

Rib Stress Fractures Among Rowers

Definition, Epidemiology, Mechanisms, Risk Factors and Effectiveness of Injury Prevention Strategies

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Abstract

Rib stress fractures (RSFs) can have serious effects on rowing training and performance and accordingly represent an important topic for sports medicine practitioners. Therefore, the aim of this review is to outline the definition, epidemiology, mechanisms, intrinsic and extrinsic risk factors, injury management and injury prevention strategies for RSF in rowers. To this end, nine relevant books, 140 journal articles, the proceedings of five conferences and two unpublished presentations were reviewed after searches of electronic databases using the keywords ‘rowing’, ‘rib’, ‘stress fracture’, ‘injury’, ‘mechanics’ and ‘kinetics’. The review showed that RSF is an incomplete fracture occurring from an imbalance between the rate of bone resorption and the rate of bone formation. RSF occurs in 8.1–16.4% of elite rowers, 2% of university rowers and 1% of junior elite rowers. Approximately 86% of rowing RSF cases with known locations occur in ribs four to eight, mostly along the anterolateral/lateral rib cage. Elite rowers are more likely to experience RSF than nonelite rowers. Injury occurrence is equal among sweep rowers and scullers, but the regional location of the injury differs. The mechanism of injury is multifactorial with numerous intrinsic and extrinsic risk factors contributing. Posterior-directed resultant forces arising from the forward

directed force vector through the arms to the oar handle in combination with the force vector induced by the scapula retractors during mid-drive, or repetitive stress from the external obliques and rectus abdominis in the 'finish' position, may be responsible for RSF. Joint hypomobility, vertebral malalignment or low bone mineral density may be associated with RSF. Case studies have shown increased risk associated with amenorrhoea, low bone density or poor technique, in combination with increases in training volume. Training volume alone may have less effect on injury than other factors. Large differences in seat and handle velocity, sequential movement patterns, higher elbow-flexion to knee-extension strength ratios, higher seat-to-handle velocity during the initial drive, or higher shoulder angle excursion may result in RSF. Gearing may indirectly affect rib loading. Increased risk may be due to low calcium, low vitamin D, eating disorders, low testosterone or use of depot medroxyprogesterone injections. Injury management involves 1–2 weeks cessation of rowing with analgesic modalities followed by a slow return to rowing with low-impact intensity and modified pain-free training. Some evidence shows injury prevention strategies should focus on strengthening the serratus anterior, strengthening leg extensors, stretching the lumbar spine, increasing hip joint flexibility, reducing excessive protraction, training with ergometers on slides or floating-head ergometers, and calcium and vitamin D supplementation. Future research should focus on the epidemiology of RSF over 4-year Olympic cycles in elite rowers, the aetiology of the condition, and the effectiveness of RSF prevention strategies for injury incidence and performance in rowing.

Rowing is an asymmetric movement performed in narrow boats with two, four or eight rowers, each with one oar. Sculling, a variant of rowing, is performed by scullers in single, double or quadruple seated two-oared boats. Both activities are often referred to as rowing, illustrating the strong links and similarities between each. Rowers apply force during the drive phase of the rowing stroke cycle via the hands on the oar(s) and the feet on the foot stretcher. The drive phase is initiated when the blade(s) enters the water. The rower's ankles, knees and hips are in a flexed position preparing for the drive phase where the legs extend moving the pelvis towards the bow of the boat, the trunk extends and arms are drawn toward the body. Peak oar force generally occurs earlier in the drive phase,^[1,2] but may shift depending on many factors. The 'finish' position occurs when the ankles plantar-flex, knees and trunk are extended and the blade(s) are withdrawn from the water.

Rib stress fractures (RSFs) are common among rowers with an average incidence of 9.2% (see

table I). Therefore, sports medicine practitioners need to understand the movements associated with rowing, the likely risk of RSF occurring in various levels of competitive rowers, the possible mechanisms, intrinsic and extrinsic risk factors, injury management and effectiveness of injury prevention strategies for RSF in rowing.

Warden and colleagues^[23] provided a comprehensive review of rib injury risk factors that affect rib loading (muscular, joint, technique and equipment) and response to rib loading (bone construction, training and gender) in rowers. Our review expands on Warden et al.'s^[23] information by providing an overview of the definition, epidemiology, possible mechanisms, possible intrinsic and extrinsic risk factors, treatment and a discussion of possible injury prevention strategies for RSFs in rowing.

1. Literature Search Methodology

Nine relevant books, 140 journal articles, proceedings from five conferences, and two unpublished presentations (obtained through personal

Table 1. Reported rib stress fracture (RSF) injury among rowers

Study	Rowers with RSF/rower population (%); denominator group ^a	Design ^b and observation period	Injured rower characteristics	Country of origin	No. of fractures	Rib fractured	Side	Region
Christiansen and Kanstrup ^[3]	6/50 (12.0); A	Retrospective case series, MR 14 mo	Gender: 2 F, 4 M Mean age: 23 y Level: 6 elite Wt: 3 LW, 1 HW 2 UN Cat: 2 SC, 4 SW	Denmark	6	1×5th 3×6th 2×7th	1 R 5 L	4×L 1×PL 1×P
Dragoni et al. ^[4]	9/103 (8.7); A	Retrospective case series, MR 6 y	Gender: 0 F, 9 M Mean age: 24.4 y Level: 9 elite Wt: 2 LW, 7 HW Cat: 6 SC, 3 SW	Italy	9	2×4th 0×5th 2×6th 2×7th 2×8th 1×9th	5 R 4 L	6×AL 2×MAX 1×PL
Hickey et al. ^[5]	14/172 (8.1); A	Retrospective cohort, MR 10 y	Gender: 12 F, 2 M Mean age: 21.7 y Level: 14 elite	Australia	17	1×2nd 16×4th to 8th	10 R 7 L	7×AAX 3×MAX 2×PL 5×UN
Karlson ^[6]	10/61 (16.4); A	Retrospective case series, I 2 y	Gender: 7 F, 3 M Level: 10 elite Wt: 5 LW, 5 HW Cat: 3 SC, 3 SW 4 both	United States	14	6×5th 2×6th 3×7th 1×8th rib 2×9th	7 R 7 L	5×AL 1×AAX 2×MAX 5×PL 1×P
Smoljanivic et al. ^[7]	4/398 (1.0); A	Retrospective cohort, QI 1 y	Gender: 4 F, 0 M Level: 4 junior elite	Junior World Championship (45 countries)	5	—	—	—
Wilson et al. ^[8]	0/20 (0.0); A	Prospective cohort, I 1 y	Level: 0 elite	Ireland	0	—	—	—
Iwamoto and Takeda ^[9]	15/185 (8.1); B	Retrospective cohort, MR 10 y	Gender: UN F, 14 M	—	15	—	—	—
McDonnell et al. ^[10]	21/179 (11.7); B	Retrospective cohort, MR 7 y	Gender: 11 F, 10 M Level: 21 elite	New Zealand	24	—	—	—
Reid et al. ^[11]	3/40 (7.5); B	Retrospective cohort, MR 4 y	Gender: 3 F Level: 3 elite	Australia	3	—	—	—

Continued next page

Table I. Contd

Study	Rowers with RSF/rower population (%); denominator group ^a	Design ^b and observation period	Injured rower characteristics	Country of origin	No. of fractures	Rib fractured	Side	Region
Bojanić and Desnica ^[12]	1; C	Retrospective case study, MR	Gender: 1 M Age: 27 Level: 1 elite Wt: HW Cat: SW	Croatia	1	1×6th	1 L	1×AL
Smoljanović et al. ^[13]	1; C	Retrospective case study, MR	Gender: 1 M Age: 19 Level: 1 club Cat: SC	Croatia	1	1×9th	1 R	1×AL
Brukner and Khan ^[14]	1; C	Retrospective case study, MR	Gender: 1 F Age: 20 Level: 1 elite Cat: SC	–	2	1×7th 1×8th	–	2×P
Galilee-Belfer and Guskiewicz ^[15]	1; C	Retrospective case study, MR	Gender: 1 F Age: 20 Level: 1 university Wt: HW Cat: SW	United States	1	1×8th	1 L	1×AL
Goldberg and Pecora ^[16]	10; C ^c	Retrospective cohort, MR 3 y	Level: 10 university	United States	10	–	–	–
Holden and Jackson ^[17]	4; C	Restrospective case series, MR 1 y	Gender: 4 F Mean age: 27.3 Level: 4 elite Cat: 4 SC	United States	7	1×4th 2×5th 2×6th 1×7th	4 R 2 L	1×L 4×PL 1×P
McKenzie ^[18]	1; C	Retrospective case study, MR	Gender: 1 M Level: 1 elite Wt: HW Cat: SW	–	1	1×9th	1 R	1×AL
Palierne et al. ^[19]	12; C	Retrospective case series, MR 5 y	Gender: 6 F, 6 M Level: 12 elite Cat: 5 SC, 7 SW	France	12	1×2nd 1×4th 2×5th 3×6th 3×7th 2×10th	4 R 8 L	1×Ant 7×L 4×P

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Table I. Contd

Study	Rowers with RSF/rower population (%); denominator group ^a	Design ^b and observation period	Injured rower characteristics	Country of origin	No. of fractures	Rib fractured	Side	Region
Sinha et al. ^[20]	2; C	Retrospective cohort, MR	—	—	2	1 × 1st 1 × 9th	—	—
Vinther et al. ^[21]	7/29 (24.1); C	Retrospective cohort, QI 6 y	Gender: 2 F, 5 M Mean age: 25.6 y Level: 7 elite Wt: 6 LW, 1 HW	Denmark	17	—	—	—
Wajswelner et al. ^[22]	22/74 (29.7); C	Retrospective cohort, U Full injury history	Gender: 13 F, 9 M Level: 12 elite, 7 club, 3 school Wt: 8 LW, 14 HW Cat: 12 SC, 10 SW	Australia	22	—	—	—
Summary of cases	Total number of rowers with RSF: 144 Among reported stress fractures, average % of RSFs reported by denominator (A) 9.2%; (B) 9.1%; (C) NA	Retrospective: 19 Prospective: 1 Range: 1–10 y	Gender: 66 F, 65 M, 13 UN Mean age: 23.1 Level: 101 elite, 11 university, 8 club, 7 juniors, 17 UN Wt: 24 LW, 30 HW, 90 UN Cat: 34 SC, 30 SW, 4 SC/SW, 77 UN	Australia, Croatia, Denmark, France, Ireland, Italy, New Zealand, United States + 45 countries represented at the Junior World Championships	169	1 × 1st 2 × 2nd 0 × 3rd 4 × 4th 11 × 5th 13 × 6th 12 × 7th 5 × 8th 6 × 9th 2 × 10th 16 × 4th to 8th 97 × UN	33 R 35 L 101 UN	1 × Ant 15 × AL 8 × AAX 19 × MAX 0 × PAX 13 × PL 9 × P 104 × UN

a Studies were organized by classification of denominator data: (A) total rower population of a team or event; (B) total rowers reporting injuries from an injury database; and (C) no clear denominator data exists.

b All studies confirmed RSFs were diagnosed clinically by a medical doctor. Data were obtained via MR, I, QI and U. When it was U of how injury data were obtained, the article explained that the diagnosis was confirmed medically with a bone scan.

c Goldberg and Pecora^[16] provided an estimation of 165 rowers per y and an occurrence of 10 RSFs over 3 y, therefore the 6.1% incidence previously reported by Warden et al.^[23] was inflated and 2% is a more accurate estimation. Due to confusion, this was excluded from the table.

Ant=anterior; **AAX**=anterior axillary region; **AL**=antero-lateral; **Cat**=category; **F**=female; **HW**=heavyweight; **I**=interview; **L**=left; **LW**=lightweight; **MAX**=mid-axillary line and inclusive of fractures reported in the 'lateral' region; **M**=male; **MR**=medical records; **NA**=not applicable; **P**=posterior; **PAX**=posterior axillary region; **PL**=posterolateral; **QI**=questionnaire and interview; **R**=right; **SC**=sculler (rower who uses two oars); **SW**=sweep (rower who uses one oar); **U**=uncertain of how data were collected; **UN**=unknown; **Wt**=weight classification.

communications) were reviewed after searching MEDLINE, SportsDiscus®, ProQuest Direct, Google Scholar, CINAHL®, and Scirus databases from 1975 to November 2010 using keywords 'rowing', 'rib', 'stress fracture', 'injury', 'mechanics' and 'kinetics'. Inclusion criteria provided the following articles: (i) data for RSFs in rowers; or (ii) relevant information for epidemiology, diagnostic tests, possible mechanisms, risk factors, management and prevention of stress fractures in general; or (iii) rowing biomechanics studies that may provide insight to the possible mechanisms or risk factors associated with RSF. Exclusion criteria were: (i) unavailable in English and not previously referred to by other sources; (ii) not specific to RSF injury in rowers and did not add knowledge to the manuscript. Additional supportive articles were sought through article reference lists. Sixty-one references were retained after determining the relevance of the information to the aim of the review.

2. Findings

2.1 Definition, Nature and Diagnosis of Rib Stress Fracture (RSF) Injury

RSF is defined as an incomplete bone fracture, occurring from an imbalance between the rate of bone resorption (where osteoclasts break down old bone) and bone formation (ossification) in the process of bone remodelling.^[4] Mechanical loading leads to bone strain, and repetitive bouts of mechanical loading (observed in rowing) can lead to bone microdamage.^[23,24] Bone typically responds by adapting its structure according to Wolff's law.^[25] If the strain rate, or magnitude or frequency of mechanical loading exceeds the ability of the bone to adapt, an accumulation of microdamage occurs, leading to a stress fracture.^[23-25]

Symptoms of RSF include generalized rib pain most commonly in the lateral chest region that increases with activity and becomes more specific.^[5,23,26] Pain may radiate along the distribution of the intercostal nerve.^[17] Pain usually increases with deep breathing and positional change,^[4] shoulder flexion, shoulder abduction, shoulder extension, trunk flexion, end-range trunk exten-

sion, scapular protraction and scapular retraction.^[15] Differential diagnosis includes serratus anterior strain, intercostal strain^[15] and should include Ewing's sarcoma especially for nonelite, young rowers without a recent history of increased training volume.^[27] Most fractures are diagnosed between 2–6 weeks of the onset of pain.^[4] Early recognition is crucial for appropriate treatment and earlier full return to rowing.

Bone scintigraphy (bone scan), radiography and ultrasonography can be used to confirm a RSF diagnosis; however, scintigraphy is the most sensitive option, preceding radiographical changes by 2 weeks.^[4,28] A RSF appears as a hot spot in bone scans, showing the uptake of a radioisotope in the fracture location (see figure 1). A period of 2–12 weeks, depending on the bone, is usually required to view stress fractures by radiography,^[29] therefore should not be used to rule out stress fracture. Plain radiographs can rule out other causes of localized bone pain such as infection or malignancy that bone scintigraphy cannot rule out.^[29] These are not typically reported among rowers, however Smoljanović and Bojanić^[27] reported a case of Ewing's sarcoma in a 13-year-old novice rower confirmed by radiography. Algorithms for making clinical decisions on imaging, diagnosis and treatment are available.^[27,28] MRI may be used for detecting stress fractures during the early stages of healing.^[28,29] However, MRI is not typically reported or discussed specifically for the diagnosis of RSFs in rowers, therefore its usefulness remains unclear.

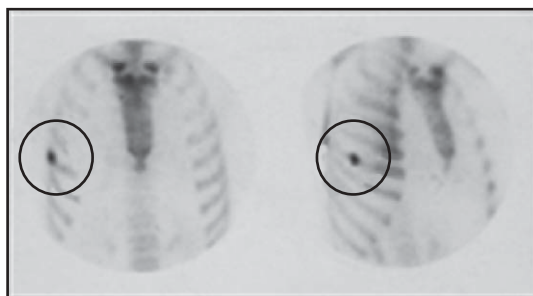


Fig. 1. Bone scintigraphy showing radioisotope uptake (circled) at the fracture location in the right anterolateral region of the sixth rib. Adapted from Warden et al.,^[23] with permission from Adis, a Wolters Kluwer business © Adis Data Information BV, 1996. All rights reserved.

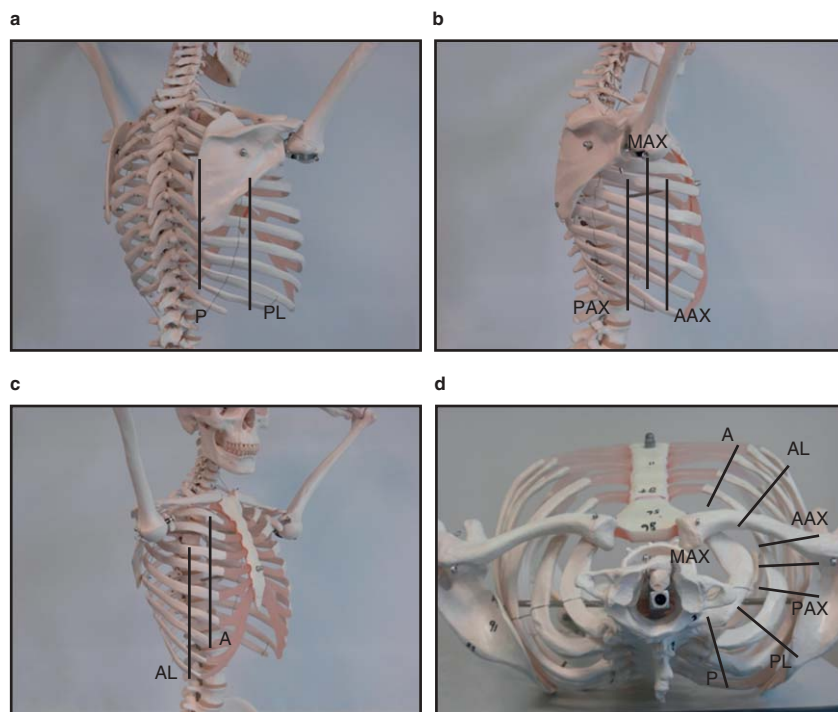


Fig. 2. Regions of the rib cage where rib stress fractures occur. (a) Posterolateral rib cage view; (b) lateral view; (c) anterolateral view; (d) transverse view. A = anterior; AL = anterolateral; AAX = anterior axilla; MAX = mid-axilla; P = posterior; PL = posterolateral; PAX = posterior axilla.

RSFs can occur in any location of any rib,^[30] but most commonly occur in the anterolateral aspect of the middle ribs. Brukner and Khan^[14] reported a RSF in the neck of the seventh and eighth ribs that had not previously been reported in rowers. No association between the injured chest side compared with rowing side among sweep rowers has been found.^[3] Although RSFs have been reported equally for sweep rowing and sculling, locations of injuries slightly differed between these two categories. In sweep rowing, 81% of RSFs occurred in the anterolateral/lateral aspects of the rib cage, while in sculling they tended to occur evenly along the anterolateral/lateral (54%) and posterolateral/posterior (46%) aspects of the rib cage.^[23] There are currently no hypothesized reasons for differences in rib fracture location between sweep and sculling, but both types of rowing require different shoulder, scapular and thoracic movement patterns that are likely responsible for loading the rib cage differ-

ently. Additionally, there have been differences in reporting where RSFs occur in various studies, making comparisons difficult. We therefore suggest the following terms and have used these when summarizing studies of reported RSF injury among rowers (presented in table I).

Regional terms have included posterior, posterolateral, lateral, anterolateral and anterior to describe location of injury around the rib cage (see figures 2a, b, c). The lateral region, in some reports,^[5,6] has been broken down to posterior axillary line, mid-axillary line and anterior axillary line. These terms refer to the regions extending downward from the axilla. The posterior wall of the axilla is formed by the shoulder muscles latissimus dorsi, teres minor and subscapularis.^[31] The imaginary line from the posterior wall downward creates the posterior axillary line (see figures 2b and d). The mid-axillary line extends from the apex of the axilla located between the first rib and the clavicle.^[31] The anterior wall of the axilla is

formed by the pectoralis major and minor muscles,^[31] and the imaginary line from the anterior wall downward depicts the anterior axillary line (see figures 2b and d).

2.2 Incidence of RSF in Rowing

Incidence rates of RSFs in rowing have been previously overestimated. Although Goldberg and Pecora^[16] stated that they could not calculate incidence rates, other studies have used their 3-year injury occurrence as the numerator instead of averaging annual occurrence, and using the annual team roster as the denominator, which yielded approximately 6%. This would be correct if the same 165 rowers remained on the team for 3 years; however, this is highly unlikely. Controlling for average injury per year and dividing by the annual roster estimated an incidence of only 2%. However, this incidence (2%) may also be underestimating true incidence because not all rowers have the same amount of exposure to training, especially among university teams where recruitment and dropout rate may be high.

Only one study^[8] provided prospective injury data in a pre-specified population of rowers during a pre-specified period of time, taking exposure to training into account for an optimal calculation of incidence rates (incidence per 1000 hours of training and competition). The incidence rates reported by other studies have used various methods (see table I). We divided the reviewed studies into three distinct denominator groups for calculating incidence of injury. Denominator A shows incidence as a percentage of rowers experiencing RSF out of the total rower population of a team or event, denominator B shows incidence as a percentage of rowers experiencing RSF out of total rowers reporting injuries from an injury database and denominator C represents studies with no clear denominator data. Denominator C also includes convenience samples^[21,22] and incidence was not calculated. Among all groups, reported occurrence rates have represented injuries spanning over varying lengths of time (1–10 years), making comparison between studies difficult.

Among reports of RSFs (see table I), incidence expressed as a percentage of rowers with RSFs

from denominator A occurred among 9.2% (range: 8.1–16.4%) of elite rowers,^[3-6,11,21] approximately 2% of university rowers,^[16] and 1% of junior elite rowers.^[7] RSF frequency among rowers from denominator B averaged 9.1% (range: 7.5–11.7%).^[9-11] The majority of studies on RSFs in rowers fall into the denominator C group and consist mainly of case studies, so incidence cannot be calculated (see table I).

Hickey et al.^[5] reported 22.6% of all injuries were chest injuries among female Australian Institute of Sport rowers between 1985 and 1994. Previous reviews^[26] have mistaken this for occurrence of RSF in rowers. Although RSFs were the most common chest injury, also included were nonspecific chest wall pain, intercostal muscle strain, pectoralis major strain, costovertebral joint injury, costochondral joint injury, costosternal joint injury, contusion and nerve entrapment. Occurrence of RSF injury was only 8.1%.

An analysis of New Zealand elite rowers' injuries showed 24 RSFs among 21 rowers out of a data base of 179 rowers over 7 years.^[10] Although RSF injury has not been an issue on a year-to-year basis for New Zealand rowers, stress fracture incidence increased in 2003 ($n=4$) and 2007 ($n=13$).^[10] These were the years preceding the 2004 and 2008 Olympics when training volume likely increased. Other than 2003 and 2007, occurrence was low with only two or less RSFs reported each year.^[10] Reporting for each year during an Olympic cycle may make determining incidence of injury more comparable.

Ribs five to seven were the most common ribs fractured, then ribs four and eight, and fewer occurrences in the upper and lower ribs. Approximately 86% of cases occurred in ribs four to eight. Although it has been reported that the posterolateral rib cage incurred the greatest bending forces,^[32] the majority of RSFs occurred from the anterolateral to mid-axillary regions (see table I). Fractures per person have ranged from one to four and have not been related to experience level.^[5]

2.3 Possible Mechanisms for RSF in Rowing

For the purpose of this review, we define the mechanism of injury as the physical action or cause of injury. Ribs are nonweight-bearing

bones and are not susceptible to impact forces during rowing. Therefore, the mechanical cause of injury is most likely muscular in nature. Two generalized theories have been identified to explain the mechanism of RSFs in rowers as follows:^[12,25,29] (i) exercise-induced muscle fatigue causes alterations in movement pattern and distribution of stress resulting in excess force transmitted to focal sites along the bone; and (ii) strong force of muscle itself acts on bone leading to rib cage compression and accumulation of damage.^[12,23,33] Given that several muscles surround the rib cage and may contribute to either rib cage compression or prevent compression, it is difficult to discern the aetiology of RSF.

2.4 Possible Risk Factors (Intrinsic and Extrinsic) for RSF in Rowing

Risk factors differ from the mechanism of injury and are predisposing factors that combined with the mechanism of injury may make a rower more prone to injury.

2.4.1 Intrinsic Risk Factors

Gender

In contrast to previous findings that female rowers are at greater risk of injury than male rowers,^[5,23] we did not observe any differences in the frequency of reported RSF injuries between genders in our analysis of data reported in the literature. Higher quality epidemiology studies that focus on injury incidence per exposed females and males would be more beneficial for determining risk rather than reported cases alone. Females are thought to be at higher risk due to differences in bone structure and hormonal factors that influence bone density.

Age

Reported RSFs are more prevalent among rowers between 22–27 years of age,^[3,5,17] which is also the age of most elite rowers. RSF injury may have little to do with age alone, but may be more influenced by level of performance and training loads. Bone, tendon and ligament stiffness do change with age, but the effect of these changes on risk of RSF is unknown.

Level of Performance

The risk of RSF increases with the level of performance. Frequency of RSFs among elite rowers^[3-5,11,21] have exceeded that of university^[16] and junior rowers.^[7] However, there have been limited studies reporting injury history among rowers at lower performance levels. There have been no literature-based reports of RSF injury among Masters level rowers, although research is possibly skewed toward papers from those who conduct research on elite and university rowers. Although limited data exists ($n=7$), there was no association between years of training and number of RSFs among elite rowers with a history of RSF.^[34] Higher occurrence rates among elite rowers may be associated with larger training volumes or other risk factors, rather than better rowers being more susceptible to RSF. Injuries in general are more prevalent during periods that coincide with more intense or prolonged training and competition.^[5]

Anatomical Factors

Chest wall muscles: Studies investigating RSF injury in rowers have focused on the involvement of the serratus anterior, external obliques, and middle and lower fibres of the trapezius. Bending stress induced by the combined contractions of the serratus anterior and external obliques is one proposed cause,^[6,10,17,30,32] but has not been supported well by research.^[23] Wajswelner et al.^[22] observed surface electromyography of the serratus anterior and external obliques during the rowing stroke timed with rib cage compression measured by an extensometer. The serratus anterior and external obliques had maximal peak contraction at opposite ends of the stroke, thus the idea that they contract together to cause rib cage compression leading to RSF injury was not supported (see figure 3). The maximal contraction of the external oblique occurs at the finish of the stroke while the contraction of the serratus anterior is very minimal. The muscle activity of the serratus anterior is larger and peaks mid to late recovery when the oar is unloaded. It is not likely that the force produced while the oar is unloaded would cause a RSF.

Warden et al.^[35] also observed that maximal rib loading coincided with minimal serratus

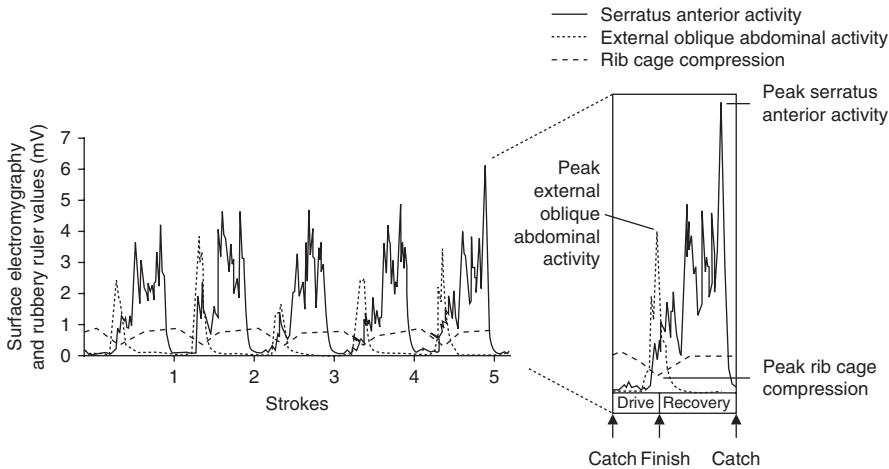


Fig. 3. Muscle activity during rowing shows peak external oblique and serratus anterior activity occur at opposite ends of the stroke, not simultaneously. Additionally, peak rib cage compression occurs at peak external oblique muscle activity. Reproduced from Warden et al.,^[23] with permission from Adis, a Wolters Kluwer business © Adis Data Information BV, 1996. All rights reserved.

anterior and rectus abdominis muscle activity, providing less support for these muscles directly causing injury. This observation supports a different theory of how RSFs may occur in rowers during the early drive phase. The forward directed force vector through the arms to the oar handle in combination with the force vector induced by the scapula retractors create a resultant force vector that acts on the posterolateral rib cage (see figure 4). When the oar handle force peaks near mid-drive, the resultant force vector will also peak. Although this is termed the 'rib cage compression theory', it is important to differentiate peak rib cage compression (observed at the finish)^[22] from peak rib cage loading that was explained by Warden et al.^[23] Peak rib cage compression occurring at the end of the stroke may not necessarily be detrimental to bone health or cause injury but may actually dissipate forces. The mid-drive coincides with the most intense pain reported in rowers with RSF by Warden et al.^[23] and the finish coincides with the most intense pain reported by Karlson,^[6] so it is also possible that an accumulation of microdamage, and subsequent stress fracture and pain, results from forces occurring at both mid-drive and the finish.

Vinther et al.^[34] provided more support to the rib cage compression theory presented by Warden

et al.,^[23] and provided less support to the theory of co-contraction of the serratus anterior and external obliques by investigating the co-contraction of the serratus anterior, external obliques and middle and lower fibres of the trapezius during ergometer rowing. Significantly larger serratus anterior and trapezius lower fibres co-contraction ($\text{EMG signal overlap}/\text{EMG}_{\text{max}}$) was observed in the RSF group ($47.5 \pm 3.4\%$ overlap), compared with the control group ($30.8 \pm 6.5\%$ overlap) at mid-drive when the oar was loaded.^[34] Serratus anterior and trapezius lower co-contraction may be responsible for posterior directed forces at mid-drive, which could lead to higher forces acting on the ribs. However, this does not explain the rationalization for strengthening the serratus anterior during rehabilitation.^[6,15,23,26] When both the serratus anterior and retractors stabilize the scapula, the angle of pull to the anterolateral rib cage may cause expansion of the rib cage (see figure 4).^[23] Fatigue of the serratus anterior and its inability to counteract the posterior directed forces at mid-drive or resist the abdominal-led rib cage compression at the finish, in this case, may cause detrimental stress to the rib cage.

Abdominal muscles: Fibres of the rectus abdominis run vertically from the pubic crest and symphysis to the costal cartilage of the fifth,

sixth, and seventh ribs and to the xiphoid process of the sternum to act in flexing the vertebral column.^[36] The rectus abdominis also compresses the rib cage anterior/posteriorly by pulling downward on the attachment sites (lower ribs five to seven and sternum) and aids in forced expiration during exercise that commonly occurs at or near the finish position in rowing.^[23] The obliques originate from the external surfaces of ribs five to eight interdigitating with the serratus anterior and insert on a long tendinous sheath that runs vertically (below the rectus abdominis) attached to the lower sternum and pelvic bone.^[36] The obliques aid in trunk flexion, rotation and forced expiration. Interestingly, 73% of the 80 RSFs reported by Warden et al.^[23] occurred in ribs five to seven (the rectus abdominis attachment) while

84% occurred in ribs five to eight (attachment sites for the rectus abdominis and external obliques). This adds further support to the abdominal-led rib cage compression theory.

Joint mobility: The overall risk of a RSF may be reduced by improving joint mobility, which is important for attenuating forces away from bone. The joints involved in the rib cage are the costochondral (attached to the sternum), costovertebral and costotransverse (attachment at thoracic spine). Increased thoracic spine flexion, which is observed after prolonged rowing,^[37] can lead to increased tension in these joints, subsequently reducing the force attenuating properties, which may lead to injury. Malalignment or vertebral rotations will also cause tension in these joints from torsional stress and uneven displacement of the ribs between right and left sides. Passive mobilization results in a reduction of pain post-injury.^[23]

Furthermore, the location of injury supports the supposition that joint hypomobility may be associated with fracture. True ribs (one to seven) articulate anteriorly with the sternum, while false ribs (eight to ten) articulate via the costochondral cartilage with adjacent ribs.^[32] Ribs 11 and 12 are floating with no anterior attachment.^[32] The costochondral cartilage allows for more movement than the attachment at the sternum, therefore may help dissipate the forces acting on those ribs resulting in lower injury occurrence to the false ribs. Warden et al.^[23] reported 67 RSFs in the true ribs. Only 13 cases of RSFs occurred in the floating ribs. Of nine cases of RSFs reported among elite Italian rowers, six occurred in the true ribs four to seven, while two occurred in rib eight and only one occurred in rib nine.^[4]

It is also important to pay particular attention to the kinetic chain distal to the site of injury.^[26] Lack of flexibility in the lumbar spine and hips shortens the stroke, and may cause an individual to compensate by increasing scapular protraction. Excessive protraction alters the resultant force between retractors (rhomboid muscle group) and the combined water resistance on the oar, leading to abnormal posteriorly directed forces on the rib cage.^[23]

Rib cage compartment models: Researchers have described the rib cage as being divided into

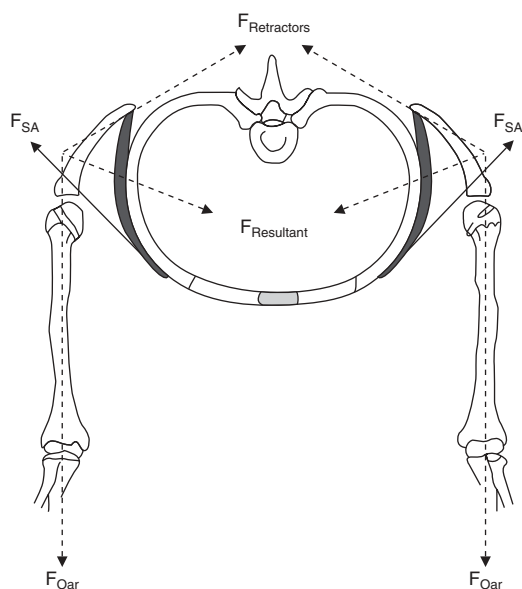


Fig. 4. A schematic of the 'rib cage compression' theory^[23] showing the combined force vectors of the oar (F_{Oar}) and scapula retractors ($F_{Retractors}$) produce a resultant force vector ($F_{Resultant}$) acting on the posterolateral rib cage. The force vector produced by the serratus anterior (F_{SA}) shows the potential protective effect of the serratus anterior on the rib cage. The angle of pull of the serratus anterior from the anterolateral rib cage causes expansion of the rib cage, not compression. In this case, risk of injury may be caused by fatigue of the serratus anterior and its inability to resist compression. It should be noted that these force vectors may not be drawn to scale, but reflect the concept of the proposed theories. Adapted from Warden et al.^[23] with permission from Adis, a Wolters Kluwer business © Adis Data Information BV, 1996. All rights reserved.

multiple compartments rather than one unit.^[38-41] The upper and lower rib cage compartments are anatomically distinct and the surrounding muscles act on them differently.^[39] These two compartments are described as the pulmonary apposed rib cage and abdominal apposed rib cage.^[39] Kenyon et al.^[38] added the abdomen as a third compartment to reduce the limitations while studying chest wall mechanics during exercise. The abdomen could have a considerable effect on expiration and increase rib cage distortion.^[39] Distortion has been defined as the difference in net pressure from the involved musculature acting on the two compartments of the rib cage.^[39]

Inspiratory muscles act to expand the rib cage, and expiratory muscles act to compress the rib cage. Respiratory muscle actions are further outlined in table II. Nondiaphragmatic inspiratory muscles (scalenes, parasternal intercostals and sternocleidomastoids) insert on ribs one to six and have actions on pulmonary but not abdominal parts of the rib cage, while the diaphragm and other abdominal muscles insert on ribs seven to 12 and have inspiratory and expiratory actions, respectively, on the abdominal apposed rib cage but not pulmonary parts of the rib cage.^[38] The internal intercostals may be responsible for considerable expiratory actions on the abdominal apposed rib cage, but has not been measured.^[38]

Rib cage distortions did not differ significantly between men and women, but tended to increase from single to prolonged coughing in both genders ($1.3 \pm 1.0\%$ to $2.3 \pm 1.6\%$; $p = 0.06$).^[40,41] Exercise at 70% of maximum work revealed lower levels of rib cage distortion than quiet breathing.^[38] This suggests a high level of coordination of inspiratory and expiratory muscles acting on both compartments of the rib cage during exercise leading to less net pressure. Studies have not explored rib cage mechanics near full workload or under fatigued conditions during exercise. However, Lanini et al.^[41] found that stimulation of the abdominal muscles helped produce a forceful cough in patients with muscular degeneration diseases. Repetitive cough has been associated with RSFs similar in location to those produced from rowing.^[6] This evidence supports that expiration or

Table II. Respiratory muscles

Inspiratory muscles (primary)
Diaphragm (contracts)
External intercostals and anterior internal intercostals
Inspiratory muscles (accessory)
Scalenes (deep inspiration)
Sternocleidomastoid
Serratus anterior/rhomboids
Pectoralis major
Pectoralis minor/lower and middle trapezius
Upper trapezius
Latissimus dorsi-posterior fibers
Erector spinae
Quadratus lumborum
Serratus posterior superior ^a
Expiratory (primary)
Diaphragm (relaxes)
Posterior intercostals
Abdominal muscles
internal obliques
external obliques
rectus abdominis
transversus abdominis
Expiratory muscles (accessory)
Latissimus dorsi-anterior fibres
Iliocostalis lumborum
Serratus posterior inferior ^a
Levatores costarum ^a
Tranversus thoracis ^a
^a Cannot be manually tested or palpated. ^[36]

forced expiration, led by the abdominals, leads to increased strain on the rib cage.

Bone density: Seven Danish national team rowers sustained 17 cases of RSF injury during the period 1994–2000.^[21] Bone mineral density scans were taken of these rowers in comparison to a control group with no history of a RSF. Lower whole-body and lumbar spine bone mineral density were consistently observed in the rowers with previous RSF than that of the control group.^[21] Generally, bone mineral density among rowers increases with magnitude of force exerted by the rower and years of training. A significant increase of 2.4% bone mineral density in experienced female university rowers was observed after 6 months of training.^[42] Experienced rowers generate more

force per stroke, supporting the idea that high stress to bone will result in increases of bone mineral density. The reduced bone mineral density associated with RSF is likely attributed to factors other than training such as nutrition and hormones.

Gender-Hormone Factors

Risk of RSFs in women may increase with menstrual disturbance or depot medroxyprogesterone injections. A female collegiate rower had intermittent amenorrhoea for 2–3 years and sustained a RSF of the eighth rib following an increase in ergometer training volume.^[15] Adjusted for treatment of amenorrhoea, risk of fracture was reduced from 91% to 83% in female naval recruits.^[43] Lappe et al.^[43] found that a form of birth control for women, depot medroxyprogesterone injections, were associated with greater stress fracture incidence. The drug is responsible for a series of hormonal changes that lead to reduced ovarian production of estradiol leading to continued loss of bone density while the drug is taken.^[44] Those with depot medroxyprogesterone injections had 48% greater risk of fracture than nonusers, and those with longer use had greater odds of fracture than those with shorter use.^[43]

Exercise-induced altered ovarian function was prevalent among elite and adolescent rowers.^[45] Lower estrogen and progesterone levels stemming from altered ovarian function were associated with reduced lumbar spine bone mineral accrual over 18 months.^[45] Furthermore, in male lightweight elite rowers, testosterone, vitamin D and years of training were related to total bone density.^[46] Exercise-induced alteration of ovarian function in women, regular use of depot medroxyprogesterone injections, and low testosterone in men may negatively influence bone mineral density by altering the mechanics of bone remodelling or prolonging the process of bone resorption.

2.4.2 Extrinsic Risk Factors

Training

Strain rate, magnitude of force and the number of loading cycles may contribute to micro-damage formation and result in the development

of a RSF.^[23] Workouts can be completed at a variety of intensities typically varying between 60% and 100% effort. Higher ranked rowers at the elite level of competition including national team members, typically generate greater force than university, club and junior rowers.^[47] The number of strokes taken each rowing session may also be higher in elite rowers. Stress fractures are mainly traced to changes in training duration, intensity or distance,^[12,24] explaining why elite rowers are more prone to this injury.

Bench pull and bench press exercises mimic scapular retraction and protraction movements that occur in the drive and recovery phases, respectively, in rowing. The forces exerted during these exercises cause considerable stress to the posterolateral rib cage, and are accentuated in scullers.^[17] A large number of rowing injuries occur during resistance training sessions and land-based rowing ergometer training, but are usually acute in nature,^[5] whereas RSFs are classified as overuse injuries. Nevertheless, the high incidence of acute injuries suggests these methods of training add considerable stress to the body, and sudden increases in training volume, particularly with land-based weights and ergometer sessions, should be avoided.

Technique

Two major rowing styles are sequential and simultaneous. A sequential rowing style emphasizes the leg drive first, followed by trunk and arm motions. During simultaneous rowing styles, the legs and trunk motions occur near the same time. International elite rowers have been successful with either rowing style.^[48] With regards to performance, Soper and Hume^[49] concluded that sequential patterns may lead to better performance outcomes. The sequential movement pattern has resulted in higher peak handle force, higher peak handle force relative to body weight, higher absolute and relative handle power and slightly longer stroke lengths relative to the rowers' height.^[48]

Vinther et al.^[34] observed sequential movement patterns in seven elite rowers with previous RSFs, compared with seven matched controls. Among healthy elite rowers, seat and handle ve-

locity during the initial drive phase were similar (0.15 m/s and 0.16 m/s, respectively)^[34] indicating a good connection between the legs, trunk and arms, which may still occur during sequential motor patterns if executed properly. In contrast, elite rowers with a history of RSF had a large difference in seat and handle velocity during the initial drive (0.25 m/s and 0.07 m/s, respectively).^[34] The faster seat velocity in this population suggested that a sequential movement pattern may have been a risk factor for injury.^[34] However, it is unclear whether these were differences in motor strategy, or poor execution of the sequential strategy among those who sustained injury. Vinther et al.^[34] also observed higher elbow-flexion to knee-extension strength ratios in the group who had received RSF. Kleshnev and Kleshnev^[48] reported that the sequential motor strategy used less leg work in the initial drive as a percentage of total leg work. However, they did not explain the comparison of absolute leg work to trunk work for the duration of the rowing stroke. It remains unclear if the sequential strategy may result in lower leg extension strength and rely on more upper body strength than that of the simultaneous strategy, which was deemed slightly more favourable in regards to efficiency.^[48] Repetitive high-loading of the upper body musculature may cause RSF injury, making the sequential motor strategy a possible risk factor for rib stress fracture injury.

Equipment

Factors that increase the magnitude of rib loading may contribute to microdamage formation and result in the development of RSF.^[23] The magnitude refers to the force acting on the rib cage, which is directly related to the amount of force the rower applies to the oar. Thus, a heavier oar load will result in more rib loading. Since the early 1990s production of the 'Big Blade' to replace the 'tulip' oars (called 'Macon oar'), there has been an increase in RSFs.^[3] The Macon oar design was longer, skinnier, and symmetrical while the Big Blade oars are shorter, broader and asymmetrical. The altered construction of the Big Blade has made rowing more efficient.^[3] The increased resistance of the blade in the water was

countered by shortening the outboard of the oar while keeping the inboard and spans the same. This allowed the rowers to reach a high load on the bigger blade with the same force on the inboard. The shorter outboard made the Big Blade oars stiffer, and the hydrodynamically more efficient blade shape loads quicker in the early drive phase. It is also easier to keep the load applied at the end of the drive. Each of these factors may be responsible for forces acting on the ribs. Rigging refers to the adjustment of rowing equipment (oars, boat and rigger) so that rowers can effectively apply propulsive forces necessary for movement.^[50] Rigging has some influence on size of force, time of peak forces and rate of force development that may affect rib strain. However, the possible influence of rigging changes on rib stress have not been investigated or explained well.

Rowers also undergo repetitive loading during their land training workouts usually with a Concept2 (Concept2 Inc., Morrisville, VT, USA) or RowPerfect rowing ergometer (Care RowPerfect BV, JV Hardenberg, the Netherlands). Developments of ergometers have included slides that allow the entire Concept2 ergometer to move rather than being fixed on the ground, a moveable seat, footplate and flywheel for the RowPerfect and a moveable seat and footplate for the dynamic Concept2 ergometer released in 2010. Rowers' stroke lengths are longer in fixed-head ergometers and increase with fatigue, particularly at the catch.^[51] During prolonged rowing, lumbar spine flexion increased towards full range of motion as a result of fatigue,^[37] increasing stress to the posterior structures of the spine. Costovertebral joints and the rib cage play an important role in providing stability to the spine.^[52] Therefore it is important to consider causes of fatigue of the spine when determining risk factors of RSF, as these stresses may also act on the ribs indirectly. Ergometer slides reduced mean forces during the same total work load performed on Concept2 stationary ergometers between 70–100% effort.^[53,54] Reduced handle forces were also observed for RowPerfect floating-head ergometers, compared with a fixed-head mechanism.^[51,55] RowPerfect floating-head ergometers allow safer

training than stationary ergometers by reducing catch and maximum net joint forces^[55] while allowing the same workload measured via external power output, heart rate and oxygen consumption.^[54] Prospective controlled studies are necessary to determine if training on a stationary Concept2 ergometer on slides, a dynamic Concept2 or a RowPerfect ergometer reduces risk of musculoskeletal overuse injury while maintaining training efficiency and performance.^[53]

Nutrition

Risk of stress fracture has also been attributed to low calcium and vitamin D intake as well as eating disorders.^[56] Vitamin D allows the body to absorb calcium via the gut and inhibits parathyroid hormone, which is responsible for bone resorption. Vitamin D is synthesized in the skin after exposure to ultra violet radiation from sunlight. Sunscreen and clothing can block the sun exposure required to synthesize active vitamin D, leading to deficiency and bone loss in severe cases.^[57] Dietary sources of vitamin D include salmon and egg yolks. Calcium helps maintain bone mineral density, so that bone can handle the stresses placed on it. Dietary sources of calcium can be found in a variety of foods such as dairy, green leafy vegetables, firm tofu, salmon, beans and fortified cereals.

Restricted caloric intake may decrease testosterone levels in male rowers, potentially having negative effects on bone mineral density if repeated often enough.^[46] Although investigations of dietary patterns among rowers are limited, more restrictive dietary patterns and eating disorders were observed among dancers with stress fractures than that of dancers without.^[58] Investigations of military recruits have been beneficial in determining effects of supplementation treatments. In a large scale study of female US naval recruits, calcium and vitamin D supplementation resulted in a 20% lower incidence of stress fractures, compared with a placebo-supplemented control group.^[43] Supplementation is ideal for military recruits and athletes, despite these groups having numerous risk factors for stress fractures, as this treatment will not interfere with training.^[43] Supplementation may be an ideal preventative

approach for elite rowers during heavy training phases.

2.5 Injury Management of RSFs

Excessive abdominal exercise should be avoided when a RSF is suspected and should be one of the last exercises re-incorporated into the programme after recovery.^[22] The use of smaller blades has been suggested as a management strategy,^[32] but implications for performance have not been examined.

Rowers responded well to 3–8 weeks of rest and modified training.^[3,5,12,17,19] Therefore early clinical diagnosis is crucial so that competitive rowers may discuss rest and modified training options with their coach. However, there was an unusual case of a 23-year-old female elite rower who had to stop rowing despite 4 months of rest.^[3] Initial treatment has involved a 1–2 week,^[3] or until asymptomatic, cessation of rowing, with analgesic modalities.^[3,15,33] Non-steroidal anti-inflammatory drugs (NSAIDs), commonly used for pain management, may negatively affect bone healing by limiting prostaglandin synthesis that has been shown to be essential for normal bone turnover and fracture healing.^[59] Although there is no conclusive evidence to document the effect of NSAIDs on stress fractures in humans, it may be wise to limit their use in patients with stress fracture.^[59] Local anaesthetic blocks are typically not given.^[3] Modified training regimens have included pain-free cardiovascular workouts (generally lower-body stationary cycling)^[33] and strengthening of the serratus anterior.^[23,32] A slow return to rowing is advised with low-impact intensity for 1–2 weeks,^[3] strengthening support structures and continued use of analgesic modalities.^[15] Taping can be used,^[5,33] although its effectiveness has not been ascertained.

2.6 Injury Prevention Strategies for RSFs in Rowing

Ensuring rowers have adequate leg extension strength and lumbo-pelvic coordination, may be one way of making sure rowers have the physical ability to produce and transmit power from the

legs to the oar handle, thereby reducing the stresses on the upper body that cause early onset of fatigue. Additionally, rowers should establish adequate coordination of the blade entry, upper-body movements and leg movements when focusing on improving leg extension strength to prevent risk of compounding the large seat-to-handle velocity ratio in the early drive.

Karlson^[6] suggested a strategy that may lead to less force on the ribs from the serratus anterior: rowing with scapulae less protracted as the oar enters the water and using less retraction of scapulae at the end of the stroke. This is based on the theory that the serratus anterior causes injury, which has not been supported well by research. Furthermore, reducing the use of the serratus anterior may lead to muscular weakness, lessen protraction, lead to poor muscle memory and decrease force production along the kinetic chain leading to diminished performance. The other suggestion of adopting less extreme layback reduces activity of the external obliques resulting in less force on the rib cage at the finish,^[6] but not throughout mid-drive. Further investigations are also necessary to determine if this modification would negatively affect performance as it would seem that less layback would shorten the stroke and result in diminished performance.

Before training and after training, a brief warm-up or cool-down followed by stretching exercises to keep the costovertebral and costotransverse joints mobile may help with absorption of rib stress. Rowers should be screened for hypomobility and malalignment of the thoracic vertebrae, ribs and surrounding areas during heavy training periods with appropriate interventions determined by sports medicine personnel. Massage may help relieve pain, improve joint mobility and reduce further risk of injury. Although no evidence for the effectiveness of these interventions can be provided specifically for RSFs, regular stretching performed for longer than 15 minutes after training was significantly associated with a lower frequency of all injuries among junior elite rowers.^[7]

Bone has the ability to alter its size, shape and structure to meet the mechanical demands placed on it. Therefore, exercises that stress the rib cage

should not necessarily be avoided in the strength and conditioning room but should be carried out carefully. Bench press and bench pull exercises place considerable compressive forces on the ribs.^[17] It is unknown whether these forces can help strengthen bone at the ribs. Despite being blamed for injury, strengthening of the serratus anterior has been suggested for RSF rehabilitation and prevention.^[15,22,23] All case studies that suggest strengthening the serratus anterior have resulted in a good recovery, therefore the serratus anterior may play a preventative role in RSF injury.^[23] In regards to nutrition, sports injuries in general might be reduced if athletes have a good understanding of how much energy they expend and what they need to replace during training periods with special attention to calcium intake or supplementation to maintain bone health. Effectiveness of these injury prevention ideas have yet to be determined.

Investigation of training programmes that increase leg to upper-body strength ratios with added focus on lumbo-pelvic coordination, strength and their effects on rowing technique may provide more insight into the involvement of the leg extensors affecting upper body rowing injuries. This could make sequential rowers more simultaneous at the catch; therefore, the effect on performance should also be determined. In addition, creating rib size and shape profiles of injured rowers may help determine rowers at high risk. In the meantime, the following are recommendations for preventing stress fracture injury:

1. Cross training can be used to maintain adequate training volume. This should help reduce fatigue of the muscles surrounding the rib cage, allowing them to play a more protective role. If high volume ergometer training cannot be avoided, it may be best to use a stationary Concept2 on ergometer slides, a dynamic Concept2 or a RowPerfect ergometer.
2. Educate female rowers on exercise-induced altered ovarian function, as this may be a sign of lower levels of estrogen or poor diet. Both lead to a loss of adequate bone density. Avoid depot medroxyprogesterone injections and consult a doctor on seeking other forms of birth control.

3. Discuss a proper diet with rowers to be sure that caloric intake, calcium and vitamin D levels are adequate to meet their individual energy requirements during training to promote bone health. Rowers may need to use vitamin D and calcium supplements during heavy training periods.

2.7 Critique of Literature

Since Warden et al.'s^[23] review on RSF injury, more reports of RSF injury have emerged. However, there has not been a substantial increase in the quality of data, shown by the lack of prospective studies, misleading denominator values, variation of observation period, lack of reporting exposure time and the variation in use of terminology when referring to regions of the lateral rib cage.

The highest quality study design investigating incidence and prevalence rates are prospective cohort studies;^[60,61] however, no further knowledge has been gained from the one prospective study presented in table I because no RSFs were diagnosed in the observed year.^[8] Despite case series and case studies regarded as the lowest quality design for epidemiology data,^[60,61] case series provided more useful information with regard to rower characteristics and specific injury location, which is crucial for the advancement of postulated mechanisms (see table I). A prospective cohort that also reported characteristics of individual cases and exposure time to training would be ideal.

Some evidence has suggested that elite rowers' RSFs do not occur evenly on an annual basis, and appear to be much larger during the year before an Olympic year when training volume likely increases.^[10] Therefore year-to-year investigations of injury among elite rowers are not equally comparable, and increases or decreases of injury rates cannot be assessed properly. An uneven year-to-year occurrence rate for RSF injury has implications for when national sport organizations should enhance resources for injury prevention programmes.

Although injury prevention strategies have been suggested, many strategies such as reducing

lay-back or shortening oars may negatively affect performance. RSF injury is problematic primarily among elite rowers, therefore researchers should be realistic about considering implications for performance when suggesting injury prevention strategies. National sport organization coaches will likely not consider strategies that may hinder performance. However, strategies that aim to reduce the risk of injury and enhance performance will be of high interest to coaches. There is currently no evidence-based best practice for reducing the risk of injury, nor treating or progressively rehabilitating RSF injury in rowers.

3. Conclusions

The quality of epidemiology data for RSFs in rowing is poor. Incidence for elite rowers should be reported prospectively by year, over 4-year Olympic cycles ending with the year of the Olympic Games. When possible, individual cases should be tabulated, and frequency of RSF should be expressed per number of exposed hours or days of training. When data from 4-year cycles cannot be collected, methodology should include which year(s) of the Olympic cycle the data were collected for better analysis of results in the future. Clinicians should confirm RSF using bone scintigraphy, and divide the lateral rib cage region into posterior axilla, mid-axilla and anterior axilla terms to enable comparison between studies.

The mechanism of injury is multifactorial with the posterior-directed resultant forces from the combined oar handle force and scapula retractors during mid-drive, or repetitive stress from the external obliques and rectus abdominis at the finish, likely responsible, rather than co-contraction of serratus anterior and external obliques. The serratus anterior most likely plays a preventative role as it is often strengthened during successful rehabilitation programmes. Additional risk factors include poor execution of sequential movement patterns, reduced leg extension strength relative to elbow flexion strength, low testosterone in men, and the use of depot medroxyprogesterone injections for women. Research has supported calcium and vitamin D supplementation to increase bone

health in military recruits; therefore, its effectiveness among rowers' bone health and injury incidence should be investigated.

Research should focus on the epidemiology reporting both incidence and prevalence over 4-year Olympic cycles for elites, aetiology and the effectiveness of injury prevention strategies to address intrinsic risk factors (gender, age, level of performance, anatomy and hormone) and extrinsic factors (training, technique, equipment and nutrition) for RSF in rowing. Further postulated mechanisms of injury should be supported by experimental research that incorporates to-scale schematics of oar force, scapular retractor forces and resultant force vectors throughout the drive phase of both sweep and sculling.

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