology.

Chest:

- ‘Rib stress injury’ (RSI) defines a spectrum of rib overuse injuries.

- Questions persist about mechanism of injury, yet new guidelines assist management, including gradation of RSI severity estimating recovery times.
- Dynamic ergometers may lower RSI risk.

Hip/Groin:

- Femoral acetabular impingement (FAI) or labral tears in athletes should be considered in the differential diagnosis.

Screening/Special Populations:

- Relative Energy Deficiency in Sport (RED-S) broadens the former ‘Female Athlete Triad’ to include male individuals and should be considered in rowers, particularly lightweight rowers.
- FISA now mandates pre-competition health screening for elite international rowers.
- Masters should undergo regular cardiac screening because of an increased incidence in atrial fibrillation.
- Juniors (below age 18 years), masters (above age 27 years), and para (various abilities) require individual consideration.

While the recent increase in rowing injury research is encouraging, there remains a significant demand for well-designed prospective studies. A better understanding of the complexities underlying the risk, treatment, and prevention of injuries in rowers will be invaluable to athletes, coaches, and medical practitioners alike. Collaboration, drawing on all areas of preventative and rehabilitative care, will ensure rowing remains a fun and safe experience for participants of all abilities.

Compliance with Ethical Standards

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Informed consent Consent for the publication of the figures was obtained from each the athletes depicted.

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