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From the Department of Health Sciences, Faculty of Medicine,
Lund University, Sweden 2008

Rib stress fractures in elite rowers

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"The pathology and prevention of rib stress fractures will be one of the most useful areas of research in rowing injuries."

Budget R, Hettinga D.M, Steinacker J. Sports medicine. In Secher NH & Voliannitis S, Editors. *Rowing*. London: Blackwell; 2007. p. 128

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List of publications

This thesis is based on the following papers, referred to in the text by their respective Roman numerals. Permission to print the published papers in this thesis was obtained from the respective journals.

Study I
Vinther A, Kanstrup I-L, Christiansen E, Alkjær T, Larsson B, Magnusson P, Aagaard P. Exercise-induced rib stress fractures: Influence of reduced bone mineral density.
Scand J Med Sci Sports 2005 15: 95-99

Study II
Vinther A, Kanstrup I-L, Christiansen E, Alkjær T, Larsson B, Magnusson SP, Ekdahl C, Aagaard P. Exercise-induced rib stress fractures: Potential risk factors related to thoracic muscle co-contraction and movement pattern. *Scand J Med Sci Sports* 2006 16: 188-196

Study III
Vinther A, Kanstrup I-L, Christiansen E, Ekdahl C, Aagaard P. Testosterone and BMD in elite male lightweight rowers. *Int J Sports Med* 2008 29: 803-807

Study IV
Vinther A, Alkjær T, Kanstrup I-L, Zerahn B, Ekdahl C, Jensen K, Larsen AH, Aagaard P. Ergometer rowing in slides: Implications for injury risk. Submitted 1/9 -2008

Study V
Vinther A, Alkjær T, Kanstrup I-L, Zerahn B, Ekdahl C, Jensen K, Larsen AH, Aagaard P. Neuromuscular activity during slide-based vs stationary ergometer rowing: Implications for exercise-induced stress fracture injury. *In Manuscript*

Description of contribution

Study I	
Study idea	Anders Vinther
Study design	Anders Vinther, Inge-Lis Kanstrup, Per Aagaard, Peter Magnusson, Benny Larsson
Data collection	Anders Vinther, Inge-Lis Kanstrup, Erik Christiansen
Data analysis	Anders Vinther, Inge-Lis Kanstrup, Per Aagaard, Peter Magnusson, Benny Larsson
Manuscript writing	Anders Vinther
Manuscript revision	Inge-Lis Kanstrup, Per Aagaard, Peter Magnusson, Tine Alkjær, Erik Christiansen
Study II	
Study idea	Anders Vinther
Study design	Anders Vinther, Inge-Lis Kanstrup, Per Aagaard, Peter Magnusson, Benny Larsson
Data collection	Anders Vinther, Tine Alkjær, Per Aagaard, Erik Christiansen
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Manuscript writing	Anders Vinther
Manuscript revision	Charlotte Ekdahl, Inge-Lis Kanstrup, Per Aagaard, Peter Magnusson, Tine Alkjær, Erik Christiansen, Benny Larsson
Study III	
Study idea	Anders Vinther, Erik Christiansen
Study design	Anders Vinther, Erik Christiansen, Per Aagaard, Inge-Lis Kanstrup
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Study IV

Study idea	Anders Vinther
Study design	Anders Vinther, Tine Alkjær, Anders H Larsen, Per Aagaard, Charlotte Ekdahl
Data collection	Anders Vinther, Tine Alkjær, Kurt Jensen
Data analysis	Anders Vinther, Tine Alkjær, Per Aagaard, Anders H Larsen, Bo Zerahn
Manuscript writing	Anders Vinther
Manuscript revision	Charlotte Ekdahl, Tine Alkjær, Per Aagaard, Inge-Lis Kanstrup, Anders H Larsen, Bo Zerahn

Study V

Study idea	Anders Vinther
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Manuscript writing	Anders Vinther
Manuscript revision	Charlotte Ekdahl, Tine Alkjær, Per Aagaard, Inge-Lis Kanstrup, Anders H Larsen, Bo Zerahn

Abbreviations

ACTH	Adrenocorticotrophic Hormone
BMD	Bone Mineral Density
bpm	Beats Per Minute (Heart Rate)
CI	Confidence Interval
CT	Computed Tomography
DEXA	Dual Energy X-ray Absorptiometry
DHAS	Dehydroepiandrosterone-sulfat
DHT	DihydroTestostesrone
DP	m. Deltoideus Posterior fibers
EMG	Electromyography
EMGmax	Maximal EMG signal amplitude (used to normalize EMG signals)
FISA	Fédération Internationale des Sociétés d'Aviron
FSH	Follicle Stimulating Hormone
FT	Free Testosterone (fraction of TT not bound to SHBG)
IRMA	ImmunoRadioMetric Assay
iRFD	Initial slope Rate of Force Development (10-30 % of Peak Force)
iSFA	Initial Shoulder Flexion Angle
L2-L4	Lumbar Vertebrae number 2, 3 and 4 (BMD measurement)
LBM	Lean Body Mass
LD	m. Latissimus Dorsi
LH	Lutenizing Hormone
lRFD	Late slope Rate of Force Development (50-70 % of Peak Force)
MRI	Magnetic Resonance Imaging
MUAP	Motor-Unit Action-Potential
$m \bullet s^{-1}$	Meters pr. second
ms	Milliseconds
mSFA	Maximum Shoulder Flexion Angle
MVC	Maximal Voluntary Contraction
N	Newton

ng ml^{-1}	Nanogram per millilitre
Nm	Newton-meter
nmol l^{-1}	Nanomol per litre
NSAID	Non-Steroid Anti-Inflammatory Drug
OEA	m. Obliquus Externus Abdominis
PF	Peak Force
PTH	Parathyroid Hormone
RIA	RadioImmuno Assay
RFD	Rate of Force Development (Δforce / Δtime)
RMS	Root Mean Square (RMS filter used to smooth raw EMG signals)
RSF	Rib Stress Fracture
SA	m. Serratus Anterior
SHBG	Sex Hormone Binding Globulin
SD	Standard Deviation
SEM	Standard Error of the Mean
SR	Stroke Rate (number of rowing strokes per minute)
TA	m. Tibialis Anterior
TL	m. Trapezius Lower fibers
TM	m. Trapezius Middle fibers
TSH	Thyroid Stimulating Hormone
TT	Total Testosterone
VL	Vastus Lateralis of m. Quadriceps Femoris
W	Watt (Joule/second)
4-AD	Δ-4-androstendione
Δ iSFA-mSFA	Shoulder angle excursion

Thesis at a glance

	Question	Methods	Results	Conclusions
I	Are rowers with previous RSF characterized by reduced BMD compared to matched controls?	DEXA-scan of Total and regional BMD in 7 rowers with previous RSF and 7 matched controls.	L2-L4 BMD was reduced by 12.9 % in RSF subjects compared to matched control rowers, but normal compared to a reference population.	As the lumbar spine is heavily loaded by rowing, L2-L4 BMD might be an indicator of skeletal adaptation to rowing. A BMD above normal might decrease the risk of RSF.
II	Are rowers with previous RSF different from matched controls regarding co-contraction of thoracic muscles, movement patterns and leg/arm strength ratio?	EMG analysis of thoracic muscles and 2-D video analysis during ergometer rowing and measurement of elbow-flexion to knee-extension strength ratio in 7 rowers with previous RSF and 7 matched control rowers.	RSF subjects displayed increased co-contraction of m. serratus and m. trapezius in the mid-drive phase, increased velocity of the seat in the initial drive phase and stronger arms relative to legs compared to controls.	The results indicated increased force applied by the upper body muscles in RSF subjects, thereby supporting the suggested injury mechanisms of rib cage compression and excessive isometric contraction of thoracic muscles in the drive phase.
III	Does a relationship between testosterone levels and BMD exist in elite male lightweight rowers?	DEXA-scan of Total and regional Body combined with measurement of androgen hormones and other blood parameters potentially related to BMD in 13 elite male lightweight rowers.	Total Body and L2-L4 BMD were positively correlated to both years of training and total testosterone (TT). After controlling for years of training a correlation between L2-L4 BMD and TT remained.	BMD in elite male lightweight rowers may be influenced by testosterone levels. However, the high levels of BMD despite lower levels of testosterone indicate that the mechanical stimulation from rowing is probably more important to BMD than testosterone levels.
IV	Does ergometer rowing in slides lead to changed biomechanics of the rowing stroke?	Measurement of handle force and position during ergometer rowing with and without slides at identical exercise intensity in 8 female and 14 male National Team rowers	Peak Handle Force was significantly reduced during slide rowing in both male and female rowers.	Ergometer rowing in slides might be hypothesized to reduce the risk of overuse injuries such as RSF due to decreased force production in each rowing stroke without compromising training intensity and performance.
V	Does ergometer rowing in slides lead to changed neuromuscular activation?	Measurement of handle force and position as well as EMG from muscles suggested to be involved in the development of RSF during ergometer rowing with and without slides at identical exercise intensity in 14 male National Team rowers	Different neuromuscular activation was observed for m. serratus, m. deltoideus m. vastus lateralis and m. tibialis anterior. Peak Force and peak muscle activation of thoracic muscles coincided during the early drive phase regardless of ergometer condition.	Slide rowing changed the neuromuscular activity of the leg muscles more than the thoracic muscles. The rib cage compression theory is supported by the observed timing of Peak Force and peak thoracic muscle activation.

Introduction

Rowing

Rowing as a sport can be dated back to the beginning of the 16th century in England and is thus the oldest modern organized sport (89). Since then the sport of rowing have naturally evolved dramatically regarding equipment, training and competitions but essentially the concept has remained the same. Rowing is one of the 5 sports included in all modern Olympic Games and today the Fédération Internationale des Sociétés d'Aviron (FISA) have more than 125 national rowing federations as members indicating that rowing is a world wide sport (www.worldrowing.com official FISA website).

Competition and Training

Rowing is an endurance sport with a demand for high muscular strength (78). All rowing competitions are performed over a distance of 2000 m with corresponding race-times of approximately 6-8 minutes depending on weather conditions and boat type. The rowing performance and success in skilled competitive rowers are closely related to maximal aerobic capacity (78). Consequently, elite rowers perform excessive amounts of training to achieve optimal physiological adaptations to meet the biomechanical requirements of the rowing stroke in terms of force, power and cadency. More than 1100 hours of training per year corresponding to over 20 hours for 50 weeks have been reported (38). To optimize rowing skills i.e. achieve optimal timing of muscular contractions and coordination of body segments the training is almost exclusively focused on rowing either on-water or using land-based rowing ergometers.

Lightweight rowing

Since the above physical demands clearly favor tall and muscular rowers (48) lightweight rowing was invented in 1925 and became an Olympic discipline in 1996 (77). In lightweight rowing the average male crew weight is limited to 70 kg and no individual rower can weigh more than 72.5 kg. The corresponding weight limits for female rowers are 57 kg and 59 kg, respectively, and weigh-in is conducted 2 hours prior to competition. Lightweight rowers, who are tall, have greater muscle mass and less fat mass tend to be most successful (79). To comply

with the weight limits the majority of lightweight rowers have been reported to employ both chronic and acute weight-loss strategies such as dieting, skipping of meals, fluid restriction and increased sweat production (sauna or exercise) (80, 85, 87). This may affect performance (81), bone turn over (87, 98), ovarian hormone function (67) and testosterone levels (32).

Biomechanics of rowing

A rowing shell is a narrow, lightweight, keel-less vessel fitted with riggers. Each of the up to 8 rowers controls one (sweep rowing) or two (sculling) oars. The rowers are seated on sliding seats facing the stern, feet strapped to the stretcher and oars locked in the riggers. Consequently, the rowers are enabled to use the legs to increase stroke length and generate more force. The riggers compensate for the narrow shell locating the oarlock outside the rowing shell (outrigger) thus providing a more optimal gearing of the oar.

The rowing stroke is usually divided into the drive phase, during which the propulsive force is generated, and the recovery phase when the rower slides back in preparation for the next drive phase. The drive phase can be divided into the catch, the mid-drive and the finish (Figure 1). The catch is when the oar enters the water, the mid-drive is when maximal propulsive force is generated and the oar is perpendicular to the boat and the finish is when the oar is removed from the water.

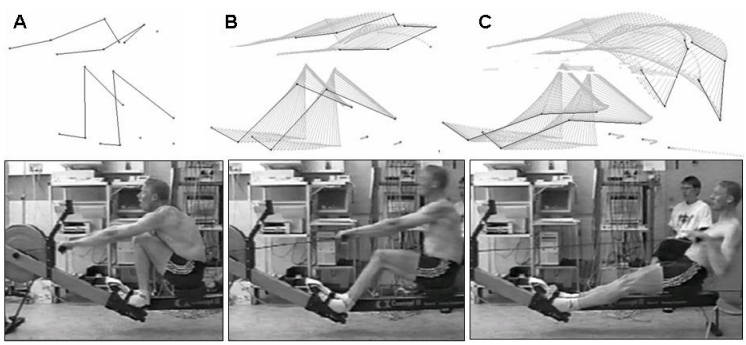


Figure 1. The drive phase of the rowing stroke divided into the catch (A), the mid-drive (B) and the finish (C). Stick diagram from 3-D video analysis of ergometer rowing (unpublished material) and pictures from 2-D video analysis of ergometer rowing (*Study II*).

Depending on the detail of the analysis the drive and recovery phases can be divided into a number of equidistant phases, respectively (53).

Rowing ergometers

The rowing ergometer was invented in the mid 19th century and has been commonly used by rowers for land-based training and testing since the 1950s (77). The modern rowing ergometers simulate on-water rowing quite well regarding force production and movement patterns of body segments except for the hands and forearms (35, 56). Consequently, the rowing ergometer is widely used for testing, crew selection and training of elite rowers (47). The Danish National Team rowers use rowing ergometers for approximately 1/3 of the total training volume to reach an internationally competitive level. In addition, ergometer rowing has become a widely used exercise modality in recreational training and fitness. Consequently, it seems highly important to examine whether training in rowing ergometers represents an elevated risk of musculoskeletal overuse injury. In support of this notion, a recent prospective investigation of injury incidence in elite rowers found that the risk of overuse injury was positively associated with the time spent by ergometer training (95). The Concept2 rowing ergometer (Concept2, Morrisville, VT, USA) is the most commonly used ergometer in both of the aforementioned settings. The oar is replaced by a handle connected by a chain to a wind resisted flywheel and the rower is placed on a sliding seat with the feet on a stretcher very similar to a rowing shell. Thus, the exercising rower moves while the ergometer remains stationary. However, the entire ergometer can be placed in slides (Figure 2), which enables the ergometer to move back and forth beneath the rower thereby imitating the movements of a rowing shell on the water. Biomechanical investigations have indicated that placement of the ergometer in slides results in altered stroke rate and/or force production at the handle (Larsen AH and Jensen K. *In manuscript*). These findings are in concordance with previous investigations of ergometer biomechanics in a RowPerfect ergometer (RowPerfect, Hardenberg, The Netherlands), where a free-floating stretcher mechanism provides a similar opportunity of the ergometer to slide relative to the subject (16, 27).

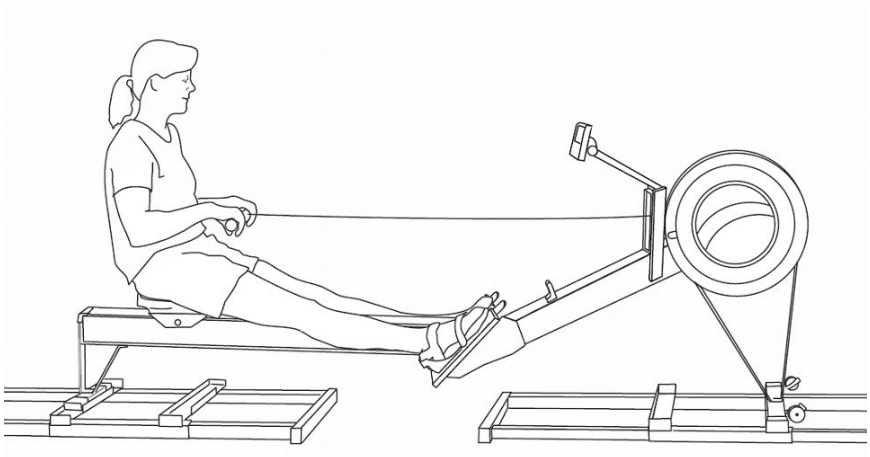


Figure 2. The Concept2 ergometer placed in slides. During slide-based rowing the ergometer moves to the right during the drive phase (while the rower moves slightly to the left) and to the left (while the rower moves slightly to the right) during the recovery phase of the rowing stroke, hence mimicking the movement of the boat during actual rowing. (Line drawing used by permission from www.concept2.com, August 26th 2008)

Rib stress fractures

Definition of a stress fracture and stress fracture pathology

"A stress fracture can be defined as a partial or complete bone fracture that results from repeated application of stress lower than the stress required in order to fracture the bone in a single loading" (19).

Bone stress can be defined as the load or force applied per unit area and results in bone deformation known as bone strain (20).

According to the above definitions stress fractures are developed over time when the natural process of bone remodeling is unable to compensate for (repair) the accumulating microdamage caused by a combination of the repetitiveness of the bone strain, the strain rate, the strain magnitude and the limited periods of recovery allowed between exposure to the bone strain (92). Consequently, stress fractures develop along a continuum starting with asymptomatic accelerated remodeling of bone. As osteoblastic bone formation is always preceded by osteoclastic bone resorption and an entire cycle of bone remodeling can take up to 4 months including a period of weakened bone during the resorption and reversal phases, accelerated remodeling may lead to further accumulation of microdamage if the bone stress is continued (20). Further accumulation of microdamage may progress into a stress reaction causing mild pain at the end of the training sessions. At this time point MRI and bone scan usually can detect the injury. If aggravating activity is continued pain may be felt earlier in the training sessions and persist for some time after the training session as a stress injury develops and progresses into a stress fracture causing pain throughout the training session and at rest. In this case, CT and X-ray imaging can visualize either callus formation or a defined fracture line. A last point in this injury continuum could eventually be a complete fracture if the athlete is able to continue the activity despite pain and discomfort. (20).

Rib stress fracture epidemiology

The first report of rib fracture due to muscular strain - in particular related to excessive coughing - dates back to 1773 as reported by Derbes et al. (33) providing in 1954 a review of cases of rib fractures not related to trauma. Several more recent case reports describe rib stress fractures related to coughing due to infections (31, 51, 71) and due to exposure to high altitude in combination with strenuous exercise (59). Rib stress fractures have also been observed during pregnancy (36,

8). During the last 40 years rib stress fractures have been observed in athletes participating in different sports: Golf (45, 60, 61, 74, 75), swimming (86), squash (70), river paddling (66), canoeing (63), tennis (45), gymnastics (45) and rowing (18, 23, 25, 39, 43, 45, 50, 64, 72, 91) Warden et al. (92) summarized the rib stress fractures observed in rowers in 2002 providing an excellent overview of most if not all reported cases: By 2002 seventy-nine (56 female and 23 male; elite: 86 %) were reported to have sustained 87 rib stress fractures located in the ribs (costae) c2 to c10 (93 % in the ribs c4-c8). Scullers and sweep rowers were equally represented. In addition, 15 (at least 14 male) cases were reported by Iwamoto et al. in 2003 (46) and in 2007 Smoljanović et al. reported 2 cases (84) and Dragoni et al. reported 9 cases (34) – all in male rowers. Consequently, by 2008 rib stress fractures have been documented in the scientific literature for a total of 105 rowers – the number of male rowers almost equalling the number of female rowers. However, only a single study (43) reported gender specific incidence and found female rowers to have a substantially elevated incidence of rib stress fractures.

Rib stress fracture diagnosis

Rib stress fractures are characterized by a history of exercise related thoracic, back or shoulder pain of more or less insidious onset (25). The onset of pain is described as a dull ache with a more sharp pain provoked by deep inspiration, couching and the aggravating exercise (rowing). Nightly pain related to side lying on the affected side and rolling over in bed is often reported (72, 77). Often the rower is able to pinpoint the exact location of the pain (24).

Clinical examination includes palpation of the ribs. A tender point localized directly on a rib in combination with pain at the exact same spot reproduced by antero-posterior and/or lateral compression of the thorax usually indicates the presence of a rib stress fracture (72).

X-ray imaging is rarely able to confirm the presence of rib stress fractures before callus formation has been formed 2-3 months after debut of symptoms (77). Thus, 99m Technetium MDP (methylene-diphosphonate) bone scan is the investigation of choice (25, 72) and a focal uptake of the radioactive tracer localized to the affected rib, as illustrated in Figure 3, can be used to confirm the diagnosis of a rib stress fracture. The vast majority of reported rib stress fractures have been diagnosed by a bone scan.

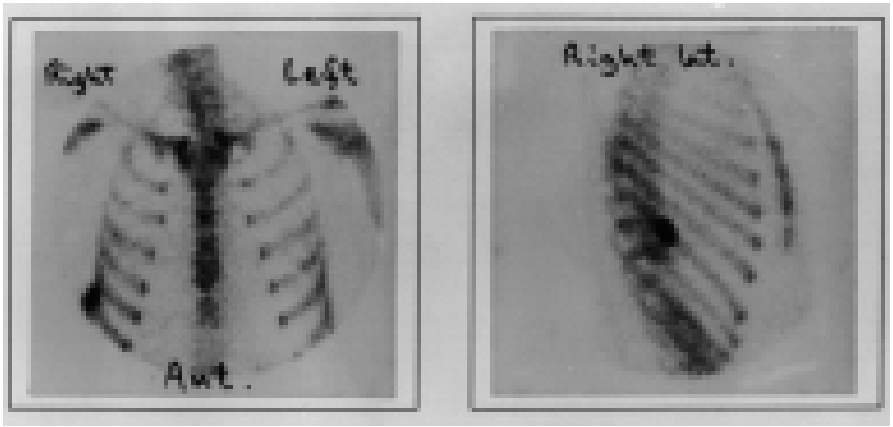


Figure 3. 99m Technetium MDP bone scan of a right sided rib stress fracture in a Danish National Team rower.

CT-scan (23) and sonography (34) have also been used to verify the presence of rib stress fractures whereas MRI has not been used.

Recently, Smoljanović and Bojanić reported a bone tumor located in the rib of a young rower initially misdiagnosed as a rib stress fracture (83). Consequently, an algorithm for the diagnosis and treatment of rib stress fractures with special emphasis on malignant differential diagnosis was also presented.

Rib stress fracture management

Normally a symptom dependent approach is taken involving a period of complete rest followed by a period of non-rowing exercise and eventually a gradual return to rowing (25, 72, 77). During this period pain and discomfort can be treated by analgesics (25), electrotherapy (72) as well as icing, thoracic spine mobilisation and strapping with tape (90). The use of NSAID should be avoided as it has been indicated to slow down fracture healing in animal models (94). Typically, rowing training is gradually resumed after 2-6 weeks of relative rest (24, 25, 72, 77). Consequently, rib stress fractures have been reported to cause the most time lost from training and competition in elite rowers (77, 92). A more aggressive management strategy involving no or a very short period of rest and intensified treatment of pain including constant strapping have been used in rowers in the lead-up to or during major competitions (90). This approach is reported to compromise pain relief to maintain performance level of the crew (90), which is in conflict with the general practice in stress fracture management in athletes where rule number one is to modify activity (12). No reports of non-union or other severe complications to rib stress fractures has been reported in the literature (22).

Potential risk factors

Risk factors for stress fractures can be divided into intrinsic risk factors (characteristics of the athletes) and extrinsic risk factors (characteristics of the environment) (21). The following intrinsic risk factors for rib stress fractures in rowers have been suggested: Low BMD (43, 45), altered bone geometry (92), menstrual disturbances (43) mobility of thoracic joints, mobility of other joints in the kinetic chain of rowing and insufficient rowing experience (92). Moreover, it was hypothesized in this thesis that rowers characterized by strong arms and upper body may achieve a relatively increased contribution to the total power output from their arms and upper body thereby potentially loading their ribs excessively. In addition, bone turnover, nutrition, reduced sex hormone production, low physical fitness, muscular strength and endurance, respectively, as well as genetic predisposition are also suggested as risk factors for stress fracture development in general (21).

Risk factors related to the structural competence of bone deserve special attention as the ability of the bones to withstand and benefit from mechanical loading is crucial for stress fracture prevention. In osteoporosis the relationship between reduced BMD and increased risk of fractures is well known (21) also regarding the risk of rib fractures (55). In younger, bone healthy and physically active individuals (athletes or military recruits) low BMD as an independent risk factor for stress fracture development is less evident although still present especially in females (15). Bone size and geometry also contribute significantly to bone strength and has been documented to be related to stress fracture incidence in both male military recruits (10) and runners (29) as well as in female military recruits (11). Bone structural properties may be influenced by sex hormones as seen in the female athlete triad where amenorrhea and reduced serum estrogen may lead to bone demineralization and stress fractures (17). As generally lowered levels of testosterone is observed in endurance trained male athletes (40) a similar mechanism regarding testosterone levels and BMD has been suggested to be present in male endurance trained athletes (13, 40) but only a few studies have found relationships between testosterone levels and BMD in male athletes (49, 93). In addition to sex hormones all other endocrine parameters related to bone metabolism and calcium homeostasis such as Parathyroid Hormone (PTH), cortisol, Thyroid Stimulating Hormone (TSH), phosphorus, creatinine, alkaline phosphastase, leptin and 25-Hydroxyvitamin D_3 may be important for the structural competence of bone.

The following extrinsic risk factors for rib stress fractures in rowers have been suggested: Any type of change in training, however small it might seem (25), oar type (25, 92), shaft length and gearing of the oar, boat size and speed, crew experience and specific weight training exercises (92), especially the bench pull exercise have received much attention regarding rib stress fracture development (72, 92).

Suggested injury mechanisms

It has been suggested that rib stress fractures in elite rowers may be the result of repeated high-force muscular contractions during the rowing stroke (92). Different injury mechanisms involving the m. serratus anterior (SA), m. obliquus externus abdominis (OEA) and the shoulder retractors either alone or in concert have been presented (92). In particular, the oppositely directed traction of SA and OEA at the end of the drive phase has received much attention as it potentially generates shear forces at the bony attachments (50, 64, 91). Further, it has been suggested that OEA alone could induce rib stress fractures at the end of the drive phase (91) it is unclear whether the co-contraction of SA and OEA should be considered detrimental (50, 64) or protective (92). It was hypothesized that the isometric contraction of the thoracic muscles at the beginning of the drive phase may inflict excessive stress forces to the ribs while transmitting the force generated by the legs to the oar (25). Moreover, Warden et al. (92) suggested that this force transmission would generate a shoulder protraction moment that has to be resisted by the shoulder retractors, which in turn results in a rib cage compression moment (Figure 4). The force of both the isometric contraction of the thoracic muscles and the rib cage compression moment have been suggested to increase during the use of the more efficient "big blade" oar that was introduced in 1991 (25, 92). Moreover, it has been suggested that greater degree of shoulder flexion in the beginning of the drive might increase the loading of the rib cage resulting from both the isometric contraction of the thoracic muscles and the rib cage compression moment (Personal communication: Bent Jensen, former Danish National Team Coach). In a commonly used rowing style, which likely is associated with increased shoulder flexion angle in the beginning of the drive, the drive is initiated by extension of the knees followed by extension of the hip and trunk in a sequential manner. This style is called the Rosenberg style and is usually characterized by higher peak force development compared to rowing styles with a more simultaneous timing of knee, hip and trunk extension (53).

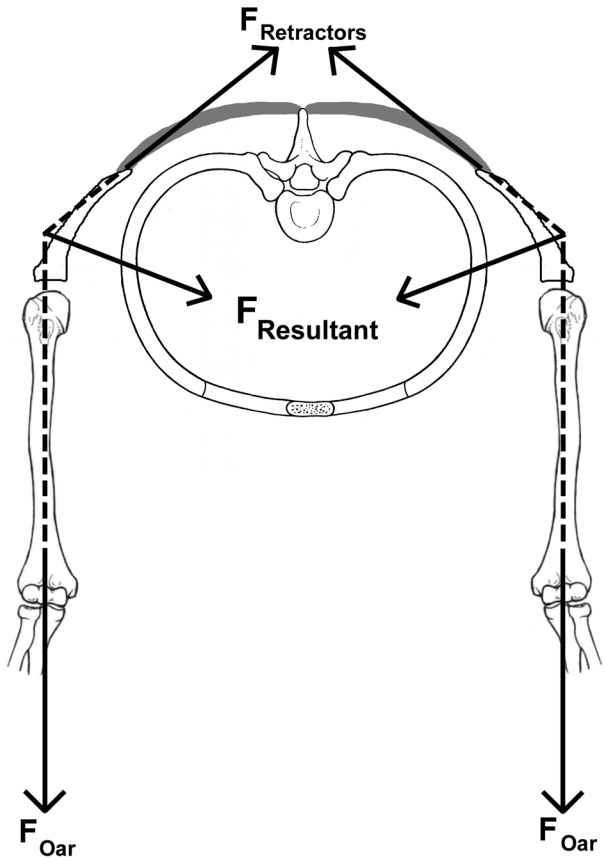


Figure 4. The rib cage seen from above at the level of the shoulder girdle illustrating the rib cage compression theory: F_{Oar}: Force vector generated by the pull of the oar on the arms of the rower generating a shoulder protraction moment. $F_{Retractprs}$: Force vector generated by the muscles retracting the scapula to resist the shoulder protraction moment. $F_{Resultant}$: The resultant force of F_{Oar} and $F_{Retractors}$ calculated by the parallelogram method generating a rib cage compression moment. (Used with permission from Warden SJ – November 9th 2008)

Prevention of rib stress fractures

Prevention of sports injuries including rib stress fractures in rowers is a main objective for athletes, coaches and medical personal. The physiotherapist has the potential to play a very important role in sports injury prevention in general and in the prevention of rib stress fractures in elite rowers in particular. In collaboration with the coaches and rowers the physiotherapist can ideally evaluate the potential detrimental and protective effects of the overall planning of training

intensity and volume during the season as well as smaller alterations in rowing technique and equipment used by the rowers. This is, however, strongly dependent on the knowledge of injury mechanisms, potential risk factors and preventive measures available to the physiotherapist and the ability of the physiotherapist to critically appraise and use this information.

The methodological approach to injury prevention research has received much attention during the past 20 years and several models have been presented. van Mechelen et al. (88) introduced a cyclic four step model: Step 1: Establishing the extent of the problem (incidence and severity). Step 2: Establishing the aetiology and mechanisms of sports injuries. Step 3: Introducing a preventive measure. Step 4: Assessing its effectiveness by repeating step 1. As step 2 of this model is absolutely critical to a successful intervention Meeuwisse presented a model on how to assess the aetiology and mechanisms of sport injuries including both intrinsic and extrinsic risk factors as well as mechanisms of injury (65). In this model athletes predisposed to injury can ideally be identified if knowledge of intrinsic risk factors is present. If the extrinsic risk factors also are known, athletes susceptible to injury can be identified among the predisposed athletes. Finally, the inciting event involving the mechanism of injury results in injury. This model has been further developed into a more comprehensive model with more focus on the biomechanical aspects of the injury mechanism in combination with sport specific information regarding the inciting event (7). The focus on the inciting event make these models well suited for evaluation of acute injuries, whereas the injury mechanism may not be related to just one inciting event in overuse injuries such as stress fractures. In this case "the inciting event" may actually be several weeks of training and competition. Consequently, it may be difficult to know which factors to modify through a prevention strategy unless all causative factors are known (7).

As described above, multiple intrinsic and extrinsic risk factors as well as several different and sometimes conflicting injury mechanisms for rib stress fractures in rowers have been suggested. None of these risk factors or injury mechanisms have, however, been verified as causative of rib stress fractures either alone or in combination and the aetiology of rib stress fractures has been described as multifactorial (92). Thus, before any preventive measures can be taken more investigations need to be conducted to examine the causative and predisposing factors for exercise-induced rib stress fractures in rowers.

Objectives

A. To investigate potential risk factors and suggested injury mechanisms involved in the development of exercise-induced rib stress fractures in elite rowers.

B. To investigate biomechanical and neuromuscular differences of ergometer rowing in stationary and sliding ergometers to indicate if the choice of ergometer may have implications for risk of injury.

Specific aims A:

1. To compare BMD of elite rowers with and without previous rib stress fracture (RSF) to investigate the hypothesis that the RSF subjects were characterized by reduced BMD.
2. To compare neuromuscular activation of thoracic muscles in elite rowers with and without previous RSF during ergometer rowing to investigate the hypothesis that the RSF subjects were characterized by increased co-contraction of m. Serratus Anterior and m. Obliquus Externus Abdominis.
3. To compare kinematic parameters related to rowing technique during ergometer rowing in elite rowers with and without previous RSF to investigate the hypothesis that the RSF subjects were characterized by increased velocity of the seat and increased shoulder flexion in the initial drive phase.
4. To compare knee extension strength to elbow flexion strength ratio in elite rowers with and without previous RSF to investigate the hypothesis that the RSF subjects were characterized by relatively increased elbow flexion strength compared to knee extension strength.
5. To investigate the potential existence of a relationship between BMD and testosterone levels of elite male lightweight rowers.
6. To investigate the timing of peak neuromuscular activity of muscles potentially involved in the development of exercise-induced RSF relative to the timing of peak handle force during stationary ergometer rowing and slide-based ergometer rowing at identical power outputs.

Specific aims B:

1. To investigate the hypothesis that placement of the rowing ergometer in slides would lead to increased stroke rate, decreased peak and mean force of the rowing stroke while possibly also affecting Rate of Force Development at identical power outputs.
2. To exploratively compare the magnitude and patterns of neuromuscular activity of muscles potentially involved in the development of exercise-induced RSF during stationary ergometer rowing and slide-based ergometer rowing at identical power outputs.

Subjects and study design

Twenty-nine rowers from the Danish National Team participated in the experiments described in *Study I, II and III*, which all were conducted prior to the 2000 Olympics in Sydney. The sample included 7 female heavyweight rowers (1 with previous RSF), 4 female lightweight rowers (1 with previous RSF), 5 heavyweight male rowers (no previous RSF) and 13 male lightweight rowers (5 with previous RSF). To retrospectively investigate differences between rowers with previous RSF and rowers with no history of RSF using a matched-pairs case-control design (*Study I and II*), controls matching the 7 rowers with previous RSF regarding gender, age, height, weight and number of years of elite training were chosen among the 21 remaining rowers. The relatively strict criteria for the matching set out prior to the matching process left no space to potential bias during selection – only one combination of subjects was possible. All 13 male lightweight rowers were included in a cross sectional descriptive investigation of BMD and its potential correlation to testosterone levels (*Study III*).

Twenty-two rowers from the Danish National Team including 2 male lightweight rowers from the previous experiments participated in the experiments described in *Study IV and V* conducted prior to the 2007 World Championships in Munich. The sample included 3 female heavyweight rowers (no previous RSF), 5 female lightweight rowers (1 RSF 5 months after the investigation), 5 male heavyweight rowers (1 with previous RSF) and 9 male lightweight rowers (2 with previous RSF). All 22 rowers were included in *Study IV* whereas only the 14 male rowers were included in *Study V*. Both studies were based on a randomized cross-over design investigating differences between two rowing ergometers and, consequently, the subjects served as their own controls.

An overview of the subjects is provided in Figure 5. Detailed description of the subjects included in the studies is provided in *Study I-V*. Generally the rowers were of international standard competing at World Cups, World Championships and the Olympics. Of the 22 rowers included in the 2007 experiments 13 went on to compete at the 2008 Olympics in Beijing and 10 of the 29 rowers from the 2000 experiments competed in either the 2000 or 2004 Olympic Games.

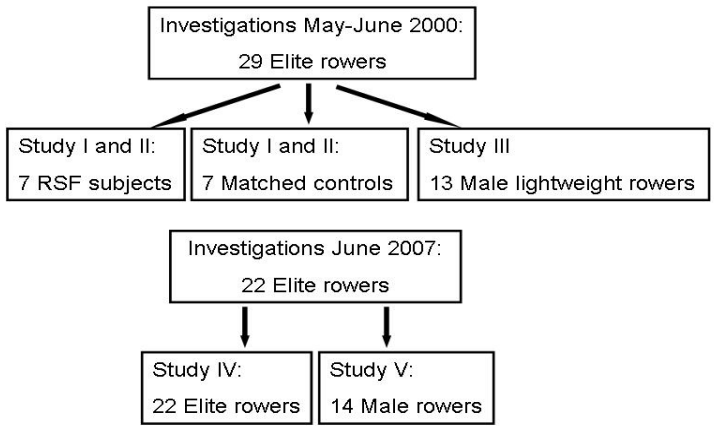


Figure 5. Overview of the investigations, studies and subjects of the thesis. Detailed description of the subject characteristics is provided in study I-V.

Methods

An overview of the different measurements used in the *studies I-V* is presented in Table 1.

Table 1. Measurements used in studies I-V

	Study I	*Study II*	*Study III*	*Study IV*	*Study V*
BMD	**X**		**X**		
Hormonal parameters			**X**		
Muscle strength		**X**			
Movement patterns		**X**			
Neuromuscular activity		**X**			**X**
Handle Force				**X**	**X**
Handle Position				**X**	**X**

Measurement of Bone Mineral Density (BMD) (Study I and III)

The BMD of the total body, femoral neck bilaterally, L2-L4 and the distal radius of the dominant arm was measured by Dual Energy X-ray Absorptiometry (DEXA) (Lunar Corporation, Madison, WI). The measurements performed in our lab have previously been found to be as reliable (CV 1.5 %) as stated by the manufacturer (42)

BMD results are presented in g cm^{-2} and in percent of a young adult Caucasian reference population given by the DEXA software. Lean Body Mass (LBM) and percent Body Fat were obtained from the whole body DEXA scans.

Analysis of blood samples (Study III)

Blood samples were collected between 8 and 9 in the morning in the beginning of the competitive season. No restrictions regarding exercise or diet were set out prior to testing. Blood samples analyzed for Total Testosterone (TT), Dihydrotestosterone (DHT) and Sex Hormone Binding Globulin (SHBG) were allowed to clot for 30 minutes at room temperature before being centrifuged for 10 minutes at room temperature and then stored at -80° Celsius. TT and DHT were meas-

ured by an in-house radioimmunoassay after extraction and subsequent celite chromatography. Inter- and intra-assay variation was for testosterone 13.8% and 8.2 %, respectively and for DHT 11.0 % and 9.1%, respectively. The sensitivity limit for both analyses was 0.05 nmol l^{-1} (62). SHBG was analyzed by a double monoclonal immunofluorometric assay (AutoDelfia, Wallac OY Finland). Inter- and intra-assay variation was 7.5 % and 5.2 % (62). Free Testosterone (FT) was estimated based on measurement of SHBG, TT and DHT and the use of the law of mass action, using the binding constant of testosterone and DHT to SHBG, and including a calculation of testosterone binding to albumin (9).

The following parameters were examined to exclude abnormalities potentially affecting BMD: Dehydroepiandrosterone-sulfat (DHAS), Δ-4-androstendione (4-AD), Parathyroid Hormone (PTH), cortisol, Leptin and 25-Hydroxyvitamin D_3 were determined using specific, single-antibody solid phase radioimmunoassay (RIA) kits specific for each hormone. Immunoradiometric assay (IRMA) was used to analyze estradiol, Adrenocorticotrophic Hormone (ACTH), calcium and calcitonin whereas Lutenizing Hormone (LH) and Follicle Stimulating Hormone (FSH) were analyzed by use of immunofluorometri. Moreover, Thyroid Stimulating Hormone (TSH), phosphorus, creatinine, alkaline phosphastase, haemoglobin and haematocrit were measured.

Measurement of isokinetic muscle strength (Study II)

To calculate the ratio between elbow flexion strength and knee extension strength concentric isokinetic (30°/sec) muscle strength was measured at (100 Hz) using a Biodex System II isokinetic dynamometer (Biodex Medical Systems Inc., Shirley, New York, USA). The measurements were preceded by a standardized warm-up procedure and the right side was tested in all subjects. The subjects were seated in a rigid chair and strapped to the seat at the chest, hip and distal thigh. The seat and backrest were adjusted to fit the individual subject and the dynamometer rotation axis was visually aligned to the lateral femoral condyle of the knee or the lateral humeral epicondyle of the elbow. Knee joint range of motion (ROM) was 90° to 5° (0° = full extension) while elbow joint ROM was 10° to 100° (0° = full extension). Three trials were performed with submaximal effort to ensure that no discomfort was caused by the straps or the chosen adjustment of the seat and backrest. Data were sampled while the subject performed three successive cyclic repetitions of either knee extension or elbow flexion with maximal effort. The highest peak joint torque (Nm) of the three trials for knee extension and elbow flexion, respectively, was used to calculate the strength ratio.

Movement analysis (Study II)

To measure the kinematical movement pattern in the sagittal plane the subjects were video taped during the final of two minutes of high-intensity steady-state ergometer rowing when EMG signals also were recorded. A standard video camera recorder (Panasonic S-VHS 625) operating at 50 Hz was placed perpendicular to the rowing ergometer at a standardized distance. Since a sampling frequency of 25 Hz generally is considered adequate for analysis of cyclic human movement (i.e. gait analysis (96) 50 Hz was considered to be sufficient for analysis of the relatively slow movement of rowing.

Subsequently all video recordings were off-line digitized and two-dimensional coordinates were calculated by direct linear transformation (Ariel Performance Analyzing System, version 3.7). Three consecutive drive phases were analyzed for each subject.

The start of the drive phase was defined as the first video frame where any posterior directed movement of the seat, the handle or the back of the rower was visually detectable. This frame and the following 49 frames were then digitized (i.e. covering a full second), which comprised an entire drive phase in all rowers.

The following points were manually plotted at each video frame during analysis: The ergometer fly-wheel axis was plotted as a fix-point and the handle, the back edge of the seat, the lateral epicondyle of the elbow, the acromion of the shoulder and a point in the mid-axillary line above the iliac crest was plotted as points of interest. The point above the iliac crest was placed making a straight line between the shoulder point and this point as parallel to the line of the thoracic spine as possible. This enabled quantification of the shoulder joint angle with respect to flexion and extension.

A digital 4th order zero-lag Butterworth low-pass filter was used to smooth all coordinate signals (96). A 6 Hz cutoff frequency was chosen since no frequency contents above or close to this threshold was observed in the coordinate signals. A spectral analysis was performed on the digitized (x,y) marker positions to further check the effectiveness of the filtering procedure and make sure that only unwanted noise was removed from the signal.

Each plotted sequence was calibrated using a 2-D calibration frame of known dimensions located in the field of veiw. The digitized data were transferred to the MATLAB software package version 3.5 (Mathworks) for further analysis.

The shoulder angle was calculated in degrees, 0° = arm parallel to the body – hand pointing downwards – and 180° flexion = arm parallel to the body – hand pointing upwards. Calculations were made with respect to flexion (positive values) and extension (negative values) throughout the 50 frames in each of the three drive phases analyzed in each subject. The following variables were calculated from the kinematic analysis: Maximum shoulder flexion angle (mSFA),

initial shoulder flexion angle (iSFA), shoulder angle excursion (Δ iSFA-mSFA). Moreover, frame to frame velocity of the seat and handle during the entire drive phase and average velocity in the initial 0-60 ms (first three frames) were calculated.

Measurement of neuromuscular activity (Study II and V)

Surface EMG analysis was performed in *Study II and V*. An identical experimental setup was used in both studies, however the muscles analyzed and the subsequent data analysis differed slightly between the studies, as explained below.

Study II and V:

EMG signals were digitally recorded in successive sweeps of six seconds duration at a sampling frequency of 1000 Hz. Bi-polar electrodes (Medicotest N-00-S, Oelstykke, Denmark, two cm inter-electrode distance) were placed over muscles on the right side of the body. Prior to placement of the electrodes the skin was shaved and cleaned with alcohol to reduce skin impedance. Proper placement of electrodes was tested prior to and during warm up on the rowing ergometer.

All EMG signals were digitally high-pass filtered with a cut-off frequency of 4 Hz (*Study II*) or 5 Hz (*Study V*) (4^{th}-order zero-lag Butterworth filter) and subsequently a moving symmetrical RMS (Root Mean Square) filter with a 50 ms time constant was used to smooth the signals (1). To enable comparison of neuromuscular activity between subjects and to minimize the effect of amplitude cancellation and to increase the reliability of the measurements, all EMG signals were normalized to the peak RMS EMG signal amplitude recorded during maximal rowing (more details given below). Recent studies have demonstrated that changes in EMG interference signal amplitude may be caused by altered patterns of temporal motor unit action potential (MUAP) summation that might occur for instance due to changes in muscle fiber geometry during the shortening and lengthening muscle actions and/or in case of systematic modulation in motor-unit firing synchronization (30, (37, 52, 97). However, the use of standardized EMG normalization procedures, as was employed in the present study, have been shown to greatly reduce (practically eliminate) the methodological problem of MUAP amplitude cancellation inherently associated with surface EMG recording (52). Maximal RMS EMG signal amplitudes (EMGmax) were obtained in two trials mimicking a start sequence performed with maximal effort using maximal ergometer resistance and complete stand still of the ergometer flywheel prior to initiation of the first rowing stroke. This procedure was chosen as rowers consistently produced greater muscle EMG signal amplitudes during the starting strokes compared to those measured during a MVC procedure of each muscle separately (unpublished results).

The maximal EMG signals were visually checked and maximal RMS EMG signal amplitudes arising from poor signal quality were discarded and if possible replaced by the maximal amplitude from another trial. If no valid maximal RMS EMG amplitude was available, the RMS EMG of the respective muscle could not be normalized and it was excluded from the analysis.

Procedures specific to Study II:

Analyzed muscles were m. Serratus Anterior (SA), m. Obliquus Externus Abdominis (OEA), m. Trapezius Middle fibers (TM) and Lower fibers (TL). Placement of electrodes: SA: Over the fleshy attachments on the sixth and seventh ribs – one electrode over each digitation. OEA: Medial to – and aligned with – the costal arch not involving m. Rectus Abdominis. TM: Medial to the superior angle of the scapula, TL: Medial to the inferior angle of the scapula close to the spine – each pair of electrodes horizontally aligned.

An external trigger was used to synchronize all data sampling relative to the catch and finish of each rowing stroke. Four data sweeps each covering two complete cycles, were sampled during the final minute of two minutes steady-state high-intensity rowing (stroke rate 28, 500 m time approximately 1 min 40 s for male rowers and 1 min 50 s for female rowers, self-chosen resistance, intensity ~ 95-100 % VO_2max (57). An example of raw EMG signals from one subject is shown in Figure 6.

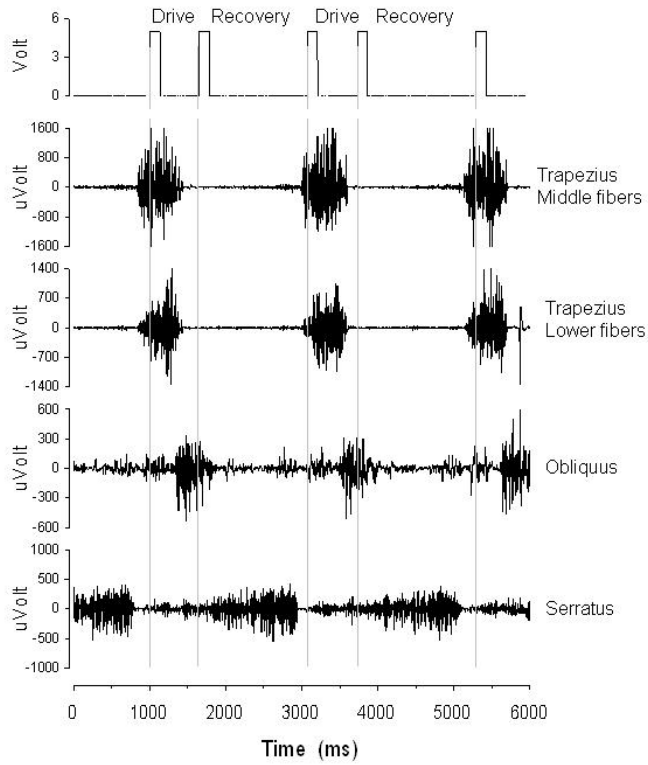


Figure 6. Raw EMG recording from various thoracic muscles during high-intensity steady-state ergometer rowing. Two rowing stroke cycles are shown. The drive and recovery phases are marked by the trigger signal (top panel).

Mean RMS EMG activity was analyzed for each muscle within the 1/3 fractions of the drive (i.e. propulsive) phase of the rowing stroke and within the 1/3 fractions of the recovery phase (76). Eight full rowing strokes were recorded in total. During subsequent analysis all EMG signals were normalized to the maximal EMG response: EMG signal amplitude / EMG_{max}*100%, abbreviated *EMG signal / EMG_{max}*. Group mean averages and median values of each of the 6 sub-phases subsequently were calculated for the RSF group and the control group, respectively.

Procedures specific to Study V:

Analyzed muscles were TM, TL, SA, OEA, m. Latissimus Dorsi (LD), m. Deltoideus Posterior fibers (DP), m. Vastus Lateralis of m. Quadriceps Femoris (VL) and m. Tibialis Anterior (TA). Placement of electrodes: TM: Medial to the superior angle of the scapula, TL: Medial to the inferior angle of the scapula close to the spine, SA: Over the digitation covering the sixth rib, OEA: Medial to the costal arch not involving the Rectus Abdominis muscle, LD: Over the most prominent part of the lateral/dorsal part of the muscle belly, DP: Over the posterior 1/3 of the muscle midway between the acromion and the humeral insertion, VL: Anterior to the iliotibial band approximately 1/3 of the distance between the lateral femoral epicondyle and the greater trochanter, TA: Over the most prominent part of the muscle belly approximately 1/3 of the distance from the apex patellae to the lateral malleolus.

Trials were performed with and without slides in randomized order at freely chosen stroke rate. For both trial types subjects were instructed to maintain 75-80 % of the average power output produced during a 6 minute maximal (all-out) rowing test, which was obtained on a separate occasion (47). Visual feedback of power output was provided by the ergometer display and each trial lasted approximately 3 minutes and 30 seconds. Resistance setting of the ergometer (drag factor) was identical in the trials using the subjects' habitual setting. 4 separate sweeps of 6 seconds duration during each trial were sampled and stored on a personal computer. Data sampling was commenced after approximately 30 seconds of each trial when the subjects rowed at a steady state. Sampling of EMG signals was synchronized with measurements of handle force and handle position and the beginning and the end of each drive and recovery phase was defined by the handle position data. Each recorded sweep contained roughly two rowing strokes depending on the stroke rate chosen by the subjects, comprising two complete drive phases of the rowing stroke and at least 1 complete recovery phase. Each sweep was visually checked and only complete recovery phases were analyzed. Consequently, 8 drive phases and 4-8 recovery phases were analyzed from each trial.

Normalized average RMS EMG output from each muscle during 0-25 %, 25-50 %, 50-75 % and 75-100% of the drive and recovery phases, respectively, was calculated adding a sub-phase to both the drive and the recovery compared to Rodriquez et al. (76). Moreover, the timing and magnitude of peak normalized RMS EMG amplitude were analyzed for each muscle.

Measurement of handle force and displacement (Study IV and V)

A custom-built light weight strain-gauge transducer was inserted between the handle and the chain to measure the magnitude of handlebar force production while a commercial available potentiometer was used to measure the displacement of the handle (P6500 series, Novotechnik, Ostfildern, Germany). The output voltage of the strain gauge was checked at loads of 10, 20, 45, 55, 80 and 105 kg resulting in a perfectly linear ($r=0.998$, $p<0.001$) Volt-to-Newton calibration equation ($N = 9.81 \cdot [30 \cdot V + 0.14]$). Similarly, the potentiometer was calibrated at 0.2, 0.4, 0.6, 0.8 and 1 m of displacement resulting in a linear ($r=0.995$, $p<0.001$) Volt-to-Meter equation: ($M = 0.34 \cdot V + 0.0035$). These calibration equations were used in a custom made MATLAB program and used to process the recorded data and calculate handle force and position. During the process of post-hoc analysis (Matlab) 4^{th}-order zero-lag Butterworth low-pass filters with cut-off frequencies of 15 Hz and 50 Hz were used to filter the potentiometer and force signals, respectively.

From the handle force and displacement data the following variables were calculated: Stroke Rate (SR), Power output, Peak Force (PF), Mean Force of the drive phase (MF), PF/MF-ratio, Time to PF, length and time of drive and recovery, Rate of Force Development (RFD) and time from initiation of the drive phase to onset of force (catch slip). The time to peak force was defined as the time elapsed from the beginning of the drive phase to the time of peak force. The onset of force was defined as the point in time when the handle force exceeded 1.5 % of peak force in male rowers and 2.0 % of peak force in female rowers. Different values for male and female rowers were chosen to match the difference in measured peak forces between male and female rowers. Three different measures of Rate of Force Development ($RFD = \Delta force / \Delta time$) were calculated: 1) Average RFD from onset of force to peak force, 2) average RFD between 10-30 % of peak force (Initial Slope - iRFD), and 3) average RFD in 50-70 % of peak force (Late Slope - lRFD). These calculations were chosen to evaluate differences in total RFD as well as in early and late phase RFD of the bell shaped force curve typically seen in the drive phase of the rowing stroke (Figure 7).

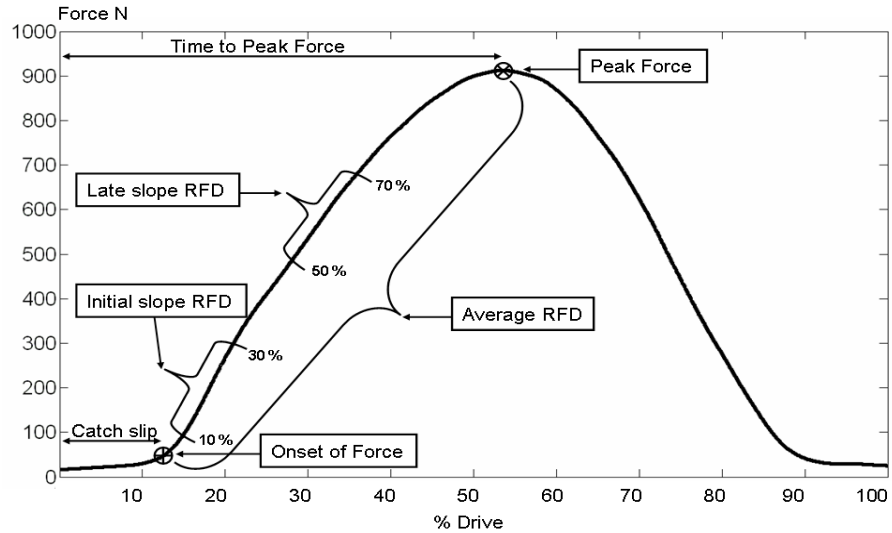


Figure 7. Average force curve from one subject during stationary ergometer rowing illustrating the majority of the measured parameters. The x-axis represents the entire drive phase defined by the handle position: 0 = Handle position closest to the flywheel denoted "The catch" and 100 = Handle position the greatest distance from the flywheel denoted "The finish".

In *study V* a third trial was performed in the stationary condition but with a stroke rate, which was matched to that used in the slide-based trial. This was done to investigate the impact of the expected change in stroke rate. As this trial felt somewhat awkward to the rowers the clinical relevance seemed rather small and consequently, the results are only provided in *study V* and not in the thesis.

Statistical analysis

In the Thesis all results are presented as mean ± SD. In the studies mean ± SEM (*Study I, II, IV and V*), median and range (*study I, II and III*) as well as mean and 95 % CI (*Study IV*) are also used.

In *Study I and II* statistical comparisons between the RSF group and the matched control group were performed using the Wilcoxon signed ranks test for paired samples. All correlation analyses were performed using the Spearman's rho test (4). The level of significance was set at p = 0.05. In *Study III* Spearman's rho was also used for both simple and partial correlation analysis (5). Correlations were only calculated for the variables of interest if possible associations were indicated by visual inspection of the scatterplots.

In *Study IV* Students T-test was used to examine differences between male and female rowers. After checking for equal variances a repeated measures ANOVA with post hoc Bonferroni corrected comparisons (6) was used to identify

differences between the three different ergometer conditions for the pre-selected main outcomes. Shapiro-Wilk test (2) was used to assess the normality of the residuals. In all but two cases normality was verified. As thorough inspection of these two cases did not give rise to any concerns that the non-normal distribution might affect the results of the statistical evaluation, data were analyzed parametrically as described above.

In *Study V* comparisons between the two analyzed ergometer conditions were performed using paired samples T-tests (3).
SPSS version 7.5 was used for the statistical analysis in *Study I-III* while version 15 was used in *Study IV and V*.

Ethics

Written informed consent was obtained from all participants prior to the investigations after approval from the regional ethics committee. In accordance with the Helsinki declaration the health and well being of the participants had the highest priority throughout the investigations. The exercise protocols used were generally considered to be less strenuous than a normal training session typically performed by the rowers (personal communication).

Results

Potential risk factors

BMD (Study I)

L2-L4 BMD was reduced by 12.9 ± 10.0 % (p=0.028) in rowers with previous RSF compared to age and gender matched controls (rowers without a history of RSF). No differences in BMD were observed between RSF subjects and controls at specifc sites of interest (femoral neck, distal radius) or for the total body. When the BMD was expressed as % of a normal young adult reference population the RSF subjects generally displayed BMD close to normal: Total Body: 101.1 ± 5.0 %, L2-L4: 99.1 ± 10.0 %, Femoral Neck: 98.2 ± 7.4 % and Distal Radius 92.1 ± 19.0 %, whereas the control subjects generally displayed BMD above normal: Total Body: 106.9 ± 8.5 %, L2-L4: 115.3 ± 9.8, Femoral Neck: 108.2 ± 19.3 and Distal Radius: 105.4 ± 13.0 %.

BMD and testosterone in male lightweight rowers (Study III)

Significant positive correlations between TT and Total Body BMD (r_s: 0.56 p= 0.046) as well as L2-L4 BMD (r_s: 0.63, p=0.021, Figure 8) were observed. Moreover, L2-L4 BMD was correlated to FT (r_s: 0.62, p=0.024) and 25-Hydroxyvitamin D_3 (r_s: 0.64, p=0.019). Total Body and L2-L4 BMD also correlated to years of training (r_s: 0.59, p=0.034 and r_s: 0.73, p=0.005, Figure 9, respectively). After controlling for years of training by calculation of partial correlation the relationship between TT and L2-L4 BMD remained present (r_s: 0.61, $p<0.05$). No correlations were observed between serum testosterone levels and BMD of the femoral neck or the distal radius, respectively.
TT serum concentration (16.9 ± 5.8 nmol l^{-1}) was in the lower part of the normal range (10.3 – 27.4 nmol l^{-1}) while BMD was close to or above the normal young adult reference population (Total Body: 102 ± 5 % L2-L4: 104 ± 11 %). Leptin concentration (1.2 ± 0.2 ng ml^{-1}) was below the normal range (2 – 5.6 ng ml^{-1}) in all subjects. Generally all other examined blood parameters related to bone health remained within or very close to normal range values in all subjects.

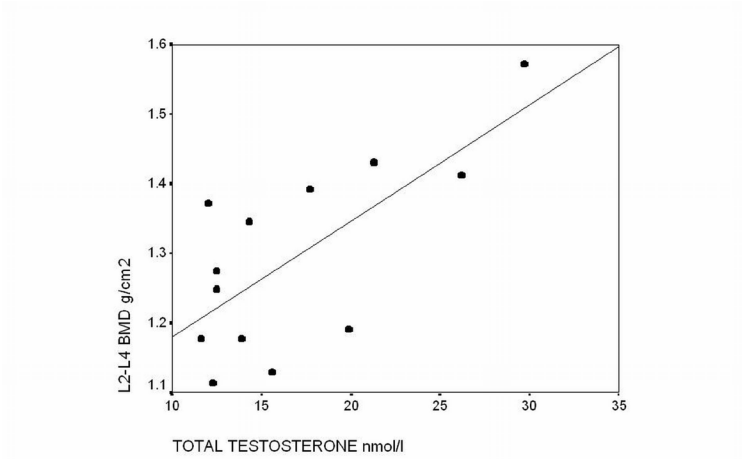


Figure 8. Correlation between L2-L4 BMD and Total Testosterone in 13 male lightweight rowers: r_s: 0.63, p=0.021

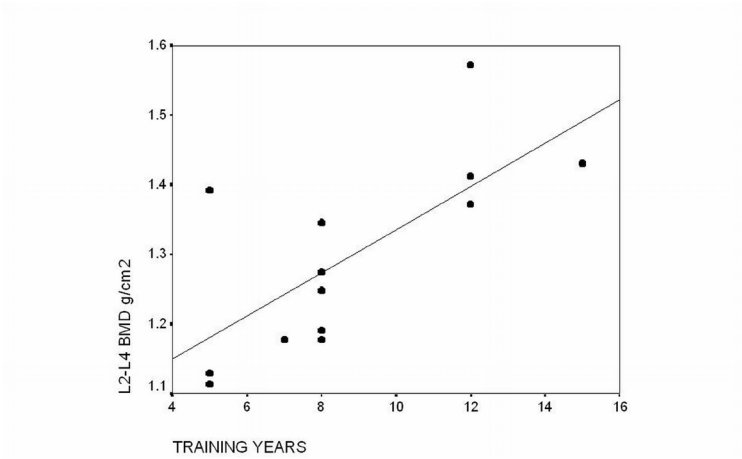


Figure 9. Correlation between L2-L4 BMD and years of elite rowing in 13 male lightweight rowers: r_s: 0.73, p=0.005

Leg-to-arm muscle strength ratio (Study II)

A reduced knee-extensor to elbow-flexor muscle strength ratio was observed in the RSF subjects (4.2 ± 0.6) compared to their matched controls (4.8 ± 0.4) (p=0.043) indicating that RSF subjects had elevated arm muscle strength compared to their level of leg muscle strength. Knee-extension peak torque and elbow-flexion peak torque did not differ between RSF and control subjects.

Suggested injury mechanisms

Rowing technique (Study II)

Different velocity patterns of the seat and handle were observed in the two subject groups in the initial 0-60 ms of the drive phase. Thus, increased velocity of the seat in the initial 0-60 ms was observed in RSF subjects (0.25 ± 0.07 $m \cdot s^{-1}$) compared to controls (0.15 ± 0.15 $m \cdot s^{-1}$) (p=0.028) resulting in a trend for an elevated differential velocity of the seat relative to the handle in RSF subjects (0.18 ± 0.22 $m \cdot s^{-1}$) compared to controls (–0.01 ± 0.17) (p=0.075).

Although the handle velocity in the initial 0-60 ms of the drive was inversely correlated to both the shoulder angle excursion (Δ iSFA-mSFA) (r_s = -0.70 p=0.011) and the time at mSFA (r_s = -0.81 p=0.001) no differences in shoulder angle parameters were observed between RSF subjects and controls.

Neuromuscular activity (Study II)

No significant differences in neuromuscular activity of individual muscles were observed during the rowing stroke between RSF subjects and their matched controls. Notably, the magnitude and timing in SA and OEA muscle co-contraction did not differ between RSF subjects and controls in the late drive phase. However, differences in muscle co-contraction were observed between SA and TL in the mid-drive phase of the stroke: *EMG signal overlap*: RSF 47.5 ± 9.0 % versus controls 30.8 ± 17.2 % (p=0.043) with corresponding *EMG signal overlap / EMG*$_{max}$ values of: RSF 16.6 ± 8.5 % and controls 13.4 ± 8.5 %. The mean *EMG signal overlap / EMG*$_{max}$ value for SA-TL of 16.6 % observed for RSF was among the highest recorded in the present study, illustrating that SA-TL co-contraction was generated at a relatively high level of muscle activity. The highest *EMG signal overlap / EMG*$_{max}$ value observed was 22.6 ± 12.4 %, which was found between SA and TM also in the mid-drive phase in RSF subjects.

Examination of individual patterns of co-contraction of the thoracic muscles revealed differences between the male lightweight rowers (RSF-male) with previous rib stress fractures and their matched controls (C-male). All five RSF-male subjects showed substantially elevated levels of muscle co-contraction as measured by *EMG signal overlap* of SA-TM (45.6 ± 23.7 %) and SA-TL (44.2 ± 18.6 %) in the mid-drive phase compared to their matched controls (SA-TM: 21.9 ± 6.3 %, p=0.043) and (SA-TL: 23.4 ± 11.4 %, p=0.043).

Timing of neuromuscular activity and force production (Study V)

Maximal neuromuscular activity (peak RMS EMG amplitude) of the thoracic muscles involved in scapula retraction occurred very close to the time of Peak Handle Force both in stationary ergometer rowing and sliding based ergometer rowing, respectively. Regardless of ergometer condition the average absolute time

differences between Peak Force and Peak RMS EMG of TM, TL, DP and LD were between 45 ± 40 ms and 116 ± 56 ms (LD and TL, respectively) corresponding to ≤ 5 % of the entire rowing stroke.

Stationary ergometer rowing vs. ergometer rowing in slides

Force production (Study IV)

The relative response to slide rowing differed between male and female rowers: Compared to stationary ergometer conditions the peak force decreased 8.4 ± 3.3 % in male rowers vs. 3.1 ± 2.2 in female rowers (p=0.001) and stroke rate increased 9.5 ± 4.3 % in males vs. 2.7 ± 2.9 % in females (p=0.001). Consequently, male and female rowers were analyzed separately.

Both male and female rowers maintained similar power outputs and heart rate during stationary and slide-based ergometer rowing: Males: Stationary: 319 ± 26 W and 155 ± 8 bpm, Slides: 321 ± 25 W and 157 ± 10 bpm. Females: Stationary 213 ± 17 W and 159 ± 8 bpm, Slides 213 ± 19 W and 161 ± 7 bpm.

Compared to stationary ergometer rowing male rowers increased stroke rate from 25.9 ± 1.2 strokes pr. minute to 28.7 ± 1.7 during sliding based ergometer rowing (p<0.0001), while decreasing Peak Force from 887 ± 87 N to 811 ± 74 N (p<0.0001) and Mean Force from 437 ± 32 N to 412 ± 29 N (p<0.0001). In addition, iRFD was lower (p=0.0024) during stationary ergometer rowing (4701 ± 1128 N/s) compared to ergometer rowing in slides (5098 ± 1219 N/s). Conversely, lRFD was greater (p=0.002) during stationary than slide-based rowing ergometry (3216 ± 376 N/s vs 2513 ± 460 N/s), indicating a substantial shift in the ascending part of the force-time curve during slide-based rowing. In female rowers, Peak Force decreased (p=0.013) from 632 ± 53 N during stationary ergometer rowing to 612 ± 52 N during sliding based ergometer rowing. All other variables examined remained similar between ergometer conditions in the female rowers.

Neuromuscular activity (Study V)

Average normalized RMS EMG activity of TM, TL, OEA and LD during each quarter of the drive phase and recovery phase of the rowing stroke generally remained highly similar between slide based and stationary ergometer conditions (Figure 10). In contrast, average normalized RMS EMG activity (%EMGmax) differed between ergometer conditions (i) for SA in the 3rd quarter of the recovery phase: Stationary: 21.9 ± 7.4 vs. Slides: 31.9 ± 11.7 (p=0.027), (ii) for DP in the 3rd quarter of the drive phase: Stationary: 47.3 ± 12.4 vs. Slides: 39.0 ± 13.7 (p=0.013), (iii) for VL in the 1st quarter of the drive phase and the 4th quarter of the recovery phase: Stationary: 58.9 ± 19.6 and 20.2 ± 11.4, respectively, vs. Slides: 51.4 ± 15.1 (p=0.007) and 7.1 ± 3.2 (p<0.001), respectively, and (iv) for

TA in the 2nd, 3rd and 4th quarter of the recovery phase: Stationary: 20.8 ± 8.8, 12.6 ± 10.2 and 5.3 ± 3.0, respectively, vs. Slides: 16.0 ± 7.3 (p=0.016), 26.2 ± 16.8 (p=0.001) and 16.3 ± 12.5 (p=0.003), respectively (Figure 11).

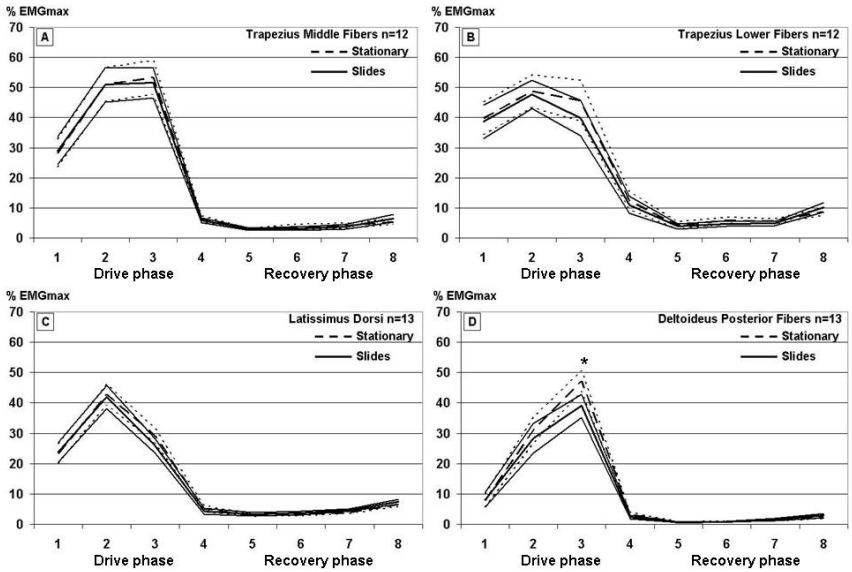


Figure 10. Neuromuscular activity (average normalized RMS EMG amplitudes ± SEM) measured during the rowing stroke. Time phases 1-4 constitutes quartiles (25% cycle time periods) of the drive phase while time phases 5-8 constitutes quartiles of the recovery phase. The solid lines represent muscle activity during slide based ergometer rowing and the dashed lines represent stationary ergometer rowing. * Denotes statistical significant differences between slides and stationary ($p<0.05$), exact p-values provided in results section. A: M. Trapezius Middle Fibers. B: M. Trapezius Lower Fibers. C: M. Latissimus Dorsi. D: M. Deltoideus Posterior Fibers

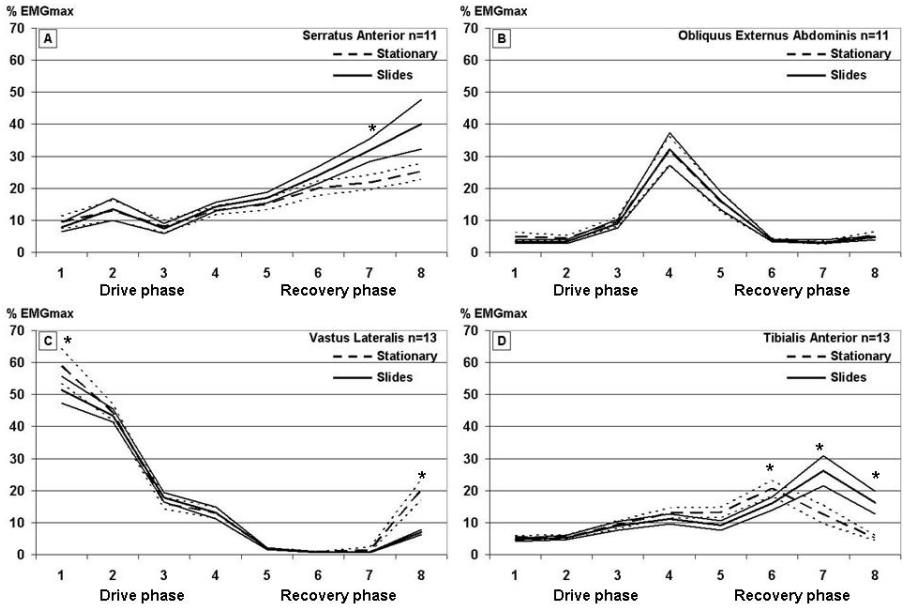


Figure 11. Neuromuscular activity (average normalized RMS EMG amplitudes ± SEM) measured during the rowing stroke. Time phases 1-4 constitutes quartiles (25% cycle time periods) of the drive phase while time phases 5-8 constitutes quartiles of the recovery phase. The solid lines represent muscle activity during slide based ergometer rowing and the dashed lines represent stationary ergometer rowing. * Denotes statistical significant differences between slides and stationary ($p<0.05$), exact p-values provided in results section. A: M. Serratus Anterior. B: M. Obliquus Externus Abdominis. C: M. Vastus Lateralis of m. quadriceps. D: M. Tibialis Anterior.

In addition, peak normalized RMS EMG activity (%EMGmax) differed between ergometer conditions for SA: Stationary: 46 ± 14 vs. Slides: 72 ± 45 ($p=0.045$), as well as for VL: Stationary: 88 ± 28 vs. Slides: 79 ± 19 ($p=0.0049$) and TA: Stationary: 35 ± 11 vs. Slides: 49 ± 27 ($p=0.039$).

Discussion

Potential risk factors

BMD (Study I)

Although the BMD of all scanned regions (including the total body BMD) seemed reduced in RSF subjects compared to their matched controls, only the difference in L2-L4 BMD was able to reach statistical significance. It shall be emphasized that BMD of the ribs, which would be highly interesting, could not be measured due to practical reasons. The small subject sample and the retrospective study design are strong limitations of the investigation and although the result indicate that reduced BMD may increase the risk of rib stress fractures in elite rowers this finding needs to be verified in larger prospective investigations. Low BMD has previously been associated with increased incidence of stress fractures of the lower extremities in athletes and military recruits (11, 14, 58, 69, 73,), however, only a single study have exclusively investigated male subjects (73). Consequently, the relationship between BMD and stress fracture incidence in male individuals remains unclear.

The fact that the most marked difference in BMD between RSF subjects and controls was found at the lumbar spine is interesting. As outlined below the BMD of the lumbar spine in rowers may reflect the magnitude of skeletal adaptation to the mechanical loading induced by rowing: It is well known that mechanical stimuli induced by dynamic loading above a certain threshold are needed to promote bone formation and that the effect of stimulation is site specific (54). The biomechanics of the rowing stroke has been reported to impose substantial mechanical loading on the skeleton – and in particular on the structures of the lumbar spine (68). Consequently, elevated lumbar spine BMD has been reported in male rowers compared to controls and triathletes (82). Moreover, 7 months of rowing training in novice male rowers led to increased BMD at L1-L4 and elevated whole-body BMC, whereas specific BMD remained unchanged for the femoral neck, the greater trochanter and Ward's triangle (26). Thus, providing support for specific loading of the lumbar spine and not the proximal femur associated with rowing.

BMD and testosterone in male lightweight rowers (Study III)

BMD of the Total Body and Lumbar spine was correlated to both TT and years of training in the 13 male lightweight rowers. After calculation of partial correlation to control for years of training only the correlation between L2-L4 BMD and TT remained significant. Generally, the rowers exhibited testosterone levels in the lower range of the normal values similar to those previously reported in endurance trained male athletes (41) including a previous study report in rowers (82) but not the study by Jürimäe et al. (49), who reported higher levels of testosterone in a different group of rowers. In the present study BMD was close to or above that of a normal young adult reference population and positively correlated to years of training suggesting that the potential influence of fluctuations in the lower part of the normal range of testosterone levels was a less important determinant for BMD than the magnitude of mechanical loading on the lumbar spine (68) induced by years of rowing.

The very low levels of serum leptin observed in the present study may be explained by the fact that leptin is correlated to body fat (28) even in lean athletes (44) as was the case with the present lightweight rowers. Similarly, Jürimäe et al. (48) reported low levels of leptin and a similar lack of association between leptin and BMD in their group of rowers.

Caloric restriction and other weight loss regimes often are employed by lightweight rowers (80, 85, 87), which may negatively affect both bone turn over (87, 98) and serum testosterone levels (32). Thus, these aspects deserve special attention in future studies of bone health in endurance trained male athletes with implicit or explicit weight limits

Leg-to-arm muscle strength ratio (Study II)

An elevated ratio of elbow-flexor to knee-extensor muscle strength was observed in the RSF subjects compared to matched controls. Assuming that RSF subjects and controls have similar rowing capacities (i.e. similar maximal power outputs) RSF subjects may achieve a larger contribution to this total power output from their arms than controls, which could be speculated to result in elevated muscular strain and stress forces at the ribs. No previous studies have been conducted to examine the upper-body to lower-body muscle strength ratio in rowers, and hence more experimental studies are needed to clarify the potential influence from this factor on stress factor incidence in rowers. Interestingly, stronger muscles have been proposed to prevent lower extremity stress fractures due to attenuated ground reaction forces potentially protecting the weight bearing bones from cyclic overloading (20). However, different injury mechanisms may well exist for bone stress fractures induced by rowing and running, respectively

Suggested injury mechanisms

Rowing technique (Study II)

Despite that an increased velocity of the seat in the initial drive phase was recorded in RSF subjects no differences were observed in the maximal shoulder flexion angle or shoulder excursion angle between RSF subjects and controls. Consequently, the hypothesis of increased shoulder flexion angle as a risk factor for rib stress fractures was not supported. The increased velocity of the seat in the RSF subjects may indicate employment of a more sequential motor strategy conforming to the Rosenberg style of rowing, which is associated with development of greater peak force compared to rowing styles with a more simultaneous timing of knee, hip and trunk extension (53). No previous studies have been conducted to examine the potential association between different styles of rowing and rib stress fracture incidence.

Neuromuscular activity (Study II)

The level of muscle co-contraction for SA and OEA in the final drive phase did not differ between RSF subjects and their matched controls. Consequently, the hypothesized injury mechanism of oppositely directed forces induced on the ribs by SA and OEA at the end of the drive phase (50) was not supported by the present data as the RSF subjects did not exhibit increased SA-OEA co-contraction.

Increased SA-TL co-contraction at high levels of neuromuscular activity was observed in RSF subjects compared to control subjects. This was especially evident in the male lightweight rowers with previous RSF, as they exhibited consistently increased co-contraction of both SA-TL and SA-TM in the mid-drive phase compared to their matched controls. Although the retrospective study design preclude knowledge of pre-injury muscle activation patterns and magnitudes of co-contraction and that it cannot be excluded that the rowers have changed their rowing technique due to rib stress fracture symptoms, the present findings lend support to the hypothesis of excessive thoracic muscle co-contraction in the drive phase as one potential cause of rib stress fractures (25).

Timing of neuromuscular activity and force production (Study V)

The observed timing of Peak handle Force and peak EMG activity of the thoracic muscles bears potential implications for the development of exercise-induced rib stress fractures. The present observations provide support for the rib cage compression theory (92) as well as the theory regarding excessive co-contraction of the thoracic muscles (25). Both injury mechanisms suggest potential detrimental rib loading to occur in the first half of the drive phase. In fact, the two suggested mechanisms of injury are tightly linked as the rib cage compression

theory implies that the shoulder protraction moment, which is closely related to the force at the handle, is resisted by the scapula retractors including LD. Contraction of the LD muscle might *per se* cause significant rib cage compression as it is wrapped around the rib cage from its wide origin (Fascia Thoracolumbalis extending from the lower 6 thoracic vertebrae to the iliac crest) to its insertion on the proximal humerus. Of all thoracic muscles included in the present analysis LD displayed the smallest time delay between Peak EMG activity and Peak Handle Force indicating almost simultaneous peak of the shoulder protraction moment and peak neuromuscular activation of LD. Moreover, the timing of peak neuromuscular activity for the scapula retractor muscles relative to the timing of Peak Force at the handle remained similar between stationary and slide-based ergometer conditions indicating a potential association between the timing of Peak EMG activity and Peak Handle Force regardless of rowing equipment.

Stationary ergometer rowing vs. ergometer rowing in slides

Force production (Study IV)

Peak and Mean Force decreased in combination with increased stroke rate in male rowers during sliding based ergometer rowing compared to stationary ergometer rowing at identical external power outputs. Similar but less pronounced trends were observed in female rowers, where Peak Force was the only parameter that reached statistical significance. In support of the present findings previous investigations of force production using a different type of slide-based rowing ergometer have yielded comparable biomechanical differences between stationary and sliding ergometer conditions (16, 27).

In addition to the above differences in peak and mean force production the shape of the force-time curve also differed between slide-based and stationary ergometer conditions in male rowers. Thus, an elevated RFD was observed in the initial part of the drive phase (10-30 % Peak Force) during sliding based compared to stationary ergometer rowing. Conversely, a reduced RFD was observed in the late phase of rising force (50-70 % of Peak Force) in the sliding condition.

The observed decreases in Peak handle Force and late slope RFD in the high-force region of the drive phase during slide-based rowing ergometry may be speculated to have implications for the risk of rib stress fracture development. According to the rib cage compression theory these findings are likely to result in decreased strain magnitude and strain rate on the rib cage suggested to arise from the shoulder protraction moment (92).

The unexpected differential responses to sliding based ergometer rowing observed between male and female rowers may result from differences in body weight.

In support of this notion, a study conducted in female elite rowers (Danish National Team) with a body weight comparable to that of male lightweight rowers yielded biomechanical responses that were more similar to that observed for the male rowers of the present investigation (Larsen AH and Jensen K. *In manuscript*).

Neuromuscular activity (Study V)

In *Study V* the observed neuromuscular activity patterns during stationary ergometer rowing generally were highly similar to those previously reported (76, 91) and the present *Study II*.

No significant differences between stationary and sliding based ergometer rowing were observed for the thoracic muscles (TM, TL, OEA, LD) in terms of the pattern of neuromuscular activity (EMG) or the magnitude of peak EMG activity. Increased neuromuscular activity was observed during ergometer rowing in slides for SA and TA during the (low-intensity) recovery phase of the rowing stroke. Conversely, during ergometer rowing in slides decreased levels of neuromuscular activity were observed for VL and DP during the initial drive phase/late recovery (VL) as well as in the mid-drive phase (DP). Specifically, the latter findings offers an explanation for the reductions in Peak Handle Force and late-phase RFD, respectively, observed in sliding-based compared to stationary eregometer conditions.

No previous study has investigated the pattern(s) of neuromuscular activity of selected thoracic muscles during sliding based ergometer rowing, and the present investigation (*Study V*) may be viewed as purely exploratory. The observed differences could, however, generally be explained by differences in the amounts of weight that was accelerated and decelerated in the slide-based ergometer condition (ergometer ≈ 35 kg) vs the stationary ergometer condition (body weight ≈ 70-100 kg).

Overall Conclusions

A. Reduced BMD compared to non-injured elite rowers may be a risk factor for exercise-induced rib stress fractures. The potential injury mechanism involving oppositely directed forces induced on the ribs by m. Serratus Anterior and m. Obliquus Externus Abdominis was not supported by the results of the present investigations, which were more in line with the rib cage compression theory in combination with the theory of excessive contraction of the thoracic muscles as potential injury mechanisms. Prospective studies are needed to further elucidate these and other potential risk factors and injury mechanisms.
B. Ergometer rowing in slides led to decreased Peak Force at the handle compared to stationary ergometer rowing at identical power outputs while affecting the patterns of neuromuscular activity of the leg muscles more than those of the thoracic muscles.

Specific conclusions A

1. The hypothesis that elite rowers with previous rib stress fractures were characterized by a reduced BMD compared to non-injured matched elite rowers was supported by the results of the present investigations.
2. The hypothesis that elite rowers with previous rib stress fractures were characterized by increased simultaneous neuromuscular activity of m. Serratus Anterior and m. Obliquus Externus Abdominis compared to non-injured matched elite rowers was not supported by the results of the present investigations.
3. The hypothesis that elite rowers with previous rib stress fractures were characterized by increased velocity of the seat in the initial drive phase compared to non-injured matched elite rowers was supported by the results of the present investigations. This was, however, not associated with increased shoulder flexion angle as initially hypothesized.
4. The hypothesis that elite rowers with previous rib stress fractures were characterized by relatively increased elbow flexion strength compared to knee extension strength was supported by the results of the present investigations. It remains speculative if this finding represents a potential risk factor for exercise-induced rib stress fractures.
5. A significant correlation between BMD and testosterone levels was found in elite male lightweight rowers. However, the mechanical load-

ing induced by years of elite rowing was a stronger governing factor on BMD than serum testosterone *per se*.

6. Almost simultaneous timing of peak neuromuscular activation of the scapular retractor muscles and peak force at the handle was observed regardless of ergometer condition. This supported the rib cage compression theory in combination with the theory of excessive contraction of the thoracic muscles as potential injury mechanisms.

Specific conclusions B

1. The hypothesis that placement of the rowing ergometer in slides would lead to increased stroke rate, decreased peak and mean force of the rowing stroke at identical power outputs was supported by the present results obtained in the male rowers. Female rowers displayed a similar but attenuated response to slide-based ergometer rowing, probably due to their lower body mass.
2. The neuromuscular activity in selected thoracic muscles potentially involved in the development of exercise-induced rib stress fractures was generally unaffected by slide-based ergometer rowing compared to stationary ergometer rowing except during the relatively unloaded recovery phase of the rowing stroke. However, during stationary ergometer conditions elevated leg extensor (Vastus Lateralis) muscle activity were observed during the initial drive phase, suggesting that handlebar force production and thus rib stress forces may be elevated in this particular condition.

Perspectives

The present Thesis intends to expand our knowledge on the following areas in the field of rib stress fracture research: Risk factors, injury mechanisms and injury prevention.

Based on the present investigations reduction in BMD appears to represent a potential risk factor for rib stress fractures and it may prove worthwhile to measure BMD in elite rowers with rib stress fracture to enable optimization of bone health in subjects with BMD below or even when close to normal age and gender matched reference populations. This could include assessment of relevant hormone levels (i.e. testosterone in male athletes) and evaluation of nutritional strategies (or lack hereof) in both male and female athletes. Thus, in the clinical setting assessment of BMD in uninjured elite rowers may prove an effective screening tool for future exercise-induced rib stress fracture. However, the observed association between BMD and stress fracture risk may be too weak and the knowledge regarding BMD in athletic populations too limited to justify generalized screening in the absence of clinical or pre-clinical symptoms (21).

Regarding the injury mechanism of rib stress fractures (RSF) the present investigations have presented data that support the theory of rib cage compression in the early drive phase as an important factor potentially related to the etiology of rib stress fracture. In contrast, the present findings lends no strong support to the hypothesis that oppositely directed rib stress forces induced by co-contraction of m. Serratus Anterior and m. Obliquus Externus Abdominis are responsible for the development of stress fracture. This knowledge might prove important in future investigations of potential preventive measures as these potential mechanisms of injury are rather different and warrants different strategies for potential modification.

If rib stress fractures are developed as a result of an excessive number of cyclic compressions of the rib cage arising from the repeated pulling movement of rowing, ergometer rowing in slides may be suggested to reduce the strain magnitude and strain rate due to decreased force production at the handle. However, during slide based rowing ergometry an increased number of loading cycles are produced per time unit as the stroke rate is increased. Moreover, it is unknown if sliding based ergometer rowing can have any beneficial or detrimental influence on the risk of developing rib stress fractures during actual on water rowing.

The present investigations generated a number of new hypothesis regard-

ing both risk factors and injury mechanisms, which potentially could inspire to future research projects. According to the four step model of sports injury prevention research presented by van Mechelen et al. the second step: Establishment of risk factors and injury mechanisms is critical for introduction of effective preventive interventions (88). The research in the field of rib stress fracture prevention in rowing has not yet completed the second step and consequently, more knowledge of potential risk factors should be achieved using prospective investigations conducted in large cohorts of elite rowers, for which multi-center investigations seem necessary.

Specific prospective randomized controlled trials are needed to test potential preventive RSF measures such as sliding-based ergometer rowing. Ideally this should be done in the same research setting as the investigations of risk factors to i) test the preventive measures in the same environment as that in which the selected risk factors were obtained and ii) use similar methods of data collection as used in the previously conducted investigations. If possible, complementary assessment techniques (i.e. isotope bone scan) may be added with benefit.

As the need for research described above comprise biomechanical investigations of movement and neuromuscular activity as well as investigations of the ability of the bones to adapt to the loading placed on them by the repetitive movements of rowing this must be an appealing area of research for sports physiotherapists, who are well suited to play a key role in this type of investigations collaborating with specialists in the relevant areas of research, the coaches and last but not least the rowers.

Abstract

The aim of this thesis was (i) to investigate potential risk factors and suggested injury mechanisms involved in the development of exercise-induced rib stress fractures (RSF) in elite rowers, and (ii) to investigate biomechanical and neuromuscular differences of ergometer rowing performed in stationary vs. sliding ergometer conditions.

BMD and isokinetic muscle strength were assessed along with electromyography (EMG) signals recorded in selected thoracic muscles and rowing technique during ergometer rowing in elite rowers with previous RSF (n=7) and in matched controls (n=7). The results indicated that the RSF subjects were characterized by reduced lumbar spine BMD, increased co-contraction of thoracic muscles, increased elbow-flexion strength relative to knee-extension strength and increased velocity of the ergometer seat during the initial drive phase of the rowing stroke. The retrospective nature and the small material of the studies preclude any strong conclusions and prospective investigations including larger materials are needed to further elucidate the potential risk factors and injury mechanisms

Testosterone levels and BMD were measured in male lightweight rowers (n=13). Correlations between BMD and testosterone levels as well as years of training were found. Relatively high levels of BMD indicated that the mechanical stimuli from several years of rowing were more important to BMD than the relatively low levels of testosterone. Testosterone was, however, correlated to lumbar spine BMD after controlling for years of training and further studies of hormonal and nutritional factors associated with BMD in male endurance trained athletes in sports with implicit or explicit weight limits are needed.

The force production during ergometer rowing with and without slides at identical power outputs was measured in 14 male and 8 female elite rowers. During slide-based ergometer rowing male rowers increased stroke rate and decreased peak force, mean force and rate of force development above 50 % of peak force. Female rowers displayed a similar but less pronounced response to ergometer rowing in slides. Slide-based ergometer rowing may be hypothesized to decrease the peak loading of the rib cage in each rowing stroke during ergometer rowing at the expense of an increased number of loading cycles. Whether slide-based ergometer rowing can decrease the risk of RSF needs to be evaluated in randomized controlled trials.

The patterns of neuromuscular activity in muscles potentially involved in RSF development in addition to the force production at the handle were measured during ergometer rowing with and without slides at identical power outputs in 14 male elite rowers. Slide-based ergometer rowing did not affect the neuromuscular activation of the measured muscles significantly, except during the relatively unloaded recovery phase of the rowing stroke. The timing of peak neuromuscular activity of the scapula retractor muscles including m. latissimus dorsi coincided with the timing of peak force at the handle supporting rib cage compression as a potential injury mechanism.

In conclusion this thesis has added some pieces of knowledge regarding the risk factors and injury mechanisms involved in the development of exercise-induced rib stress fractures in elite rowers. This knowledge might be useful for and give inspiration to future studies of rib stress fracture prevention in elite rowers.

Summary in Danish

Formålet med denne afhandling var at undersøge potentielle skadesmekanismer og risikofaktorer af betydning for udvikling af stressfrakturer i ribbenene hos eliteroere, samt at undersøge forskelle i biomekanik og neuromuskulær aktivering af udvalgte muskler under ergometerroning med og uden skinner under ergometeret.

For at undersøge om roere med tidligere ribbensbrud adskilte sig fra roere uden tidligere ribbensbrud hvad angik knoglemineralindhold og muskelstyrke samt muskelaktiveringsmønster og roteknik under ergometerroning blev disse parametre undersøgt hos 7 roere med og 7 matchede roere uden tidlige ribbensbrud. Roere med tidligere ribbensbrud viste sig at være karakteriseret ved lavere knoglemineralindhold i lændehvirvlerne, større muskelstyrke i albuebøjerne i forhold til knæstrækkerne samt øget grad af samtidig aktivering af muskler omkring brystkassen i midten af trækfasen og øget hastighed af sædet i begyndelsen af trækfasen. Da undersøgelserne dels er retrospektive og dels omfatter ganske få roere kan der ikke konkluderes noget endeligt. Prospektive studier med flere roere er nødvendige for at kunne undersøge potentielle skadesmekanismer og risikofaktorer nærmere.

En undersøgelse af testosteronniveau og knoglemineralindhold hos 13 mandlige letvægtsroere viste at knoglemineralindhold i lændehvirvlerne var korreleret til både testosteronniveau og antal af år med rotræning. Forholdsvis højt knoglemineralindhold i kombination med forholdsvis lave testosteronniveauer indikerede at knoglemineralindholdet var blevet påvirket mere i positiv retning af den mekaniske belastning forbundet med roning end af den potentielt negative effekt af relativt lavt testosteron. Knoglemineralindhold i lændehvirvlerne var dog fortsat korreleret til testosteronniveau efter at der blev korrigeret for antal år med rotræning, og fremtidige studier af knoglehelbred hos mandlige udholdenhedstrænede atleter fra sportsgrene med vægtgrænser bør undersøge såvel hormonbalancens som ernæringstilstandens betydning.

Kraftudviklingen ved håndtaget under ergometer roning med og uden skinner under ergometeret blev målt under roning med standardiseret intensitet hos 14 mandlige og 8 kvindelige eliteroere. Med ergometeret på skinner øgede de mandlige roere deres tagfrekvens og mindskede deres maksimale kraft, gennemsnitskraft samt kraftudviklingshastighed i den øverste del af kraftkurven – altså tæt på den maksimale kraftudvikling. De kvindelige roere viste samme tendens men i noget mindre omfang og kun reduktionen i den maksimale kraft var sta-

tistisk sikker. Det er således muligt, at ergometer roning på skinner kan mindske den kraft brystkassen påvirkes med i hvert rotag, dog med den konsekvens at der udføres flere rotag. For at undersøge om ergometerroning på skinner kan reducere risikoen for udvikling af stressfrakturer i ribbenene, er det nødvendigt at foretage klinisk kontrollerede randomiserede undersøgelser af skadeincidensen under ergometerroning med og uden skinner.

Den neuromuskulære aktivering af muskler potentielt involverede i udviklingen af stressfrakturer i ribbenene blev målt samtidig med måling af kraftudviklingen ved håndtaget under ergometerroning med og uden skinner. Generelt blev den neuromuskulære aktivering kun påvirket af om ergometeret stod på skinner i den relativt ubelastede fremstræksfase af rotaget. Den maksimale aktivering af de muskler, der trækker bagud i skulderbladet opstod næsten samtidig med den maksimale kraft målt ved ergometerets håndtag, uanset om ergometeret stod på skinner eller ej. Dette styrker den antagelse at ribbensbruddene opstår som følge af en sammenpresning af brystkassen, når der trækkes hårdt i håndtaget i starten af rotaget. Sammenpresningen er foreslået at kunne opstå netop når musklerne, der trækker bagud i skulderbladet, skal overføre kraften fra bensparket til håndtaget eller åren.

Alt i alt kan denne afhandling bidrage med små men værdifulde informationer til brug ved fremtidige undersøgelser af forebyggelse af stressfrakturer i ribbenene hos eliteroere.

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