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Recovery of Muscle Function Following Strength Training in Rowers

Thomas Ian Gee

PhD

2012

Recovery of Muscle Function Following Strength Training in Rowers

Thomas Ian Gee

A thesis submitted in partial fulfilment of
the requirements of the University of
Northumbria at Newcastle for the degree of
Doctor of Philosophy

Research undertaken in the
School of Life Sciences

February 2012

Abstract

Strength training using free weights is performed by athletes in many sports as a means of enhancing performance. However, there is a dearth of research investigating the acute impact of bouts of this form of strength training on muscle function, which closely mimics the athletes' sport or event. High forces are produced during a rowing race and subsequently strength training forms an integral part of the overall training programme for rowers. However, there is little documented evidence regarding the strength and conditioning practices occurring in rowing. Therefore the aims of this thesis were to investigate and draw conclusions regarding the strength and conditioning practices occurring within British rowing and to evaluate the impact of typical bouts of strength training on muscle function in rowers.

To investigate the strength and conditioning practices within British rowing a questionnaire was completed by 32 coaches and semi-structured interviews were undertaken with two coaches of elite rowers (study 1). Information from both sources indicated that rowers performed two to three strength training sessions per week, involving Olympic lifting and multi-joint free weight strength exercises, performed across multiple sets with low to moderate repetition ranges. Physical testing most commonly involved assessment of cardiovascular endurance, muscular power and strength. Twenty four hours of recovery were generally afforded between strength training and intensive rowing training while longer periods were permitted before rowing races (≥ 48 h). Prior to the intervention studies, the reproducibility of subsequently assessed measures was assessed using trained rowers (study 2). Typical error (%) was low for 2000 m mean power (2.4 %), and low to moderate for the assessments of strength and power (3.0-5.9 %). Measures of peak blood lactate (11.5 %), creatine kinase (21.0 %) and surface electromyography (11.1-44.8 %, across various sites) demonstrated greater variability similar to previous studies. For studies 3 and 4, trained rowers performed 250 m and 2000 m rowing tests respectively, alongside various measures of muscle function before and after an acute bout of free weight multi-joint strength training (ST). For both studies, increases in perceived muscle soreness and CK indicated that muscle damage was present after ST for 24-48 h. Maximal power generating ability was decreased in both studies as evidenced by decrements in the 250 m test, power strokes, and jump height. However, in study 4, 2000 m rowing time was unaffected, leading to the conclusion that the specific muscle function required for the power tests was affected through damage to type II muscle fibres. Findings from study 1

indicated that rowers commonly perform strength training three times per week; therefore study 5 investigated the impact of this weekly frequency of strength training on muscle function. Twenty four hours after three bouts of ST within a five day period, trained rowers experienced significant decreases in maximal voluntary contraction, jump height and power stroke tests as well as increases in CK and soreness; however as with study 4, 2000 m performance was unaffected. Trends for decreases in peak lactate and anaerobic energy liberation ($p < 0.10$, *Effect Size* = 0.40-0.56) were present alongside significant increases in EMG at three sites during the post-ST 2000 m test. These findings suggest a decreased utilisation of the anaerobic capacity coupled with increased central motor drive suggesting a change in muscular recruitment patterns during the follow up 2000 m rowing test.

It would appear that following extensive strength training, physiological processes were adapted during subsequent rowing exercise, to compensate for the loss in higher threshold muscle fibre function, in order to affect the same level of rowing performance achieved in the rested state. These findings might suggest that participants operated within a physiological reserve and/or that multiple-exercise-regulation-algorithms exist with which a similar exercise performance can be achieved.

Publications arising from this thesis

Chapter 4

Gee, T. I., Olsen, P. D., Berger, N. J., Golby, J. & Thompson, K. G. (2011) 'Strength and conditioning practices in rowing', *Journal of Strength and Conditioning Research*, 25 (3), pp. 668-682.

Chapter 5

Gee, T. I., French, D. N., Gibbon, K. C. & Thompson, K. G. (In Press) 'Consistency of pacing and metabolic responses during 2000-m rowing ergometry', *International Journal of Sport Physiology and Performance*.

Chapter 6

Gee, T. I., Olsen, P. D., Garland Fritzdorf, S. W., White, D. J., Golby, J. & Thompson, K. G. (2012) 'Recovery of rowing sprint performance after high intensity strength training', *International Journal of Sports Science and Coaching*, 7 (1), pp. 109-120.

Chapter 7

Gee, T. I., French, D. N., Howatson, G., Payton, S. J., Berger, N. J. & Thompson, K. G. (2011) 'Does a bout of strength training affect 2,000 m rowing ergometer performance and rowing-specific maximal power 24 h later?', *European Journal of Applied Physiology*, 111 (11), pp. 2653-2662.

Published abstracts arising from this thesis

Chapter 4

Gee, T., Olsen, P., Thompson, K. & Golby, J. (2008) 'Strength and conditioning practices in rowing', *Journal of Sports Sciences*, 26 (S2), p. S121.

Chapter 6

Gee, T., Olsen, P., Thompson, K., Golby, J., Garland, S. & White, D. (2008) 'Recovery of rowing sprint performance after high intensity strength training', *Journal of Sports Sciences*, 26 (S2), p. S66.

Chapter 8

Gee, T. I., French, D. N., Howatson, G., Gibbon, K. C., Caplan, N., Moloney, S. B., Corkery, A., Toms, C. J. & Thompson, K. G. (2011) 'The effect of a series of strength training sessions on 2000 m rowing ergometer performance and muscle function', *British Journal of Sports Medicine*, 45, p. A14.

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Table of abbreviations

P_{aer}	Aerobic metabolism
P_{anaer}	Anaerobic metabolism
ANOVA	Analysis of variance
b.min ⁻¹	Beats per minute
BF	Biceps femoris
Ca ²⁺	Calcium ions
CO ₂	Carbon dioxide
CK	Creatine kinase
$\dot{V}\text{CO}_2$	Carbon dioxide production
CMJ	Counter movement jump
CGM	Central governor model
CI	Confidence intervals
<i>ES</i>	Effect size
EMG	Electromyography
ES	Erector spinae
E-C	Excitation-Contraction
GA	Gastrocnemius
GG	Greenhouse Geisser
GM	Gluteus maximus
HIR	High-intensity rowing training session
HR	Heart rate
U/L	International unit
[Lac ⁻]	Blood lactate
LDH	Lactate dehydrogenase
LD	Latissimus dorsi
LIR	Low intensity rowing training session
LSD	Fisher's least significant difference test
P_{tot}	Mean power
μL	Micro litre
MVC	Maximal voluntary contraction
1 RM	One repetition maximum
O ₂	Oxygen

$\dot{V}O_2$	Oxygen consumption
$\dot{V}O_{2\max}$	Maximum oxygen uptake
PS	Power strokes
RPE	Rating of perceived exertion
RA	Rectus abdominis
RER	Respiratory exchange ratio
$r.\text{min}^{-1}$	Revolutions per minute
$s.\text{min}^{-1}$	Strokes per minute
SD	Standard deviation
SPE	Smallest practical effect
SSJ	Static squat jump
ST	Strength training session
TE	Typical error
VM	Vastus medialis

Acknowledgements

I wish to sincerely thank all of the following people:

The participants: Thank you for taking time to be involved in the research, without your commitment none of these investigations would have been possible.

Prof. Kevin Thompson: Firstly thank you for providing the original funding for the research. I would mostly like to thank you for your lengthy commitment to myself and to the body of research for that I am forever grateful.

Dr. Peter Olsen: Thank you for your initial guidance in the formation of the research project and also for your enthusiasm and time commitment.

Dr. Duncan French and Dr. Glyn Howatson: For the insight provided to assist me in developing the latter stages of my research and always being available for correspondence as and when I have required it.

Mr. Karl Gibbon: Thank you for the many hours you gave to assist me with data collection in 2010 and 2011.

Declaration

I declare that the work contained in this thesis has not been submitted for any other award and that it is all my own work. I also confirm that this work fully acknowledges opinions, ideas and contributions from the work of others.

Name:

Signature:

Date:

1. Introduction

1.1 Introduction

Rowing is an Olympic sport which is popular worldwide and is considered one of the most demanding endurance sports (Russell *et al.*, 1998). A typical rowing competition takes place over a 2000 m course and lasts between 5.5-7.0 min (Steinacker, 1993). Research has shown that during a 2000 m effort the rower is dependent on aerobic metabolism for 84-88 % of total energy production (Russell *et al.*, 1998; Pripstein *et al.*, 1999; de Campos Mello *et al.*, 2009). Mean power during a race will vary between 450-550 W, however peak stroke power may reach as high as 1200 W (Steinacker, 1993). Therefore strength and power are seen as vital components to overall performance (Ingham *et al.*, 2002; de Campos Mello *et al.*, 2009), hence the classification of rowing as a strength-endurance sport (Maestu *et al.*, 2005b).

Rowing-specific maximal strength and power have been found to be amongst the strongest predictors of 2000 m rowing ergometer performance. Maximal power and force produced during five strokes are highly correlated with 2000 m ergometer performance ($r = 0.93-0.95$) (Ingham *et al.*, 2002; Nevill *et al.*, 2011). Furthermore, elite rowers have been found to be stronger, more powerful and possess a greater fat-free mass than amateur rowers (Izquierdo-Gabarren *et al.*, 2010). Considering the relationship between strength, power and rowing performance, it is unsurprisingly strength and power training is commonly practiced amongst rowers (Ivey *et al.*, 2004; McNeely *et al.*, 2005). Published guidelines recommend that rowers should perform a resistance training programme that focuses on the development of maximum strength, utilising multi-joint exercises such as the Olympic lifts, and the squat and deadlift, with low repetitions and loading between 85-95 % of one repetition maximum (1 RM) (Ivey *et al.*, 2004; McNeely *et al.*, 2005). Research studies implementing prolonged (8 week) strength training interventions, which have featured strength training prescription similar to that described above, have consistently led to improvements in rowing performance (Ebben *et al.*, 2004b; Gallagher *et al.*, 2010; Izquierdo-Gabarren *et al.*, 2010). Despite the published recommendations and effectiveness of strength training as a training modality for rowing, there is no published research documenting the current strength and conditioning practices that occur within rowing.

Although rowers commonly perform strength training within their training programme, the effect of acute bouts on rowing specific performance are unknown. Furthermore, there is limited research which has addressed the effects of acute bouts of strength training on

sports specific muscle function. Raastad and Hallen (2000), Scott *et al.* (2003) and Hoffman *et al.* (2010) are the only authors to assess the impact of a bout of strength training, featuring free weight barbell exercises, on subsequent sport specific functional performance (vertical jump, 30 min sub-maximal run and barbell squat strength / power respectively). Instead researchers have focused on the effects of protocols that aim to induce muscle damage on subsequent sports specific muscle function. Protocols of high volume barbell squats and plyometric jumps have led to prolonged (48-72 h) decrements in jump height (Byrne & Eston, 2002a; Marginson *et al.*, 2005; Skurvydas *et al.*, 2006; Twist & Eston, 2007; French *et al.*, 2008; Skurvydas *et al.*, 2008), cycling peak power (Byrne & Eston, 2002b; Twist & Eston, 2005; Twist & Eston, 2007), 10 m and 20 m run sprint time (Twist & Eston, 2005; Davies *et al.*, 2009b; Highton *et al.*, 2009) and prolonged running and cycling performance (Marcora & Bosio, 2007; Davies *et al.*, 2008; Davies *et al.*, 2009a; Twist & Eston, 2009). The applicability of the aforementioned findings to the athletic setting is limited, since the protocols chosen were designed to cause muscle damage rather than model strength and power training sessions commonly practiced by athletes (Atkinson & Nevill, 2001; Byrne *et al.*, 2004). Additionally, the participants recruited for the majority of these studies were not trained athletes, therefore the results cannot confidently be applied to athletic populations, since athletes are thought to be less susceptible to muscle damage due to the repeated bout effect (McHugh, 2003; Marcora & Bosio, 2007).

It is recommended that rowers perform between two and three strength training sessions per week (Ivey *et al.*, 2004). Furthermore, for athletes aiming to concurrently develop endurance and strength capabilities, three strength training sessions per week are recommended (Garcia-Pallares & Izquierdo, 2011). No previous research has investigated the effects of a 'typical' one week frequency of strength training on rowing performance. Several researchers have investigated the effects of short term protocols (4-7 days) of strength training on various aspects of muscle function (Hakkinen *et al.*, 1988a; Warren *et al.*, 1992; Fry *et al.*, 1994a; Fry *et al.*, 1994b; Fry *et al.*, 1994c). These studies observed that effects on muscle function are highly influenced by athletic status. With competitive weightlifters displaying maintenance of competition lift performance despite being exposed to a 100 % increase in training volume over a week (Hakkinen *et al.*, 1988a; Warren *et al.*, 1992; Fry *et al.*, 1994b). However, whilst exposed to lower training loads non-competitive 'resistance-trained' males have demonstrated significant decreases in

sprinting ability and maximal strength following 4-7 days of multi-joint strength training (Fry *et al.*, 1994a; Fry *et al.*, 1994c; Kraemer *et al.*, 2006).

In light of all this information, the purpose of this thesis was to investigate and draw conclusions regarding the strength and conditioning practices occurring within British rowing and to evaluate the impact of bouts of strength training on various parameters of sport specific power producing ability and 2000 m ergometer performance in rowers. This was conducted over five sequential investigations.

The first study provides a descriptive analysis of the strength and conditioning practices within British rowing. Information concerning strength training prescription, fitness testing and recovery periods following strength training were elicited from a questionnaire study and two semi-structured interviews.

The information from the descriptive analysis ensured that the planned intervention studies followed an externally valid design. Before the initiation of the intervention studies the reproducibility of the planned physiological assessments was established. These assessments involved tests of strength and power, markers of muscle damage and 2000 m rowing ergometer performance with related physiological measures.

The third study investigated the impact of a high-intensity strength training session on rowing sprint performance and muscle function. The featured bout of strength training was designed in accordance with descriptive information elicited from study one. Markers of muscle damage, jump height and 250 m ergometer sprint performance were assessed before and at 24-, 48- and 72 h following the strength training session.

The fourth study investigates the impact of a bout of strength training on 2000 m rowing ergometer performance and muscle function. As an extension of measures assessed during the third study an extensive range of power tests and markers of muscle damage were assessed over a period of 48 h following the single bout of strength training.

The final study investigates the impact of a typical weekly frequency of strength training (three bouts) on 2000 m ergometer performance and muscle function. Measures of respiratory exchange and surface electromyography allowed for intricate analysis of the impact of the protocol of strength training on 2000 m ergometer performance.

2. Literature review

2.1 Literature review

This review of literature initially discusses how strength and conditioning has developed as a profession within modern sport and specifically outlines research concerning the practice of strength and conditioning coaches. Following this, the physiological demands of rowing and training practices of rowers with particular reference to strength training are discussed. The review then focuses on the impact of exercise induced muscle damage, caused by protocols simulating strength and power training bouts, on various assessments of sport specific functional performance. The literature concerning the effect of short duration protocols of multi-joint strength training on muscle function is then reviewed as well as studies involving short term periods of increased training volume in rowers. Finally, mechanisms and indirect markers of exercise induced muscle damage are discussed.

2.2 Strength and conditioning practices in modern sport

To date, there have been a number of studies which have focused on the professional practices of strength and conditioning coaches. This research has primarily been conducted on coaches working in North America. A proportion of these studies have involved investigating the practices of strength and conditioning coaches who work with a specific sport (Finamore, 1992; Ebben & Blackard, 2001; Massey *et al.*, 2002; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005; Magnusen, 2010). These specific sports are those most popular in America namely; American Football, Baseball, Ice Hockey and Basketball. The other proportion have investigated practices of strength and conditioning coaches working in colleges (Durell *et al.*, 2003), high schools (Duehring *et al.*, 2009; Duehring & Ebben, 2010) and across a range of professional sports (Sutherland & Wiley, 1997). All of the aforementioned studies, with the exception of Massey *et al.* (2002), have utilised surveys to elicit descriptive information. Interestingly the studies by Ebben *et al.* (2004a), Simenz *et al.* (2005) and Ebben *et al.* (2005) all featured a survey which was adapted from that which was used by Ebben & Blackard (2001). This survey was divided into the following sections; background information, physical testing, flexibility development, speed development, plyometrics, strength / power development, unique aspects and comments.

In addition to the discussed studies concerning North American strength and conditioning coaches there has also been a survey which has investigated resistance training practices of strength and conditioning coaches working with elite Spanish team sport athletes (Reverter-Masia *et al.*, 2009) and a survey of the training practices of elite

British Powerlifters (Swinton *et al.*, 2009). On reviewing the aforementioned studies it is apparent there is no research addressing strength and conditioning prescription within any continuous endurance sport. Since strength training is an integral form of training for many endurance athletes (Garcia-Pallares & Izquierdo, 2011), this information would be useful and informative to strength and conditioning practice.

2.3 Physiological demands of rowing and characteristics of rowers

Rowing is described as strength-endurance sport (Maestu *et al.*, 2005b). A typical rowing race takes place on a 2000 m course and lasts, depending on boat type and environmental conditions, 5.5-7.0 min (Steinacker, 1993). The rowers' energy requirements are primarily met by aerobic metabolism (Secher, 1993a). Modern research suggests that the energy contribution to rowing is between 84-88 % aerobic and 12-16 % anaerobic (Russell *et al.*, 1998; Pripstein *et al.*, 1999; de Campos Mello *et al.*, 2009). Compared to other locomotive endurance events, the cadence during a rowing competition is fairly low with the stroke rate generally varying between 32-38 strokes per minute ($s \cdot \text{min}^{-1}$). Mean power during a race will vary between 450-550 W, however maximal stroke power may reach as high as 1200 W (Steinacker, 1993). This differentiation between mean and maximal power is due to the reverse J shaped pacing strategy employed during rowing races (Garland, 2005; Brown *et al.*, 2010). This strategy is characterised by a high power output during the initial phase, followed by a decrease in power output in the middle of the event culminating with an end-spurt in the final stages, which is completed with a higher power output than the middle phase but lower than the initial phase (Abbiss & Laursen, 2008). In rowing the start of the race is characterised by extremely high force and power outputs as crews aim to quickly get the boat up to 'race pace' (Garland, 2005). This powerful start is tactically and psychologically advantageous in rowing, as gaining placement at the front of the race will allow rowers, who look backward down the course, to be able to monitor the position of other boats and react to any sudden advances from other competitors and also avoid the wake of other boats (Garland, 2005). Therefore even though the anaerobic contribution to a 2000 m race is relatively low, it is imperative that the rower has sufficiently developed anaerobic capabilities, notably muscle strength and power to rapidly break the boat from a position of inertia and compete for position in the initial segment of a race and also to finish strongly (Maestu *et al.*, 2005b). Indeed the limiting factors to optimal performance

in rowing have been identified as maximum strength, starting power, and muscular endurance (Steinacker, 1993).

Several key factors have been shown to affect physical performance during rowing and these have been shown to be in line with the requirements of a typical strength-endurance sport. Rowers need physical strength to achieve a high power per stroke and endurance to sustain powerful strokes over the race, whilst displaying specific motor and tactical skills (Steinacker *et al.*, 1986; Secher, 1993b). Mechanical power generation for rowing depends on aerobic and anaerobic energy supplies, however this must be balanced with efficiency or technique (Jensen, 1994). Efficiency is the relationship between energy expenditure and boat velocity, and depends on the technical skill of the rower (Maestu *et al.*, 2005b). Differences in efficiency have been demonstrated between rowers and non-rowers, however no differences were detected between elite rowers selected, versus those not selected, for World Championships (Lakomy & Lakomy, 1993). This indicates that efficiency expressed on a ergometer is only a rough estimate of technique in the boat (Jensen, 1994). Maximum oxygen uptake ($\dot{V}O_{2\max}$) has been observed to be higher in international rowers than those of a club standard (Ingham *et al.*, 2007) and values have been reported at 6.5 to 7.0 L.min⁻¹ or 72-78 ml.kg.min⁻¹ in international heavyweight rowers (Fiskerstrand & Seiler, 2004). Research suggests that the power output at $\dot{V}O_{2\max}$ achieved during incremental rowing ergometer tests is the best predictor of 2000 m ergometer performance, with correlation coefficients of $r = 0.95-0.96$ (Ingham *et al.*, 2002; Nevill *et al.*, 2011).

Anthropometric characteristics have been shown to distinguish between elite and sub-elite rowers. From data of 140 male open class rowers competing at the 2000 Olympic Games, elite rowers were found to be 1.94 m tall and to weigh 94 kg (Kerr *et al.*, 2007). A high lean body mass has been found to be a significant attribute of international elite rowers (Bourgois *et al.*, 2000; Izquierdo-Gabarren *et al.*, 2011) and correlates strongly with 2000 m ergometer time ($r = -0.77$ to -0.91) (Yoshiga & Higuchi, 2003b; Mikulic, 2009). Internationally successful rowers have significantly greater proportions (70-85 %) of slow twitch muscle fibres than national standard rowers (66 %) (Larsson & Forsberg, 1980; Clarkson *et al.*, 1984). A high percentage of slow twitch fibres is seen as a determining factor for elite endurance performance due to the increased oxidative capacity of this fibre type compared to fast twitch fibres (Joyner & Coyle, 2008). Qualities related to muscle strength and power have been shown to be strong predictors of rowing performance. Nevill *et al.* (2011) and Ingham *et al.* (2002) found maximal power and force produced during the five power stroke to be highly correlated with 2000 m ergometer performance ($r = 0.93-$

0.95). Other authors have found strength and power tests to be significantly correlated with 2000 m ergometer performance (Russell *et al.*, 1998; Riechman *et al.*, 2002). Furthermore, measures of jump height and isometric rowing strength distinguish elite from non-elite rowers (Secher, 1975; Battista *et al.*, 2007).

2.4 Characteristics of rowing training

During the course of a rowing race, aerobic metabolism predominates (de Campos Mello *et al.*, 2009) however anaerobic alactic and lactic capabilities are also stressed significantly as evidenced by peak power outputs in the region of 1200 W and peak blood lactate [Lac⁻] levels of 11-19 mmol.L⁻¹ (Steinacker, 1993; Shephard, 1998; Gallagher *et al.*, 2010). Therefore the training of successful rowers has to be established on the focus of aerobic training with the concurrent development of anaerobic and strength qualities (Maestu *et al.*, 2005b). International rowers have been reported to perform 1100 to 1200 h of training per year (Fischerstrand & Seiler, 2004) but the split of training components was not explicit.

The majority of training volume consists of endurance training at an intensity below the anaerobic threshold ($< \sim 2 \text{ mmol.L}^{-1}$), which has been characterised as the mainstay of success in rowing (Secher, 1993a). Dependent on environmental conditions, it is recommended that the specific rowing training of the international rower should account for 65-70 % of the total training time (Jensen & Nielsen, 1993; Messonnier *et al.*, 2005), since training kilometres on the water are positively related to the success in championships (Steinacker *et al.*, 1998). The benefits of low intensity training were shown by Ingham *et al.* (2008), who found that a group performing 12 weeks of low intensity rowing training ($< 75 \% \dot{V}O_{2 \text{ max}}$) elicited improvements in power achieved at lactate threshold and power at a [Lac⁻] level of 4 mmol.L⁻¹ compared to a group performing mixed intensity training ($< 75 \%$ and 84-93 % $\dot{V}O_{2 \text{ max}}$) over the same time period. Through the pre-competition phase low intensity training volume is gradually reduced, however even during the competitive period this training still predominates, accounting for 70 % of total training (Maestu *et al.*, 2005b).

Additional training time is mainly focused on high-intensity rowing training and strength training. The prevalence of high-intensity rowing training increases in the competition period and accounts for 5-10 % of training volume dependent on phase (Steinacker, 1993; Guellich *et al.*, 2009). Categories of high-intensity training have been defined as intensive endurance ([Lac⁻]: 2-4 mmol.L⁻¹, 75-85 % race pace) highly intensive endurance ([Lac⁻]: 4-8 mmol.L⁻¹, 85-100 % race pace), race-specific velocity endurance ([Lac⁻]: 4-6 mmol.L⁻¹, 95-110 % race pace) and velocity (106-112 % race pace) (Guellich

et al., 2009). Strength training is commonly featured year round and has been reported to account for between to 10-23 % of total training time in elite rowers (Steinacker *et al.*, 2000; Messonnier *et al.*, 2005; Guellich *et al.*, 2009).

2.5 Previous models of strength and power training and testing prescription for rowers

Few articles have described or made recommendations for strength and conditioning practices in rowing with only one guide for strength training prescription having been published by Ivey *et al.* (2004). This guide provided recommendations for various phases of the preparatory training period in collegiate female rowers including; anatomical adaptation, maximum strength and power training, fitness testing, injury prevention and flexibility development. The ‘maximum strength’ training phase described in this plan featured two sessions a week and generally three sets of eight repetitions were prescribed per exercise. This phase involved mainly strength based exercises such as squats, bench press, low cable row, step-ups, bent over row and Romanian deadlift. However, power based exercises such as the hang clean and high pull were also included. A ‘power’ training phase was also described and featured three workouts a week, during which more power based exercises were prescribed such as the hang clean, dumbbell push jerk, power shrugs, step up with jump, vertical jumps with a weighted vest and various explosive medicine ball exercises. Power exercises were generally performed for 3-5 sets of 3-5 repetitions. Currently the article by Ivey *et al.* (2004) is the only published research source which has given clear guidelines for strength training prescription for rowing. Clearly there is a need for a greater understanding of strength and conditioning practices in rowing.

As opposed to Ivey *et al.* (2004), who gave recommendations on strength training prescription, McNeely *et al.* (2005) published an article titled ‘Strength and power goals for competitive rowers’, which gave guidelines on the assessment of strength and power. This article identified the squat, deadlift and bench pull as exercises to be utilised for the assessment of strength. The authors listed strength to body mass goals for rowers to aim to achieve on each of this exercises (Table 2.1). Standards were outlined for a range of levels of rower from High School to Olympic level. For example according to guidelines an Olympic rower should aim to squat 1.9 times their body mass. The setting of the specific standards was based on data collected over 10 years from rowers of varying ages and ability (McNeely, 2001). The guide also recommended that a ‘Modified Wingate’ 30 s

sprint on a rowing ergometer was an appropriate test of peak and average anaerobic power for rowers (Table 2.2).

Table 2.1 Strength to body mass factors for men, as published by McNeely *et al.* (2005)

	High school (<i>n</i> = 154)	U23 (<i>n</i> = 91)	Club (<i>n</i> = 103)	National (<i>n</i> = 40)	Olympic (<i>n</i> = 26)
Squat	1.0	1.3	1.4	1.7	1.9
Deadlift	1.0	1.3	1.4	1.7	1.9
Bench Pull	0.7	0.9	1.05	1.2	1.3

Table 2.2 Peak and average power goals for the 30 s modified Wingate test, as published by McNeely *et al.* (2005)

Category	Peak power (watts)	Average power (watts)
Heavyweight men (<i>n</i> = 41)	900–1100	725–875
Lightweight men (<i>n</i> = 32)	650–800	510–720
Heavyweight women (<i>n</i> = 54)	550–700	380–475
Lightweight women (<i>n</i> = 27)	400–500	350–425

2.6 Strength training exercise selection for rowing

A prerequisite to specificity and hence optimal transference of strength and power gains to functional performance is the biomechanical and physiological understanding of both the weight training exercise and the sporting activity of interest (Cronin *et al.*, 2007). Electromyography analysis suggests that muscle groups are active in combination during rowing (Wilson, 1988). Accordingly it is recommend that rowers perform strength training exercises that require the upper and lower body to work together in a coordinated manner, leading to whole body strengthening (Rodriguez *et al.*, 1990).

Olympic Weightlifting techniques, as well as the squat and the deadlift are whole body exercises requiring coordinated actions of many muscle groups for their successful performance (Escamilla *et al.*, 2000b; Gourgoulis *et al.*, 2000; Miletello *et al.*, 2009),

which is why these exercises have been highlighted as appropriate for rowers (Ivey *et al.*, 2004; McNeely *et al.*, 2005). Research has shown that during the propulsive phase of the rowing stroke the leg drive contributes 50 % to total force production, with 30 % attributed to hip and trunk extension and the upper body contributes 20 % (Kleshnev & Kleshnev, 1998; Tachibana *et al.*, 2007). As with the rowing stroke, the lower body and hip musculature is predominantly recruited during the aforementioned exercises and this serves as justification as to why they should form the foundation of rowers' strength training program (Escamilla *et al.*, 2000a; Escamilla, 2001; Kipp *et al.*, 2011). The Olympic weightlifting exercises the snatch and the clean feature distinct initial and secondary pulling actions on the barbell in their performance (Souza *et al.*, 2002; Gourgoulis *et al.*, 2004). The secondary pull features a greater force and power output than the initial pull and is characterised by concomitant triple extension at the ankle, knee and hip (Souza *et al.*, 2002). Similarly in rowing, initial and secondary pulling actions on the oar are featured in the performance of a stroke, with the greatest force produced during the secondary action, which features a triple extension at the aforementioned joints (McGregor *et al.*, 2004). Increasing strength in whole body exercises such as squats and deadlifts will provide a platform to then develop increased power through Olympic weightlifting techniques (McBride *et al.*, 1999; Ivey *et al.*, 2004). Subsequently development of strength and power in the Olympic lifts would theoretically translate to improving force producing capabilities during the kinematically similar task of rowing (Ivey *et al.*, 2004).

Apart from Olympic lifting style exercises and whole body strength lifts such as squats, upper body pulling exercises are also commonly recommended for the strength training and testing of rowers (Ivey *et al.*, 2004; McNeely *et al.*, 2005). These exercises condition the latissimus dorsi which is active as an agonist during the rowing stroke as well as a range of synergistic muscles (Cronin *et al.*, 2007; Fenwick *et al.*, 2009). The three most commonly suggested for rowers in published literature, are the seated cable row or low cable row, the bench pull and the bent over row (Ivey *et al.*, 2004; McNeely *et al.*, 2005; Cronin *et al.*, 2007). Of the three, the seated cable row is the most kinematically similar exercise to the rowing stroke, with the legs supported by a footplate which is horizontal to the seated position, whilst the loaded cable is held by the arms originating from a position close to the supported feet (Cronin *et al.*, 2007). The bench pull has been cited as a means of testing upper body pulling strength (Ivey *et al.*, 2004; McNeely *et al.*, 2005). Although kinematically the exercise shares less characteristics with the rowing stroke than the bench pull, the exercise is thought to afford increased acceleration through the latter part of the lift (Cronin *et al.*, 2007). Therefore if increased force and power

through the latter stages of the stroke are desired then the bench pull provides a useful addition to the rowers' strength training program. The bent over row is performed standing and requires the most stability to maintain postural alignment, hence the exercise is valuable to train synergistic and stabiliser muscles in addition to prime movers involved with upper body pulling actions (Fenwick *et al.*, 2009). Upper body pushing exercises such as the bench press and shoulder press which condition primarily the pectoral, deltoid and triceps brachii muscles are also recommended for rowers (Ivey *et al.*, 2004). Their inclusion is generally for the purpose of upper body muscle balance since the kinematics of the rowing stroke dictates that the muscles these exercise condition do not contribute significantly to stroke power generation (McGregor *et al.*, 2004).

2.7 The effects of concurrent programmes of strength training and rowing training on rowing performance

Previous research has assessed the effect of concurrent endurance and strength training programmes on rowing performance (Lawton *et al.*, 2011). A proportion of these studies have assessed the effectiveness of programmes combining strength and rowing training; where a single group of participants performed a set training intervention over eight to ten weeks (Kramer *et al.*, 1993; Syrotuik *et al.*, 2001; Kennedy & Bell, 2003; Webster *et al.*, 2006; duManoir *et al.*, 2007). These interventions have commonly led to significant improvements in strength, power and rowing performance. However, the lack of multiple treatment groups (for example; rowing training only vs. strength training and rowing) restricts interpretation of the training effect caused by the strength training. Therefore, for the purpose of this review only studies featuring multiple training groups will be discussed in more detail.

Initially Bell *et al.* (1989) compared the effects of high and low velocity resistance training on various parameters of rowing performance in well-trained male rowers. Following the four session a week, five week protocol both groups significantly increased isokinetic strength in comparison to a control group, although neither intervention led to improvements in rowing performance. However, the strength protocol employed which was a circuit of twelve hydraulic variable resistance machines, is not commonly used or recommended in the training of rowers (Ivey *et al.*, 2004; McNeely *et al.*, 2005). Therefore the applicability of the findings to the training practice of rowers was questionable. More recently authors have assessed the effectiveness of multi-joint free weight strength training programmes on rowing performance. Ebben *et al.* (2004b) assigned female university

rowers to either high load (5-12 repetitions) or high repetition (15-32 repetitions) strength training groups. Participants performed eight weeks (three and two weekly sessions for the first six and last two weeks respectively) of resistance training featuring the multi-joint free weight strength exercises. Strength training led to improvements in performance time, total power and power per stroke during a 2000 m rowing ergometer test. Interestingly, varsity rowers who performed high load training demonstrated greater improvement compared with those who performed high repetition training, whereas novice rowers who performed high repetition training demonstrated greater improvement compared with those who performed high load training. Gallagher *et al.* (2010) demonstrated that an eight week programme of whole body, free weight, high load strength training (3-5 sets x 3-5 repetitions) resulted in practically relevant greater decreases in 2000 m time than either high repetition strength training (2-3 sets x 15-30 repetitions) or a control group performing solely rowing training. Izquierdo-Gabarron *et al.* (2010) prescribed an eight week concurrent endurance and strength training programme to club standard rowers. The strength protocol featured the bench pull, seated cable row, lateral pull-down and power clean, performed for 3-5 sets using a loading range between 75-92 %. After 8 weeks the participants experienced increases in strength, power and rowing performance. Interestingly gains were superior for a group performing the four exercises using 2-5 repetitions per set rather than a group who achieved 4-10 repetitions per set by performing to volitional failure. The authors theorised that the performance of the repetition to failure programme may have surpassed a threshold of training volume whereby sub-optimal adaptations in strength and endurance would result.

When considering the findings from the studies which have implemented strength training alongside rowing training over prolonged periods, it would seem that high-load, moderate volume resistance training using multi-joint free weight exercises for two to three sessions a week is most effective for well-trained competitive rowers. A recent review of the literature concerning concurrent strength and endurance training for rowing and canoeing was conducted by Garcia-Pallares & Izquierdo (2011). The authors recommended that strength training should be performed three times a week with each session comprising of four to six multi-joint exercises, with an emphasis on maximal strength and power development with loads of ≥ 85 % of 1 RM and exercises performed across 3-5 sets comprising of 1-6 repetitions. However, similarly to Izquierdo-Gabarron *et al.* (2010), the authors cautioned that training to repetition failure should be avoided arguing that a moderate number of repetitions not to failure provides a favourable environment for achieving greater enhancements in muscle power, strength and sport

specific performance. The authors commented that using the 'not to failure' approach permits faster recovery from strength training allowing rowers to perform subsequent endurance sessions of higher quality. It has previously been shown that a prolonged resistance training program utilising the repetition failure approach has resulted in greater stress to the neuroendocrine system than a program utilising the not to repetition failure approach (Izquierdo *et al.*, 2006). After a twice a week, 16 week strength program, participants performing sets to repetition failure experienced a decrease in concentrations of the anabolic hormone insulin-like growth factor 1 (Izquierdo *et al.*, 2006). Concomitantly a group performing repetitions not to failure experienced increases in resting testosterone and decreases in resting cortisol whilst these hormones were unchanged for the repetition failure group. Circulating testosterone and cortisol have been proposed as physiological markers to evaluate the tissue-remodelling process during a strength training period (Kraemer & Ratamess, 2005), with an increase in the testosterone to cortisol ratio indicating an increase in the anabolic status of skeletal muscle. These findings suggest that adopting a not to failure approach has more favourable effects on hormonal and adaptive status, and seems to be superior for athletes performing concurrent strength and endurance training.

2.8 The monitoring of training in rowers over acute periods

Various authors have monitored the training of elite rowers over short duration periods of increased training volume (Maestu *et al.*, 2005b). For the purpose of this review only studies featuring a training period of less than three weeks duration will be discussed. When monitoring the training of international junior rowers, Steinacker *et al.* (1998) observed a high load training phase encompassing ~ 3.2 h of daily training for 18 days. This training volume equated to a 100 % increase relative to prior training load with ~ 90 % of total training time consisting of extensive rowing training and 'unspecific' low intensity exercise such as stretching and gymnastics below lactate threshold (4 mmol.L^{-1}), while ~ 10 % of training time was a combination of strength training and running. After this extensive training phase, 2000 m rowing ergometer time was increased by ~ 8 s. The authors characterised that an overreaching effect had occurred since psychological mood disturbances and increased CK levels accompanied the decrease in rowing performance. Similarly to Steinacker *et al.* (1998), Jurimae *et al.* (2002; 2004) have reported significant decreases in rowing ergometer performance following intensive periods of training. Jurimae *et al.* (2002; 2004) recorded decreases in 2000 m ergometer performance of ~ 4 and 9 s respectively following six day periods of increased training volume which equated

to ~ 20 h representing a ~ 100 % increase in average weekly training volume. The authors described the training prescription during these periods which consisted of ‘low intensity endurance training (rowing or running)’, equating to 85 % of total training time, 10 % of the prescribed training was ‘resistance training’, the remaining 5 % of training time was spent performing ‘high-intensity anaerobic training (rowing)’. In contrast to the previous three studies, Maestu *et al.* (2005a) found 2000 m rowing ergometer performance to be unaffected following a three week period of increased training load. This was despite choosing from a similar participant population (junior national standard male rowers) and using a similar increase in training volume during the intensive training period (~ 20 h; ~ 100 % increase in average weekly training volume).

The main difference between the training protocols prescribed by Maestu *et al.* (2005a) to those of Steinacker *et al.* (1998) and Jurimae *et al.* (2002; 2004) was the contribution of strength training to total training volume. Participants in the study by Maestu *et al.* (2005a) performed; 45 % strength training, 45 % endurance training (running, swimming and or ergometer rowing) and 10 % ball games (basketball and/or soccer). This represented a large reduction in endurance and rowing based training, replaced by a higher volume of strength training as compared to Steinacker *et al.* (1998) and Jurimae *et al.* (2002; 2004). The acute stress hormone response to singular bouts of rowing training and strength training has been assessed by Kokalás *et al.* (2004). The authors found prolonged endurance rowing (60 min) to cause a greater disruption to hormonal homeostasis, including a significant rise in the stress hormone cortisol, compared to the response following a bout of multi-joint high load strength training (85-90 % 1 RM). The findings from the aforementioned studies which imposed an increased training load combined with the acute stress response of rowing endurance vs. strength training, might suggest that overreaching in terms of endurance training is more detrimental to 2000 m rowing performance than overreaching in terms of additional strength training.

2.9 Strength and power performance following exercise induced muscle damage (EIMD)

Various types of exercise challenges have been used to cause exercise induced muscle damage (EIMD) which subsequently leads to decrements in muscle function. Characteristically these challenges have featured loaded eccentric muscle actions imposed on a singular muscle group through non-sport specific means such as isokinetic dynamometry (Byrne *et al.*, 2004). For the purpose of this review muscle damaging

exercise challenges that have been designed to model strength and power training sessions of athletes will be discussed. The effects of these protocols on sport specific functional performance; which model sporting movements such as jump and sprint tests are reviewed.

A number of studies have attempted to assess the impact of protocols designed to induce muscle damage on subsequent sports specific functional performance. However, to the author's knowledge there is no research addressing the effect of acute strength training, featuring Olympic weightlifting-style exercises, on subsequent physical performance in any athletic population. This is somewhat surprising since Olympic weightlifting is used by a wide variety of athletes to enhance performance (Tricoli *et al.*, 2005). Raastad and Hallen (2000) and Hoffman *et al.* (2010) are the only authors to assess the impact of a bout of strength training featuring a protocol of free weight barbell exercises, on subsequent sports specific strength and power producing ability. In the study by Raastad and Hallen (2000) participants, who were strength and power athletes, performed 3 sets of 3 repetitions on squats and front squats at a 3 RM load and 3 sets of 6 repetitions on leg extensions with a 6 RM load. Before and at various time-points in the 33 h following the protocol participants maximal vertical jump ability was assessed. Jump height was significantly reduced at 3-, 7-, 11- and 22 h post exercise before returning to baseline levels at 33 h. Hoffman *et al.* (2010) utilising strength and power athletes as participants, prescribed a strength training session featuring the squat, deadlift and barbell lunge exercises performed for 4 sets of 10 repetitions at 80 % 1 RM. When participants repeated 4 sets of 10 repetition (max target of repetitions) squats at 80 % 1 RM at 24 and 48 h following the strength training bout, the number of repetitions achieved and peak and mean power were all significantly reduced.

In general, few studies have investigated the acute effects of bouts of representative strength and power training on functional performance, rather studies have been focused on the effects of protocols that induce muscle damage through dynamic loaded eccentric actions. Many of these studies have featured protocols of high volume plyometric jumps, which commonly feature 100 repetitions spread across 5 or 10 sets (Semark *et al.*, 1999; Marginson *et al.*, 2005; Twist & Eston, 2005; Skurvydas *et al.*, 2006; Twist & Eston, 2007; Skurvydas *et al.*, 2008; Davies *et al.*, 2009b; Highton *et al.*, 2009), or barbell squats commonly performed for 100 repetitions spread across 10 sets (Byrne & Eston, 2002a; 2002b; French *et al.*, 2008). Such protocols have led to prolonged (48-72 h) decrements in jump height (Byrne & Eston, 2002a; Marginson *et al.*, 2005; Skurvydas *et al.*, 2006; Twist & Eston, 2007; French *et al.*, 2008; Skurvydas *et al.*, 2008), cycling peak power (Byrne & Eston, 2002b; Twist & Eston, 2005; Twist & Eston, 2007), 10 m and 20 m run sprint time

(Twist & Eston, 2005; Davies *et al.*, 2009b; Highton *et al.*, 2009) and sprint agility performance (Highton *et al.*, 2009). Descriptions and findings of the aforementioned studies are shown in table 2.3.

The application of the findings in the studies listed in table 2.3 to an athletic setting is limited because the protocols used were designed to cause muscle damage rather than model strength and power training sessions practiced by athletes (Atkinson & Nevill, 2001; Byrne *et al.*, 2004). Additionally, the participants recruited for the majority of these studies were not trained athletes, therefore the obtained results cannot confidently be applied to athletic populations, since trained athletes are thought to be less susceptible to muscle damage due to the repeated bout effect (McHugh, 2003; Byrne *et al.*, 2004; Marcora & Bosio, 2007) (see section 2.11.3). Furthermore, it has been argued that the lack of relation between the functional tests performed and the athletic history of the chosen participants serves to decrease the applied relevance and external validity of the findings involved (Atkinson & Nevill, 2001; Byrne *et al.*, 2004). Yet, the vast majority of studies reported in the literature have continued to measure non-sports specific functional performance (in relation to the recruited participants) when investigating muscle damage (Raastad & Hallen, 2000; Byrne & Eston, 2002a; 2002b; Marginson *et al.*, 2005; Skurvydas *et al.*, 2006; Skurvydas *et al.*, 2008; Twist *et al.*, 2008).

Table 2.3 Studies assessing the effect of acute bouts of strength and plyometric training on sport specific power producing ability

Study	Participant description	Muscle damaging exercise	Muscle damage	Performance
Studies using a bout of strength training	Reastad & Hallen (2000)	3 sets x 3 repetitions with back squats and front squats, 3 sets x 6 repetitions knee extensions	CK increased at 7, 11, 22 and 33 h	SSJ height decreased at 3, 7, 11 and 22 h
	Byrne & Eston (2002a)	8 (5 male, 3 female) recreationally active non-strength trained participants	10 sets x 10 repetitions of barbell squats at 70% body mass load	SSJ, CMJ and drop jumps (DJ) all reduced at 1, 24, 48 and 72 h
	Byrne & Eston (2002b)	7 (5 male, 2 female) recreationally active non-strength trained participants	10 sets x 10 repetitions of eccentric phase of barbell squats at 80% concentric 1 RM	Wingate peak power output (PPO) reduced at 1, 24, 48 and 72 h
	French <i>et al.</i> (2008)	26 males, recreational to regional standard games sport athletes with > 1 year of prior strength training	6 sets x 10 repetitions barbell squats at 100% body weight	CMJ reduced at 48 h. No change in 10 to 30 m sprint time. No change in agility test time
	Hoffman <i>et al.</i> (2010)	15 male strength and power athletes	4 sets x 10 repetitions with 80% 1 RM squat, deadlift and barbell lunge	Decreases at 24 and 48 h for number of repetitions for squat at 80% 1 RM and peak and mean squat power
	Semark <i>et al.</i> (1999)	25 male rugby union and field hockey players	7 sets x 10 repetitions of DJ	No effect on 5, 10, 20 or 30 m run sprint
	Marginson <i>et al.</i> (2005)	10 males	8 sets x 10 repetitions of CMJ	SSJ and CMJ height decreased at 0.5, 24, 48 and 72 h
	Twist & Eston (2005)	10 male university team sport athletes	10 sets x 10 repetitions of CMJ	Cycling PPO decreased at 0.5, 24, 48 and 72 h. 10 m run sprint performance decreased at 0.5, 24 and 48 h
	Skurvydas <i>et al.</i> (2006)	12 recreationally active non-strength trained males	5 sets x 20 repetitions of CMJ	CMJ decreased at 2 and 24 h
	Twist and Eston (2007)	19 (12 male, 7 female) recreationally active non-strength trained participants	10 sets x 10 repetitions of CMJ	DJ decreased at 24, 48 and 72 h. Cycling PPO decreased at 24 and 48 h
Studies using a bout of plyometric training	Skurvydas <i>et al.</i> (2008)	11 recreationally active non-strength trained males	Soreness increased at 24, 48 and 72 h. CK increased at 24 and 48 h	DJ decreased at 1, 4, 8, 24 and 48 h
	Davies <i>et al.</i> (2009)	11 (7 female, 4 male) university netball and basketball players	5 sets x 20 repetitions of DJ from 60 cm platform	Decreased 5, 10 and 20 m run sprint performance at 48 h. No effect on CMJ or agility test
	Highton <i>et al.</i> (2009)	12 recreationally active non-strength trained participants	10 sets x 10 repetitions of CMJ	Decreased 5, and 10 m run sprint and agility run performance at 24 and 48 h

2.10 Endurance performance following EIMD

There has only been one study which has assessed endurance performance following a protocol of free weight resistance training exercises. This study was conducted by Scott *et al.* (2003), who had physically active participants perform a 30 min sub-maximal treadmill run before and 24-30 h after a bout of strength training. The strength training session featured the barbell squat, weighted lunge, weighted step up and stiff leg deadlift. Each exercise was performed with 3 sets of 10 repetitions. In the post-strength training, running trial, measures of $\dot{V}O_2$ and $[Lac^-]$ were unaffected, compared to the baseline trial, despite increased ratings of perceived exertion (RPE) throughout the trial. The authors theorised that the increased RPE was likely due to the significant muscle soreness experienced by the participants' following strength training. The authors offered three explanations as to why $\dot{V}O_2$ was unaffected following strength training; a) the extent of muscle damage was insufficient to produce mechanical or physiological changes that could alter $\dot{V}O_2$; b) undamaged muscle fibres may have been recruited from the available pool of fibres and were able to compensate for any damaged fibres; and c) the resistance exercises used to induce delayed onset muscle soreness (DOMS) were not sufficiently specific to affect responses to running activity. The authors recommended that athletes select low intensity training sessions when they are experiencing DOMS.

Aside from the study by Scott *et al.* (2003), various authors have assessed the impact of muscle damaging exercise challenges (commonly high volume protocols of jumps or barbell squats and prolonged downhill running) on subsequent cycling or running endurance performance. This research has generally involved either assessment of physiological responses during sub-maximal exercise (Gleeson *et al.*, 1995; Calbet *et al.*, 2001; Braun & Dutto, 2003; Scott *et al.*, 2003; Chen *et al.*, 2007; Chen *et al.*, 2008) or incremental tests to volitional exhaustion (Gleeson *et al.*, 1998; Davies *et al.*, 2008; Davies *et al.*, 2009a). Descriptions and findings of the studies featuring bouts of strength training and plyometric jumps are shown in table 2.4. Across these studies, endurance performance has been negatively affected following the exercise challenges. However, the use of the featured endurance protocols has been questioned on the basis that they possess low ecological validity since the featured protocols do not simulate or model the demands imposed throughout a typical endurance cycling or running event (Schabert *et al.*, 1998; Atkinson & Nevill, 2001).

In terms of athletic performance, a more reliable and externally valid means of assessing endurance performance would involve protocols in which athletes are required to complete a fixed amount of work or to cover a given distance in the shortest possible time

[time trial] or to complete a maximal amount of work in a specific time period (Schabert *et al.*, 1998; Atkinson & Nevill, 2001; Hopkins *et al.*, 2001) following muscle damage. This style of protocol was used in studies by Marcora & Bosio (2007) and Twist & Eston (2009) who both reported ~ 4 % decreases in the distance run in 30 min and the distance cycled in 5 min, respectively, following muscle damaging protocols involving plyometric jumps. Considering the lack of physiological changes during the follow up time trials in each of these studies, the authors attributed decreases in performance to the increased sense of effort reported by the participants. The authors reasoned that participants compensated for the increased sense of effort by exercising at a lower power output, so that their RPE was maintained within tolerable limits. In these studies, despite the exercise tests being more applicable to the athletic setting than those previously discussed, the participants were not trained endurance athletes. In light of this issue, Marcora & Bosio (2007) cautioned that their results could not confidently be applied to high level athletes, since this population might be less susceptible to exercise induced muscle damage due to the repeated bout effect.

Table 2.4 Studies assessing the effect of acute bouts of strength and plyometric training on endurance performance

Study	Participant description	Muscle damaging exercise	Muscle damage	Performance
Scott <i>et al.</i> (2003)	16 (8 male, 8 female) recreationally active participants who ran > 3x weekly, non-strength trained	3 sets x 10 repetitions with barbell squat, weighted lunge, weighted step up and stiff leg deadlift	Soreness increased at 12, 24, 36 and 60 h	Follow up trial at 24-30 h: $\dot{V}O_2$ and [Lac ⁻] were unaffected during submaximal run. Increased ratings of RPE throughout the trial
Marcora and Bosio (2007)	30 (24 male, 6 female) recreational trainers: sports science students and runners, non-strength trained	10 sets x 10 repetitions of DJ from 35 cm platform	Increased CK and soreness at 48 h. No effect on limb girths	30 min run TT performance decreased by 4 % at 48 h. Trend for increased RPE. $\dot{V}O_2$ and [Lac ⁻] were unaffected
Davies <i>et al.</i> (2008)	9 recreationally active males, non-strength trained	10 sets x 10 repetitions smith machine squats at 70 % body mass load	CK and soreness increased at 24 and 48 h	Reduced time to exhaustion in incremental cycling test at 48 h. RPE and $\dot{V}O_2$ unaffected throughout trial
Davies <i>et al.</i> (2009)	10 recreationally active males, non-strength trained	10 sets x 10 repetitions smith machine squats at 70 % body mass load	CK increased at 24 h. Soreness increased at 0.5 and 48 h	Reduced time to exhaustion in cycling incremental test at 48 h. RPE increased in follow up trial
Twist and Eston (2009)	7 recreationally active non-strength trained participants	10 sets x 10 repetitions of CMJ	Soreness increased at 48 h	5 min cycle TT performance decreased by 4 % at 48 h. $\dot{V}O_2$ and [Lac ⁻] decreased. Authors attributed increased perceived exertion for performance decrease

2.11 The effect of short-term protocols of strength training on strength and power

Several researchers have investigated the effects of short term protocols (four to seven days) of strength training on various aspects of muscle function (Hakkinen *et al.*, 1988a; Warren *et al.*, 1992; Fry *et al.*, 1994a; Fry *et al.*, 1994b; Fry *et al.*, 1994c; Kraemer *et al.*, 2006). However, none of these studies employed functional tests which assessed endurance performance. In a study by Kraemer *et al.* (2006), participants described as ‘resistance trained males’ performed whole body strength training featuring eight free weight exercises each employing 3 sets of 10-12 repetitions on four consecutive days. Twenty-four hours after the final session participants experienced significant decreases in 1 RM squat and bench press. Using a squat protocol featuring 8 sets of 1 repetition at 95 % 1 RM for five consecutive days, Fry *et al.* (1994a) reported significant decreases in 9 and 37 m running sprint performance in weight trained males. Fry *et al.* (1994c) reported decreases in isokinetic strength using a similar squat protocol and participant population (10 sets x 1 repetition at 100 % 1 RM for seven consecutive days). Research involving increased short term training load in competitive elite weightlifters have featured a much higher training volume than was featured in the aforementioned studies. Hakkinen *et al.* (1988a), Warren *et al.* (1992) and Fry *et al.* (1994b) subjected weightlifters to two or three daily strength training session over seven days, which represented a 100 % increase in regular training volume. Performance on the competition lifts; the snatch and clean and jerk, were unaffected 24 h after the protocols. These findings suggest that the effects of strength training on muscle function are highly influenced by the athletic status of the featured participants, with elite strength trained athletes having a greater ability to recover muscle function following periods of high volume strength training in comparison to recreational strength trainers. This superior tolerance to training has been attributed to positive adaptations occurring within the endocrine system from exposure to high volume training Fry *et al.* (1994c). These include a greater maintenance of testosterone levels and the testosterone to cortisol ratio in response to high volume strength training.

2.12 Potential mechanisms associated with loss of muscle function following muscle damaging exercise

There have been a number of proposed theories for the decrease in muscle function following muscle damaging exercise. Theories attributed to explain decrements in muscle function feature both peripheral and central factors, however as highlighted by Warren *et*

al. (2002) reduced performance is likely to be the result of a complex interaction of a number of mechanisms.

2.12.1 *Peripheral factors*

The initial dysfunction occurring as a consequence of damaging eccentric exercise has been attributed to the over-stretching and disruption of sarcomeres and damage to the Excitation-Contraction (E-C) coupling system (Morgan & Allen, 1999; Warren *et al.*, 2001). When the myofibrils of a muscle fibre are stretched while contracting, some sarcomeres resist the stretch more than others (Proske & Allen, 2005). It appears that sarcomeres acting on the descending limb of the force-length curve are preferentially disrupted, after which they then return to their resting length (Morgan & Allen, 1999). However, with repeated eccentric actions a growing number of sarcomeres will become overstretched starting with the weakest. Upon subsequent muscle relaxation myofilaments in some overstretched sarcomeres may not re-engage, and the force production of the muscle fibre becomes affected as the disrupted sarcomeres can no longer contribute to force production (Morgan & Proske, 2004). This effect is thought to be the initial cause of reduced muscle function following damaging exercise (Proske & Allen, 2005).

Excitation-Contraction coupling is the sequence of events that starts with the passage of the action potential along the sarcolemma and ends with the release of calcium ions (Ca^{2+}) from the sarcoplasmic reticulum (Ingalls *et al.*, 1998). It has been suggested that damage to the E-C coupling system occurs after the initial damage to sarcomeres (Morgan & Allen, 1999; Proske & Morgan, 2001). Damage to the E-C coupling system involves disruption to the t-tubules, sarcolemma and the sarcoplasmic reticulum (Takekura *et al.*, 2001). These disruptions result in a reduced rate of Ca^{2+} release from the sarcoplasmic reticulum and a reduction in tension during evoked contractions (Warren *et al.*, 1993; Ingalls *et al.*, 1998). Damage to the E-C coupling system is thought to have a lesser impact on dynamic movements which feature the stretch-shortening cycle (for example counter movement jump) since the preparatory pre-stretch increases the duration of the muscle's active state allowing more Ca^{2+} to become available to the myofibrils. This explanation has been attributed for the comparative maintenance of counter movement jump height in relation to static squat jump height following muscle damaging exercise (Byrne & Eston, 2002a).

After these initial processes, another mechanism involving muscle fibre degeneration and regeneration (Kendall & Eston, 2002) has been associated with losses in muscle function. At this stage, around 24-48 h after the damaging event, symptoms of DOMS appear and subside, mediated by the inflammatory response that accompanies

muscle fibre damage (MacIntyre *et al.*, 1996). It is suggested that this muscle fibre damage is preferential to type II fibres (Byrne *et al.*, 2004). The tension generated during eccentric muscle actions is higher than that for either isometric or concentric actions (Roig *et al.*, 2009). In spite of this, reduced motor unit activation is present during eccentric actions (Enoka, 1996). The result of this is an increased stress on a smaller number of active fibres during eccentric actions. Consequently numerous authors have reported selective damage to type II muscle fibres after exercise which favours eccentric muscle actions (Friden *et al.*, 1983; Choi *et al.*, 2011). Friden and Lieber (1992) proposed that during the initial stages of eccentric exercise, type II fibres become instantaneously fatigued due to their low oxidative capacity and as a consequence of being unable to regenerate ATP, these fibres enter a state of rigor, resulting in mechanical disruption. The structure of type II fibres renders them less robust than type I fibres to cope with the stress of intensive exercise. Type II fibres possess narrower Z-lines equating to lower thick and thin filament attachment and therefore weaker sacromere connection (Friden *et al.*, 1983).

2.12.2 Central factors

Central nervous system mediated decreases in muscle activation in response to heavy resistance exercise are likely the result of either a decrease in central neural drive or proprioceptive feedback from the muscle due to soreness and swelling (Hakkinen, 1993). The twitch interpolation technique, which features direct stimulation of active muscle, has been used to assess voluntary activation after eccentric exercise (Rutherford *et al.*, 1986; Newham *et al.*, 1987; Saxton & Donnelly, 1996). Using this technique any additional force produced during an maximal voluntary contraction (MVC) by an superimposed electrical impulse is the result of incomplete (< 100 %) voluntary activation and highlights the presence of central fatigue (Byrne *et al.*, 2004). However, findings from studies using this approach have indicated that the level of voluntary activation during MVCs is the same following EIMD as to in a rested state (Rutherford *et al.*, 1986; Newham *et al.*, 1987; Saxton & Donnelly, 1996). Therefore proprioceptive feedback from sore muscles resulting in voluntary inhibition is likely to cause decreases in function following EIMD rather than a decrease in the discharge rate of motor units (Hakkinen, 1993; Twist & Eston, 2009). In accordance with this, several authors have suggested that the detrimental effect of EIMD on endurance performance is mediated by an increased perception of effort (Marcora & Bosio, 2007; Davies *et al.*, 2009a; Twist & Eston, 2009). This increased sense of effort originates from increased levels of muscle soreness resulting from EIMD and leads to a self limiting effect on performance as a lower power output is selected in order to exercise within tolerable limits (Twist & Eston, 2009).

2.12.3 Repeated bout effect and mechanisms of protection in strength trained individuals

Unlike the aforementioned theories, the repeated bout effect is associated with a reduced loss of muscle function following damaging exercise. The repeated bout effect refers to when a novel bout of eccentric exercise induces skeletal muscle damage, but repeating the same exercise within several weeks results in significantly less damage and is characterised by a smaller reduction and faster recovery of parameters of muscle function (Nosaka *et al.*, 2001). Marginson *et al.* (2005) reported smaller decrements in maximal jump height following a damaging bout of plyometric jumps that was repeated two weeks after an initial bout. Eston *et al.* (1996) showed that a group performing 100 eccentric actions of the knee extensors encountered less severe symptoms of muscle damage in response to downhill running performed two weeks later.

It has been proposed that the adaptation process in response to damage from an initial bout of eccentric exercise involves repair of the damaged fibres and incorporation of additional sarcomeres in series. It is envisaged that the extra sarcomeres are added without changing fibre length, so that sarcomere length is less for a given fibre length (Proske and Morgan, 2001). As a consequence, during a stretch across a given portion of the muscle's working range, the initial sarcomere length will be less, and the stretch will be distributed across a larger number of sarcomeres. The presence of the extra sarcomeres produces a shift of the muscle's length-tension relation in the direction of longer lengths (Brockett *et al.*, 2001). It is therefore less likely for sarcomeres to be stretched onto the descending limb of their length-tension relation, which is the region of instability and disruption (Proske & Allen, 2005). Another characteristic of the repeated bout effect is that a complete recovery of muscle function following a damaging bout is not required for the protective effect to be expressed (Ebbeling & Clarkson, 1990). A secondary eccentric exercise bout performed in the early recovery stage (1-5 days) after the first exercise bout does not exacerbate muscle damage or retard recovery from the initial bout (Paddon-Jones *et al.*, 2000; Nosaka & Newton, 2002).

When viewing table 2.3 it seems apparent that studies recruiting participants from athletic populations have recorded lower decrements in functional performance following damaging exercise bouts than those recruiting from non-athletic populations. This is likely due to the individuals from athletic populations being previously exposed to exercise featuring muscle actions similar to those featured in the muscle damaging protocols. In section 2.11 the reviewed literature showed that individuals with a history of chronic strength training (competitive weightlifters) were able to tolerate short term protocols (four

to seven days) of strength training much better than less trained individuals. The performance of periods of intensive strength training has been shown to result in adaptations which result in a superior tolerance to the stress imposed by strength training. These adaptations include favourable effects on the endocrine system, protein synthesis and the central nervous system. Elite weightlifters with more than two years training experience exhibited significant post-exercise testosterone increases while no such increases existed for those with less than or equal to two years training (Kraemer *et al.*, 1992). Similarly, Fry *et al.* (1994b) found a group of weightlifters attending consecutive annual national training camps experienced increases in testosterone post training whereas the previous year decreases in the hormone were recorded, indicating an increased tolerance to the training load after the subsequent year. Hakkinen *et al.* (1988b) has showed an increase in a array of androgenic hormones following two years of training in elite weightlifters and concluded that prolonged intensive strength training in elite athletes may influence the pituitary, leading to increased serum levels of testosterone. The three aforementioned studies indicate that testosterone levels are increased with weightlifting training age. Since increased testosterone is strongly associated anabolism and adaptability (Kraemer & Ratamess, 2005), subsequently this should create more optimal conditions to utilise more intensive training leading to increased strength development.

Following a protocol of two weeks of daily strength training utilising leg press and hack squats, Raastad *et al.* (2003) recorded increases in 3-methyl-histidine urine excretion and urea blood concentration in strength trained males. The authors proposed that an increase in concentration of these two metabolites indicated an increased skeletal muscle protein turnover. Theoretically an increased protein turnover may lead to an increased rate of recovery due to a rapid exchange of damaged structures, which would subsequently allow a greater frequency of strength training (Raastad *et al.*, 2001). In addition to favourable effects on endocrine function and protein synthesis, it has been proposed that neural adaptation following strength training protects against exaggerated muscle damage and functional disruption (McHugh, 2003). High stress among a few active fibres has been suggested as a mechanism of damage (Friden *et al.*, 1983). It has been proposed that neural adaptation following strength training may lead to a better distribution of the workload among fibres (Nosaka & Clarkson, 1995). In studies involving protocols of eccentric training of 3 and 6 weeks duration the EMG per unit of force increased by ~ 20% (Komi & Buskirk, 1972; Hortobagyi *et al.*, 1996). This increase indicates contractile stresses are distributed among a greater number of active fibres and therefore a lower potential for fibre damage exists (McHugh *et al.*, 2001).

2.13 Markers and symptoms of EIMD

Direct damage to muscle structures following muscle damaging exercise can be measured by electron and/or light microscopy and histological techniques (Proske & Morgan, 2001). Using these methods the presence of disrupted sarcomeres and damage to the E-C coupling system can be observed (Morgan & Allen, 1999). With more relevance to training practice in the athletic setting and the current thesis, various indirect markers can give practitioners an indication of the damage incurred to muscle, a selection of which are discussed below.

2.13.1 *Intramuscular proteins*

The appearance of intramuscular proteins in the bloodstream is considered an indirect indicator of damage to muscle fibres. Measuring the concentrations of creatine kinase (CK), myoglobin and lactate dehydrogenase in the blood are most commonly used in EIMD research (Brentano and Krueel, 2011). Creatine kinase is an enzyme which catalyses the exchange of high-energy phosphate bonds between phosphocreatine and adenosine diphosphate produced during muscle contraction (Brancaccio *et al.*, 2007). Since CK is located almost exclusively in skeletal and cardiac muscle tissues it is said to be the most appropriate indicator of a breakdown in muscle cell structure (Lee *et al.*, 2002). Furthermore, CK does not typically leak out of undamaged cells, hence an increase is primarily interpreted as an increased permeability or breakdown of the muscle cell membrane (Friden & Lieber, 2001). In response to protocols of multi-joint free weight strength training and high volumes of squats and plyometric jumps CK values have been shown to generally peak at 24 h and stay elevated for 48 h following the exercise bout (Raastad & Hallen, 2000; Byrne & Eston, 2002a; 2002b; Twist & Eston, 2005; Skurvydas *et al.*, 2006; French *et al.*, 2008; Davies *et al.*, 2009b; Hoffman *et al.*, 2010). The accompanying decrements in functional performance in the aforementioned studies generally occurred for 48 h following the damaging bout, therefore it seems that CK provides a useful marker for dynamic functional impairment. Limitations do exist with monitoring CK in response to training stress. Basal levels of CK have shown high variability (TE = 19 %), also distinct low and high CK responders to exercise stress have been classified (Totsuka *et al.*, 2002), therefore the effects of imposed exercise interventions on CK levels must be interpreted with caution (Hartmann & Mester, 2000).

2.13.2 *Rating of perceived muscle soreness*

Delayed-onset muscle soreness (DOMS) is characterised by the sensation of muscle discomfort after intense exercise, with an on-set at 8-24 h and peak in intensity at 24-72 h (Miles & Clarkson, 1994). In the context of this thesis, DOMS might therefore affect

rowing performance when a race or high quality rowing session is programmed within 8-72 h after strength training exercise. The performance of unaccustomed exercise and activities which emphasise eccentric muscle actions are known to result in DOMS (Friden & Lieber, 2001; Proske & Morgan, 2001). Soreness is thought to arise from damage and inflammation of non-contractile connective tissue (Kendall & Eston, 2002). The soreness associated with DOMS can be described as tenderness, since pain is experienced during mechanical stimulation such as contracting, stretching or palpating the muscle rather than chronic pain resulting from overt muscle injury (Proske & Allen, 2005). The most common method of measuring perceived soreness is with the use of visual analogue scales (Spiering *et al.*, 2007). Typically the assessment of perceived soreness will involve participants being requested to perceive pain during a simple dynamic task, such as bodyweight squats, which provides mechanical stimulation of the musculature after which the visual analogue scale rating is given (Goodall & Howatson, 2008). Using this measurement tool, authors have recorded significant increases in soreness following free weight strength training and dynamic muscle damaging exercise protocols, persisting for 48 h to 72 h with peaks at 24 h and 48 h (Marginson *et al.*, 2005; Twist & Eston, 2005; Skurvydas *et al.*, 2006; Twist & Eston, 2007; French *et al.*, 2008; Davies *et al.*, 2009b; Highton *et al.*, 2009; Hoffman *et al.*, 2010).

2.13.3 Limb girths

Measurement of limb girths is a simple technique to assess oedema and swelling associated with the inflammatory response that occurs as a result of muscle damage (Clarkson *et al.*, 1992). Girth circumferences from the thigh, calf and upper arm have commonly been assessed following protocols aimed to induce muscle damage (Hart *et al.*, 2005; Howatson *et al.*, 2005; French *et al.*, 2008; Davies *et al.*, 2009b). When eccentric actions have been directed at a singular muscular site, for instance eccentric biceps curls for the upper arm, then significant and prolonged (72-96 h) increases in girth measurements have commonly resulted (Brockett *et al.*, 2001; Hart *et al.*, 2005; Howatson *et al.*, 2005). However, when whole body dynamic damaging protocols (plyometric jumps or barbell squats) have been implemented less severe increases in girths have resulted (Semark *et al.*, 1999; French *et al.*, 2008; Davies *et al.*, 2009a). Furthermore, no changes have resulted with participants who had been regularly exposed to similar eccentric actions (Davies *et al.*, 2009b). Indicating that the repeated bout effect counteracts muscle damage to the degree that potentially damaging exercise bouts do not result in pronounced oedema.

2.14 Summary

Strength training is practiced amongst rowers as an important part of their overall training programme. The relationships between assessments of strength and power and rowing performance suggest that the development of strength and power is integral to the maintenance and improvement of rowing performance. Furthermore imposed longitudinal strength training interventions have consistently led to improvements in rowing performance. However, descriptive information documenting the strength and conditioning practices within rowing is lacking. The documenting of strength and conditioning practices in rowing is required in order to produce externally valid intervention studies where these practices can be assessed. The effects of exercise-induced muscle damage on sport-specific functional performance have been assessed by previous authors. The bouts used to elicit damage commonly involve high volume protocols of plyometric jumps and barbell squats, and less frequently; batteries of strength training exercises. These protocols have led to acute (< 72 h) decrements in sports-specific muscle function. However, the imposed bouts have not accurately reflected the training practice of highly trained competitive athletes. Knowledge of the potential functional impairment caused by bouts of strength training modelled from qualitative insight into current training practices would create more applicable findings to the athletic setting. This information would be useful in the structuring of athlete training programs and the determination of appropriate frequency, intensity and volume of imposed bouts of strength training.

3. General methods

3.1 General methods

This thesis features a descriptive analysis of strength and conditioning practices within British rowing (chapter 4) and four progressive quantitative experimental studies designed to examine the impact of strength training on rowing performance and muscle function. For ease of interpretation the study in chapter 4 will be referred to as study 1, chapter 5 as study 2, chapter 6 as study 3, chapter 7 as study 4, and chapter 8 as study 5. The methods described in this chapter are those generic to the majority of studies. Studies 1, 3 and 4 were conducted at Teesside University following institutional ethical approval from the School of Social Sciences and Law. Studies 2 and 5 were performed at Northumbria University following institutional ethical approval from the School of Life Sciences. Participants recruited for the experimental studies were club standard rowers competing in national level events such as the ‘Head of the River Race’, the ‘Henley Royal Regatta’, the ‘National Rowing Championships of Great Britain’ and the ‘British Universities and Colleges Sports Rowing Championships’. Participants were recruited from rowing clubs throughout the North East of England via face to face contact at their place of training and also via email correspondence. After volunteering for the study, participants were informed of the procedures, associated risks and benefits before providing informed consent (Appendix A).

3.2 Descriptive analysis of strength and conditioning practices within British rowing

In order to ensure the planned intervention studies followed an externally valid design, in relation to strength training practices and testing procedures occurring within rowing, a descriptive analysis involving a questionnaire based study and two semi-structured interviews were performed.

3.2.1 Strength and conditioning practices in rowing

A survey was designed titled ‘Strength and conditioning questionnaire’, (Appendix B) which was an adapted version of the questionnaire developed by Ebben & Blackard (2001). The survey contained fixed-response and open-ended questions. The process of content analysis, described by Patton (1990), was used to decipher information from open-ended questions. The survey was distributed to coaches responsible for the strength and conditioning prescription of rowers and a total of 32 responses were received.

3.2.2 Strength and conditioning practices in rowing: perspectives of two elite coaches

Semi-structured interviews of an international rowing coach and the country's lead strength and conditioning practitioner employed by the British rowing and the English Institute of Sport respectively were undertaken (interview questions are shown in appendix C and D). Each interview lasted for approximately one hour and both were subsequently transcribed. Inductive and deductive content analysis were performed on the interview transcripts in accordance with methods described by Patton (1990) which led to the establishment of six primary themes;

- Coach information
- Strength training prescription
- Perceptions / opinions of the benefit of strength training to rowing
- Recovery from strength training
- Fitness testing
- Overall training programme structure

3.3 Strength training session

A similar strength training session (ST) was used for studies 3, 4, and 5. The exercise selections, intensity and volume of this session were devised based on descriptive information in study 1. For each study, ten days prior to commencement of the experimental protocols, the participants' one repetition maximum (1 RM) was assessed on the following exercises; snatch or snatch grip high pull, clean, back squat, bent over row or bench pull, and bench press according to guidelines provided by the National Strength and Conditioning Association (Baechle & Earle, 2008). In the ST, a load equivalent to 85 % of each participant's 1 RM was assigned to each of the aforementioned exercises. The load assigned for the Romanian deadlift was 75 % of the 1 RM achieved for the back squat exercise. It was reasoned that 1 RM assessment of this exercise would be problematic due to the movement characteristics, which involve controlling the eccentric portion of the lift (Brandon & Cleather, 2007). Slight changes to the session were made in subsequent chapters. In studies 4 and 5, the bent over row was excluded and replaced with the bench pull. In studies 4 and 5, 15 kg was used for weighted sit-ups instead of the original 10 kg. In study 5, the snatch was replaced with the snatch grip high pull.

In preparation for the ST, participants performed a warm-up, which involved exercises which mimicked those in the session with a 20 kg Olympic barbell. The

participants then completed the ST. This session featured Olympic weightlifting style exercises (the clean and the snatch / snatch grip high pull), and classical strength training exercises (the back squat, Romanian deadlift, bench press, bent over row / bench pull and weighted sit-ups). Two min rest was allocated between each set. Verbal encouragement was given to the participants during the performance of the featured exercises. These exercises are performed routinely by rowers (Ivey *et al.*, 2004; McNeely *et al.*, 2005) and the participants regularly performed the featured exercises in their training. In their supervised training period before the initiation of the studies, the participants generally followed a similar loading, rest period, set and repetition scheme as featured in the ST. On a limited number of isolated occasions participants failed to complete the final repetition of an exercise, in these cases the barbell load was reduced by 2.5-5 kg (under the discretion of the supervising experimenter) for the next set of the exercise.

3.4 Anaerobic strength and power tests

Throughout the intervention studies, anaerobic power tests were used to assess sports specific power producing ability. Listed below are the tests used frequently throughout the thesis chapters.

3.4.1 Maximal voluntary contraction (MVC)

For studies 2 and 5, maximal voluntary contraction force (MVC) of the right leg knee extensors was determined using a strain gauge (MIE Medical Research Ltd, Leeds, UK) (Figure 3.1). The strain gauge was attached to the right ankle while the participants' sat on a laboratory assessment chair with the internal knee joint angle at 90 ° (verified by a goniometer). This joint angle has commonly been used for assessment of MVC following bouts of muscle damaging exercise (Marginson *et al.*, 2005; Skurvydas *et al.*, 2006; Duffield *et al.*, 2010). Two submaximal trials at 70 %, and 90 % of perceived maximum followed by three maximal trials, each separated by 30 s, were completed. The MVC which produced the highest force output was used for data analysis. Each contraction lasted for approximately 3 s, and all participants were given verbal encouragement throughout.

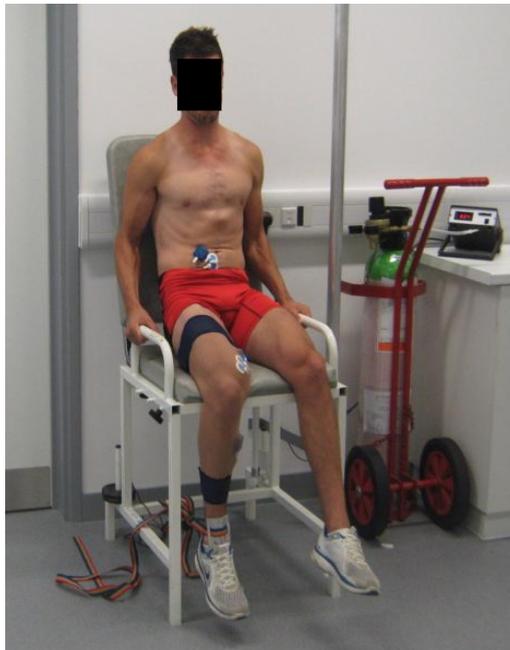


Figure 3.1 Maximal voluntary contraction of the leg extensors

3.4.2 *Static squat jump (SSJ) and counter movement jump (CMJ)*

The Just Jump measurement system (Just Jump, Probotics, Huntsville, AL, USA) was used for assessment of jump performance in studies 3 and 4 and an optical measurement system (Optojump Next, Microgate, Bolzano, Italy) was used for assessment of jump performance in studies 2 and 5 (Figure 3.2). Three (studies 2 and 5), four (study 3) and five (study 4) independent trials of both the static squat jump (SSJ) and counter movement jump (CMJ) were conducted with 30 s between each jump, the highest jump for each being recorded for data analysis. The participants positioned themselves in the centre of the Just Jump contact mat or two Optojump infrared units (depending on study) and were instructed to place their hands on the iliac crest. The SSJ test began from an erect standing position, from which participants were told to squat down to a position where their thighs were at a 90 ° angle in relation to the lower leg. Participants held this position for three seconds and then were instructed to jump vertically for maximal height. The CMJ test began from an erect standing position with participants maintaining their hands on the iliac crest. The participants squatted to their perceived optimal depth and immediately ascended to jump vertically for maximal height. The SSJ and CMJ tests have been commonly used to assess functional performance following muscle damaging exercise (Raastad & Hallen, 2000; Byrne & Eston, 2002a; Marginson *et al.*, 2005; Skurvydas *et al.*, 2006; French *et al.*, 2008) and are regularly used to monitor power in a wide variety of sports (Bret *et al.*, 2002; Apostolidis *et al.*, 2004; Di Cagno, 2008; Requena *et al.*, 2009).



Figure 3.2 Static squat jump and counter movement jump tests

3.4.3 Power strokes (PS)

For studies 2, 4, and 5, maximal stroke power was assessed using an air-braked rowing ergometer [Concept 2 Model C (for studies 2 and 5; figure 3.3) and Concept 2 Model D (for study 4), Concept 2 Ltd, Wilford, Notts, UK] with a drag factor set at 140 [in accordance with the British International Rowing guidelines for ergometer testing (Ingham *et al.*, 2007)]. Participants initially rowed sub-maximally for one min at which point they were instructed to perform two build up strokes which were followed by the first of five consecutive maximal effort power strokes (PS). All participants were required to hold a rate of 30 strokes per minute ($s \cdot \text{min}^{-1}$) during the PS, as described previously (Ingham *et al.*, 2002). For studies 2 and 5, surface EMG and handle force were measured during the power strokes, details of the methods relating to which can be viewed in 3.6.7 and 3.6.8.



Figure 3.3 Five power stroke test

3.5 2000 m rowing ergometer test

The 2000 m rowing ergometer test was used as the primary assessment of sports specific performance in studies 2, 4, and 5 (Figure 3.4). This test is commonly performed by competitive rowers for monitoring simulated race performance and can act a determining factor for crew selection (Kennedy & Bell, 2003; Webster *et al.*, 2006). Furthermore, 2000 m ergometer performance has been shown to strongly correlate with 2000 m single scull on-water performance in elite international male rowers ($r = 0.72-0.80$) (Mikulic *et al.*, 2009a; Mikulic *et al.*, 2009b).



Figure 3.4 2000 m ergometer test
with online gas analysis as used in studies 2 and 5

3.5.1 Ergometer and warm-up

For the aforementioned studies the test was performed on an air-braked rowing ergometer [Concept 2 Model C (for studies 2 and 5) and Concept 2 Model D (for study 4), Concept 2 Ltd, Wilford, Notts, UK] with a drag factor set at 140 [in accordance with the British International Rowing guidelines for ergometer testing (Ingham *et al.*, 2007)]. Before the initiation of the test, participants rowed sub-maximally for five min which acted as a warm-up.

3.5.2 Visual feedback

For study 4, during the test participants were given feedback from the rowing ergometer screen, which displayed the distance in metres, time in min:s, 500 m split time in min:s and $\text{s}\cdot\text{min}^{-1}$. This feedback was typical to that which the group of participants regularly experienced when performing rowing ergometer training and testing and has been used elsewhere in the assessment of the impact of training interventions on 2000 m ergometer performance (Ingham *et al.*, 2008). For studies 2 and 5, the only feedback given to participants was their stroke rate and distance remaining. Participants were only informed of their time for each trial at the completion of the final 2000 m trial. The feedback conditions were the same of those provided by Schabort *et al.* (1999).

3.5.3 Heart rate monitoring (HR)

For studies 2, 4 and 5, heart rate (HR) was recorded using the Polar monitoring system (Polar Electro, Kempele, Finland); participants wore a chest strap transmitter interfaced via short range telemetry with a wrist unit which then displayed the HR in beats per minute ($\text{b}\cdot\text{min}^{-1}$). A member of the experimental team held this unit and recorded the displayed value. For study 4, the value was recorded every 30 s during the test, whereas the value was recorded every 10 s for studies 2 and 5.

3.5.4 Rating of perceived exertion (RPE)

For all studies, participants reported their rating of perceived exertion (RPE) [6-20 scale; Borg (1970)] from a visual scale immediately after the test was completed.

3.5.5 Blood lactate assessment [Lac^-]

For studies 2, 4 and 5 capillary blood samples for the assessment of [Lac^-] were drawn at the completion of the test and at 1-, 3-, 5- and 7 min of recovery (see 3.8.1 Blood lactate analysis).

3.5.6 Expired respiratory gas parameters

During studies 2 and 5, expired breath-by-breath respiratory gas exchange parameters [oxygen consumption ($\dot{V}\text{O}_2$) and carbon dioxide production ($\dot{V}\text{CO}_2$)] were measured continuously using an automated online metabolic cart (Cortex, Metalyzer, Leipzig, Germany), which has previously been demonstrated to be a valid and reliable instrument for measurement of such parameters during exercise (Meyer *et al.*, 2005). Data from the metabolic cart [$\dot{V}\text{O}_2$, respiratory exchange ratio (RER)] were interpolated and averaged over 1 s intervals. Calibration of the gas analyser and accompanying flow turbine were performed before each trial using certified standard gases [15.00 % oxygen (O_2), 5 %

carbon dioxide (CO₂) and a 3 L syringe (Hans Rudolph, Kansas City, USA). Contributions of aerobic (P_{aer}) and anaerobic metabolism (P_{anaer}) to mean power (P_{tot}) during each 500 m stage were calculated according to methods previously described (de Koning *et al.*, 1999) using a established exercise efficacy for trained rowers performing 2000 m ergometer testing (Hagerman *et al.*, 1978).

3.5.7 Surface electromyography analysis (EMG)

For studies 2 and 5, surface EMG was recorded from seven anatomical sites and measured during power strokes and the 2000 m test. In addition during study 5, EMG of the vastus medialis was solely recorded during the MVC measurement. Preparation and placement was performed in accordance with the SENIAM guidelines (Hermens *et al.*, 2000) with exception of the rectus abdominis and latissimus dorsi for which procedures described by Ng *et al.* (1998) and Horsley *et al.* (2010) respectively were adopted, (see table 3.2 for description of sites and placement). For each site, reduction in skin impedance was achieved before attachment of the electrodes by shaving and cleaning with alcohol followed by skin abrasion with a standard electrode gel constituent and paper towel (Norrbrand *et al.*, 2010). Surface EMG was collected at a sampling frequency of 1000 Hz and amplified (1000x) using a 16 channel wireless telemetric system (Myon RFTD-E16, Myon AG, Baar, Switzerland) interfaced with a multifunction data acquisition module (USB-6210, National instruments, Austin, Texas, USA). Data were recorded within commercially available software (MyoResearch XP, Noraxon, Scottsdale, Arizona, USA) prior to being exported for analysis within alternative software (LabChart 7, AD Instruments, Oxford, UK). Once exported the raw EMG data were high pass filtered with a cut off frequency of 15 Hz and the filtered data were fully rectified. Mean rectified EMG recorded during each 500 m stage of the 2000 m test and during the MVC was normalised against the mean rectified EMG recorded during the PS, and subsequently expressed as a percentage. Peak EMG recorded during the MVC was normalised against the peak EMG recorded during the PS.

Table 3.1 Description of EMG electrode placement locations and orientations used during the 2000 m test and power strokes for studies 2 and 5

Anatomical sight	Location	Sensor orientation
Gastrocnemius (medialis)	On the most prominent bulge of the muscle.	In the direction of the leg.
Rectus abdominis	Electrodes were placed in a cephalad/caudad orientation at 2 cm inferior to the navel and 1 cm lateral to the midline.	Vertical.
Biceps femoris	The electrodes were placed at 50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia.	In the direction of the line between the ischial tuberosity and the lateral epicondyle of the tibia.
Gluteus maximus	Electrodes were placed at 50% on the line between the sacral vertebrae and the greater trochanter. This position corresponds with the greatest prominence of the middle of the buttocks well above the visible bulge of the greater trochanter.	In the direction of the line from the posterior superior iliac spine to the middle of the posterior aspect of the thigh.
Latissimus dorsi	The electrodes were placed 2 cm apart, approximately 4 cm distal to the inferior angle of the scapula.	At an oblique angle of approximately 25 degrees.
Erector spinae (longissimus)	The electrodes were placed at 2 finger width lateral from the proc spinosus of L1.	Vertical.
Vastus medialis	Electrodes were placed at 80% on the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament.	Almost perpendicular to the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament.

3.5.8 Force analysis

For studies 2 and 5, the rowing ergometer was instrumented with a load cell (RLTO500 kg, RDP Electronics Ltd, Wolverhampton, UK) located in series between the handle and drive chain. This was interfaced with a data acquisition module (PowerLab 4.5, AD Instruments, Oxford, UK) with the analogue data recorded using LabChart 7 (AD Instruments, Oxford, UK). The analogue data were converted from Volts to Newtons using an equation determined during the calibration (see below), which was performed prior to data collection. Mean data were presented for each 500 m segment of the 2000 m trial.

$$\text{Force} = \text{volts} \times 535.41$$

Handle position was measured using a draw wire potentiometer (SR1A-125, Celesco, Chatsworth, USA) which was mounted next to the flywheel of the rowing ergometer. The

draw wire was attached to the load cell so that the wire travelled parallel to the chain of the ergometer. The sensor provided a voltage reading that indicated position. This was interfaced with a data acquisition module (PowerLab 4.5, AD Instruments, Oxford, UK) with the analogue data recorded using LabChart 7 (AD Instruments, Oxford, UK). The voltage was converted to position using the following equation

$$\text{Position} = \text{volts} \times -0.1381$$

3.6 Markers of muscle damage

Indirect markers of muscle damage were assessed before and after the prescribed strength training bouts. Rating of perceived soreness, and creatine kinase (described in blood analysis section) were assessed for all experimental studies, limb girths were assessed for studies 2, 3, and 4 and lactate dehydrogenase was assessed in study 4 (described in blood analysis section).

3.6.1 Rating of perceived soreness

In all experimental studies, rating of perceived muscle soreness was assessed via a visual analogue scale (Appendix E), previously used in the literature (Avery *et al.*, 2003; Spiering *et al.*, 2007). This scale was a 10 cm long horizontal line anchored at either end with a small vertical line. Each anchored point was labelled as either ‘No pain / soreness’ (on the most left point of the scale representing a rating of zero) or ‘Pain / soreness as bad as it could be’ (on the most right point of the scale representing a rating of ten), respectively. Participants were instructed to mark their level of subjective pain using a vertical line along the continuum. The distance of the participants’ mark on the scale in relation to the left most point of the scale was measured in cm and this distance represented their soreness rating.

3.6.2 Limb girths

During experimental studies 2, 3, and 4, limb girth measurements were taken from the mid-thigh, mid-calf and upper arm using a standard tape measure in adherence with procedures produced by Lohman (1988). To ensure consistency all measurements were assessed on the right side of the body and the same experimenter assessed girths on all testing occasions. Participants stood in the anatomical resting position for all girth measurements. Mid-thigh girth was measured around a point equidistant from the trochanterion and the tibiale laterale. Mid-calf girth was found by moving the position of

the tape measure up and down the limb segment to find the maximal segmental girth. Upper arm girth was measured around a point equidistant from the acromion process of the scapula and the head of the radius.

3.7 Blood analysis

Throughout the series of experimental studies, finger-tip capillary blood samples were collected for analysis of certain biomarkers. $[\text{Lac}^-]$ was analysed during studies 2, 4 and 5. Creatine kinase was measured during all experimental studies and Lactate dehydrogenase was measured during study 4.

3.7.1 Blood lactate analysis $[\text{Lac}^-]$

For study 4, a 20 μL capillary blood sample was collected for analysis of $[\text{Lac}^-]$ using the YSI 2300 STAT Plus™ (YSI Inc. Yellow Springs, OH, USA) which had detection limits between 0 to 30 mmol/L^{-1} . The analyser ran a self calibration programme which was repeated during every 15 min of use. For studies 2 and 5, a 20 μL capillary blood sample was taken for analysis of $[\text{Lac}^-]$ using the Biosen C_Line Sport (2 channel) lactate and glucose analyser (EKF Diagnostic, Barleben, Germany), which has detection limits between 0.5 to 40.0 mmol/L^{-1} . The analyser ran a self-calibration programme which initiated once the unit was switched on and repeated during every hour of use.

3.7.2 Creatine kinase analysis (CK)

For studies 3 and 4, to determine plasma creatine kinase (CK) activity, a capillary blood sample of 70 μL was collected. This sample was then centrifuged at 2000 revolutions per minute ($\text{r}\cdot\text{min}^{-1}$) for 8 min and 10 μL of plasma supernatant was drawn from the capillary tube with a pipette. The supernatant was then dispensed onto designated test slides and the VITROS® DT60 II Chemistry System (Ortho-Clinical Diagnostics, Rochester, NY, USA), which had been calibrated prior to use, was used for analysis. During studies 2 and 5, Blood CK concentration was determined using the Reflotron® Plus (Roche, Grenzach-Wyhlen, Germany), which has detection limits of 24-1400 International units (U/L). Analysis required a 30 μL capillary whole blood sample being dispensed onto designated test strips.

3.7.3 Lactate dehydrogenase analysis

For study 4, to determine plasma lactate dehydrogenase (LDH) activity, a capillary blood sample of 70 μL was collected. This sample was then centrifuged at 2000 $\text{r}\cdot\text{min}^{-1}$ for 8 min and 10 μL of plasma supernatant was drawn from the capillary tube with a pipette. The

supernatant was then dispensed onto designated test slides and the VITROS® DT60 II Chemistry System (Ortho-Clinical Diagnostics, Rochester, NY, USA), which had been calibrated prior to use, was used for analysis.

3.8 Statistical analysis

Due to different statistical methods being used across the experimental studies, statistical methods will be described in each chapter.

4. Descriptive analysis of strength and conditioning practices within British rowing

4a. Strength and conditioning practices in rowing

4a.1 Introduction

Rowing is an Olympic sport which is popular worldwide and is considered one of the most demanding endurance sports (Russell *et al.*, 1998). A typical rowing competition takes place over 2000 m rowing course and lasts 5.5-7.0 min (Maestu *et al.*, 2005b). The dominant energy contribution in race rowing is from aerobic metabolism (Messonnier *et al.*, 1997), however anaerobic qualities such as muscular strength and power are also seen as important predictive factors in terms of the overall performance (Celik *et al.*, 2005). Research has identified rowing specific strength and power to correlate well to 2000 m ergometer performance. For example Riechman *et al.* (2002) found that 76 % of the variation in 2000 m rowing ergometer performance time was predicted by peak power in a 30 s rowing Wingate test while Secher (1975) observed that maximal isometric rowing strength is significantly higher in international rowers than both national and club rowers. In a study by Ingham *et al.* (2002) international rowers performed five maximal rowing strokes. Maximal power and force produced during the five strokes were highly correlated with 2000 m ergometer performance ($r = 0.95$). Rowing performance has also been found to be related to lower body strength and power. Battista *et al.* (2007) reported that varsity rowers possessed higher vertical jumps than novice rowers (~ 3 cm). Russell *et al.* (1998) have found maximal isokinetic knee extension at 1.05 radians per second to be significantly correlated ($r = -0.40$) with 2000 m ergometer time and Yoshiga & Higuchi (2003a) found 2000 m ergometer performance to significantly correlate ($r = 0.62$) with bilateral leg extension power in a study of 332 young oarsmen. These findings suggest that strength and power are essential physical components in rowing. Indeed the limiting factors to optimal performance in rowing have been identified as maximum strength, starting power, and muscular endurance for medium (2000 m) to long distances (6000 m) (Steinacker, 1993).

It has been shown that rowing performance is highly correlated with maximal strength and power; therefore it would seem appropriate that rowers should concentrate on developing these qualities (Secher, 1975; Russell *et al.*, 1998; Ingham *et al.*, 2002;

Riechman *et al.*, 2002; Yoshiga & Higuchi, 2003a; Ivey *et al.*, 2004; Battista *et al.*, 2007). Maximal strength and power have been shown to be optimally developed by training with heavy loads and low repetitions per set of an exercise (Campos *et al.*, 2002; Newton *et al.*, 2002). Indeed, McNeely *et al.* (2005) recommend a resistance training programme that focuses on the development of maximum strength, with low repetitions and loading between 85-95 % of one repetition maximum (1 RM) being the most effective for improving rowing performance. Electromyography analysis suggests that the muscle groups that are used during rowing are active in combination (Wilson, 1988). Therefore it is recommend that rowers perform strength training exercises that require the upper and lower body to work together in a coordinated manner, leading to whole body strengthening (Rodriguez *et al.*, 1990). Olympic Weightlifting techniques, as well as the squat and the deadlift are whole body exercises requiring coordinated actions of many muscle groups for their successful performance (Escamilla *et al.*, 2000b; Gourgoulis *et al.*, 2000; Miletello *et al.*, 2009), which is why these exercises have been highlighted as appropriate for rowers (Ivey *et al.*, 2004; McNeely *et al.*, 2005). Ebben *et al.* (2004b) found that an eight week resistance training programme based around the aforementioned exercises led to improvements in performance time, total power and power per stroke during a 2000 m rowing ergometer test in both novice and varsity female university rowers.

Despite these findings few articles have described or made recommendations for strength and conditioning practices in rowing. Indeed only two guides for strength and conditioning prescription and assessment of rowers have been published. A guide for strength training prescription for the preparatory training phase in collegiate female rowers has been published (Ivey *et al.*, 2004). This guide gave recommendations for anatomical adaptation, maximum strength and power training, fitness testing, injury prevention and flexibility development. The 'maximum strength' training phase described in this plan featured two sessions a week and generally three sets of eight repetitions were prescribed per exercise. This phase involved mainly strength based exercises such as squats, bench press, low cable row, step-ups, bent over row and Romanian deadlift. However, power based exercises such as the hang clean (on day one) and high pull (on day two) were also included. A 'power' training phase was also described. This phase featured three workouts a week during which more power based exercises were prescribed including the hang clean, dumbbell push jerk, power shrugs, step up with jump, vertical jumps with a weighted vest and various explosive medicine ball exercises. Sets and repetitions on these power exercises generally ranged between three to five sets and three to five repetitions. Some strength based exercises were also included within this phase and generally

performed for two to three sets of eight repetitions. McNeely *et al.* (2005) have published a report documenting recommended strength and power tests, and performance goals for competitive rowers. This report recommended 1 RM testing on the squat, bench pull and deadlift for assessment of maximum strength, and a 30 s ‘modified Wingate test’ on the rowing ergometer to assess anaerobic power. The authors also list strength to body mass standards for the squat, bench pull and deadlift, and power output standards for the 30 s rowing sprint test that should be achieved across differing levels of rower. Currently these articles by Ivey *et al.* (2004) and McNeely *et al.* (2005) are the only published research which has given clear guidelines for strength training prescription for rowing.

To date there have been a number of studies which have focused on the strength and conditioning practices of strength and conditioning coaches in North America (Sutherland & Wiley, 1997; Ebben & Blackard, 2001; Durell *et al.*, 2003; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). However, to the author’s knowledge there is no research addressing strength and conditioning prescription within rowing or indeed any continuous endurance sport. Information related to common trends in exercise prescription for rowers could act as a useful reference source when designing training programmes and developing ecologically valid intervention studies.

The aim of this study was to survey a variety of training practices of coaches responsible for the strength and conditioning of rowers.

4a.2 **Methods**

4a.2.1 Experimental approach to the problem

The survey titled ‘Strength and conditioning questionnaire’ was adapted from research by Ebben & Blackard (2001). The adapted questionnaire was pilot tested with an advisory group of six strength and conditioning coaches and exercise physiologists. The survey contained six sections: personal details, physical testing, strength and power development, flexibility development, unique aspects of the programme and any further relevant comments regarding the athlete’s prescribed training programme. The survey was distributed to rowing coaches and strength and conditioning coaches who worked with rowers throughout Great Britain. Great Britain is presently one of the most successful rowing nations in the world. In the 2008 Olympics in Beijing and the 2004 Olympics in Athens, Great Britain finished first and third respectively in the rowing medal table. With the considerable global success of British rowers it was envisaged that the data obtained

from this survey on strength and conditioning practices would provide a useful reference to be used worldwide by those involved in the preparation of rowers.

4a.2.2 Data collection

Before the initiation of data collection ethical approval was granted by Teesside University. Mailed surveys were sent with a self-addressed, stamped envelope, and an introductory letter describing the project was included with all mailed questionnaires. A number of coaches were also approached face to face at their place of work and rowing competitions. Data was collected between May 2007 and May 2008.

4a.2.3 Data analysis

The survey contained fixed-response and open-ended questions. Answers to open-ended questions were content-analysed according to methods described by Patton (1990) which have been previously used in other surveys of professional sports strength and conditioning practices (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). Investigators were trained and experienced with qualitative methods of sports science research and content analysis. For data analysis, each investigator generated raw result data and higher-order themes via independent, inductive content analysis and compared independently generated themes until agreement was reached at each level of analysis. When higher-order themes were developed, deductive analysis was used to confirm that all raw data themes were represented.

4a.3 Results

4a.3.1 Personal details

Thirty two (28 male, 4 female) of 54 (59.3 %) coaches responded to the questionnaire. Twenty two of the participants were rowing coaches and the other ten were strength and conditioning coaches. All coaches were currently engaged in strength and conditioning activities with rowers at the time of data collection. Mean age of the participants was 31.7 ± 5.8 years. Mean coaching experience was 10.5 ± 7.2 years. Twenty five coaches reported having fellow coaching staff. Examples of fellow staff given by respondents were; “Sports science support team”, “Work within a coaching team of four, shared responsibilities for coaching university group”, or with, “World class start colleagues (coaches of national youth-age rowers)” or as, “Part of a coaching team of 12 coaches for Olympic squad backed up two chief coaches” (texts in italics are direct quotations taken from the

completed questionnaires). Table 4a.1 provides a breakdown of the rowing coaches in terms of the highest level of athlete they had coached.

Table 4a.1 Highest level of athlete worked with by coaches

Olympic	National	Regional	Club	University
11	11	1	6	3

4a.3.2 Formal education

Eighty one percent of respondents held a bachelors degree, and 34 % held a masters degree. Of those who held a bachelors or a masters degree 54 % and 82 % were in an exercise science or related field respectively. One respondent held a postgraduate certificate in education (PGCE) while two held PhDs.

4a.3.3 Certification

4a.3.3.1 Rowing coaches

The most prevalent certifications were those offered by the Amateur Rowing Association of Great Britain (n = 6). Three coaches possessed a British Amateur Weightlifters Association qualification. Other qualifications possessed included: “United Kingdom Coaching Certificate level 3 rowing coaching”, “United Kingdom Coaching Certificate level 2 strength and conditioning”, “Australian rowing level II”, and a “Diploma in sports massage”.

4a.3.3.2 Strength and conditioning coaches

Amongst strength and conditioning coaches the most widely held certification was the United Kingdom Strength and Conditioning Association; Accreditation (n = 10; 100 %). The second most prevalent was the National Strength and Conditioning Association; Certified Strength and Conditioning Specialist (n = 6; 60 %). Other certifications held by respondents (n ≤ 2) included “American College of Sports Medicine Health Fitness Instructor”, “British Amateur Weightlifters Association Award”, “Premier Training Fitness Instructor and Personal Trainer”, and the “USA Weightlifting Award”, “YMCA Fitness Instructor Award”.

4a.3.4 Physical testing

Thirty respondents indicated they conducted physical testing on rowers. Coaches were asked, when testing was performed (Figure 4a.1), what parameters of fitness are tested (Figure 4a.2), and what specific tests are used. Coaches reported testing an average of between four to five parameters of fitness. Coaches reported testing cardiovascular endurance using the following; “ergometer tests”, “5 km, 30 minute, 16 km or rowing ergometer”, “step test”, “18 km ergometer”, “1 hour test”. Muscular strength was assessed with either the; “1 RM squat, deadlift, bench pull”, “concept II dynamometer (world class start testing protocol)”, and “1 RM squat, push-pull, deadlift”. Muscular power was determined using “vertical jump and max Olympic lift”, “max power at 100 ° per s”, and “250 m ergometer”, “Ballistic measurement system - 12 rep squat and clean” and “ergometer power strokes”. Muscular endurance was measured via; “ergometer tests and repetition maximum strength tests”, “inverted rows, supine hold”, using either the “concept II dynamometer” or “row perfect ergometers”. Body composition was assessed using the; “sum of seven skinfolds”, “caliper fat tests”, “skinfolds three site”, and the “body stat machine”. Flexibility tests included; “sit and reach plus range of motion (joint tests)”, “stretch bench tests”, “hamstring measuring”, “movement pattern tests”, and a “physio assessment protocol”. Speed tests included; “rating tests on-water”, “ergometer sprints”, “racing water and ergometers”, “2000 m ergo”. Only three coaches reported assessing acceleration using the; “dynamometer”, “cleans, or a squat accelerometer”.

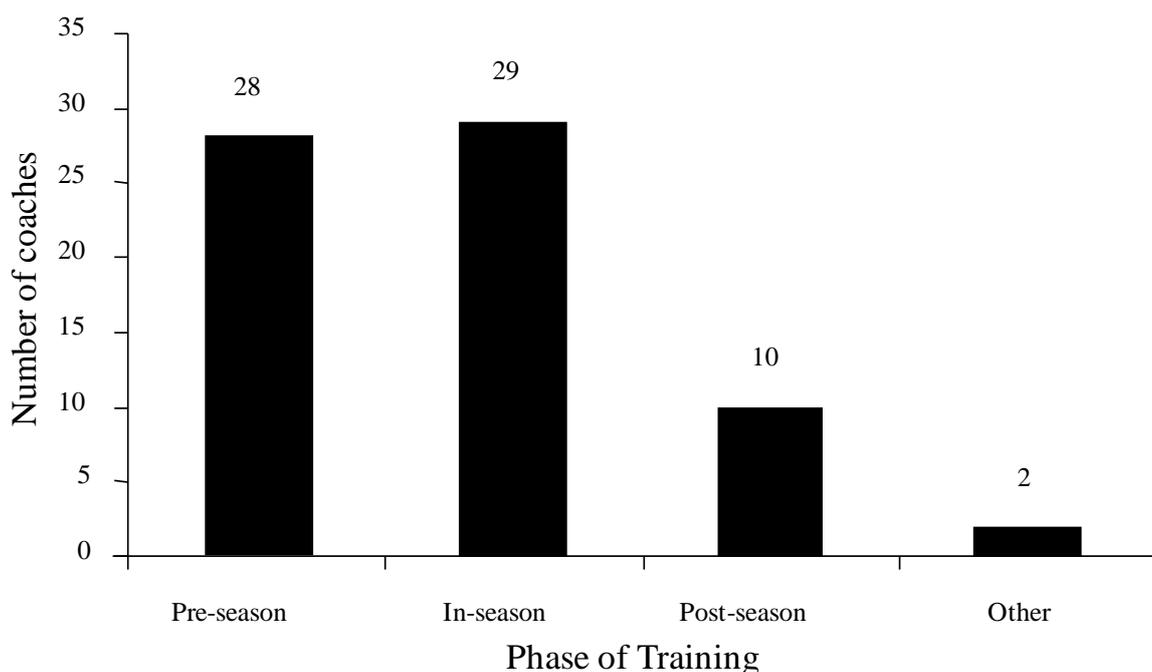


Figure 4a.1 Training phase when variables of athlete fitness are assessed by coaches

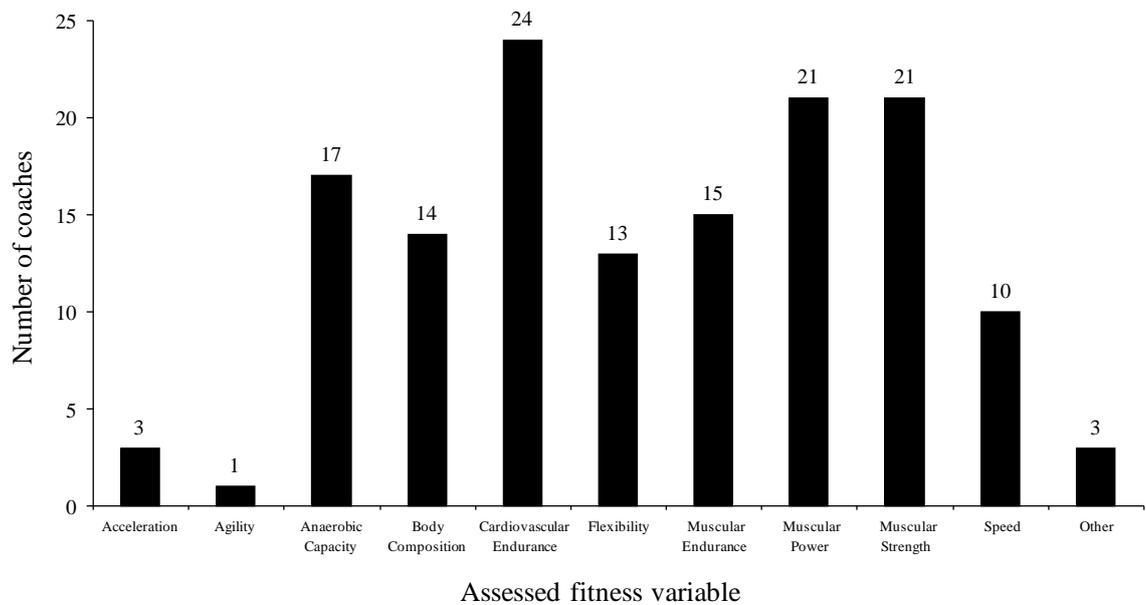


Figure 4a.2 Variables of athlete fitness tested by coaches

4a.3.5 Strength and power development

The first question in this section asked coaches, if they thought strength training benefits rowing performance. All coaches stated that they believed strength training was of benefit to rowing performance. Fourteen coaches left comments in relation to this question which included; “Increases power per stroke, overall strength levels”, “Absolutely, strength can be transferred into boat speed with correct technique”, “Improved fibre recruitment, neural activation, ability to exert force, skill component”. The second question in the strength and power development section asked coaches whether their rowers performed strength training. Thirty of 32 coaches reported that their rowers performed strength training.

4a.3.5.1 In-season training

The next sub-section within the strength and power development section focused on in-season strength and power training practices. For the first question in this sub-section coaches were asked how many days of the week that in-season strength and power training was performed; eight coaches indicated strength and power training was performed 2 times per week, eight coaches reported 2-3 times per week, eight coaches reported 3 times per week, two coaches indicated one time per week, two coaches reported 1-2 times per week, one coach reported 3-4 times per week and one coach indicated 4 times per week.

The third question within this sub-section asked coaches to determine the average length of their in-season strength training sessions. Thirteen coaches indicated that the sessions lasted between 60-75 min. Eight coaches reported that sessions last between 45-60 min. Four coaches reported that sessions last 75+ min. Three coaches indicated that

sessions last 30-45 min. Two coaches reported that sessions last between 45-60 min and 60-75 min. The final question in this sub-section asked coaches to indicate the number of sets and repetitions typically used for strength training exercises during the in-season. Responses were content analysed and resulted in the creation of four higher-order themes, including (a) sets with repetitions under 8 specified, (b) sets with large repetition range specified, (c) sets with repetitions 8 and above specified, (d) miscellaneous. Table 4a.2 lists the higher-order themes, total number of coaches whose responses make up the theme, and representative raw data within each higher-order theme.

Table 4a.2 Sets and repetitions used during in-season programmes

Higher-order themes	Number of responses	Select raw data representing responses to this question
Sets with repetitions under 8 specified	11	3-5 sets of 3-6 repetitions. Work is mainly with lightweight rower-body mass is therefore an issue; thus often perform low volume of work 4 sets of 4-6 repetitions. In-season 3-4 sets x 5 repetitions (strength development).
Sets with large repetition range specified	7	Cycle 3x10-12/3x6-8/3x3-5 on 3-6 weekly cycles. 3-5 sets 5-20 repetitions. 3-4 sets of 5-12 repetitions.
Sets with repetitions 8 and above specified	5	4x 30-50 repetitions-rest 1 min. 4 sets 8-15 repetitions. 3x15 3x10 3x8.
*Miscellaneous	3	Variable. Various.

*Answers which could not be associated with any of the broad identified themes

4a.3.5.2 Off-season training

For the off-season training sub-section, coaches were initially asked the number of days per week the rowers engage in strength training. Nine coaches indicated strength and power training was performed 3 days per week. Seven coaches reported 2 days per week. Five coaches reported 4 days per week. Two coaches each reported 2-3 days per week and 3-4 days per week. One coach reported 1 day per week and one coach reported 2-4 times per week.

The next question addressed the average length of off-season strength training sessions. Twelve coaches indicated that the sessions last between 60-75 min. Five coaches reported that sessions last between 45-60 min. Five coaches reported that sessions last 75+ min. Four coaches indicated sessions last between 30-45 min. One coach reported that sessions last 15-30 min. The final question in this sub-section asked coaches to indicate the number of sets and repetitions typically used for strength training exercises during the off-season. Content analysis resulted in the creation of four higher-order themes, including (a) sets with repetitions under 8 specified, (b) sets with large rep range specified, (c) sets with

repetitions 8 and above specified, (d) miscellaneous. Table 4a.3 depicts higher-order themes, total number of coaches' responses comprising each theme, and select raw data that are representative of responses.

Table 4a.3 Sets and repetitions used during off-season programmes

Higher-order themes	Number of responses	Select raw data representing responses to this question
Sets with repetitions 8 and above specified	8	3x20 3x15 3x10. 3x15-20 repetitions - rest 1 min. 4x10-12 (50 % max).
Sets with large repetition range specified	7	cycle 3x10-12/3x6-8/3x3-5 on 3-6 weekly cycles higher repetition cycles in off season. 5x10 repetitions (early conditioning) 4x3 repetitions (strength phase). 4-5 sets 3-12 repetitions.
Miscellaneous	6	5x5 min at controlled stroke rates (14-24 s.min ⁻¹). 3-4 sets. Various.
Sets with repetitions under 8 specified	4	3-4 sets of 3-5 repetitions. 4-5 sets x 5 repetitions (strength). 4 sets of 4-6 repetitions.

4a.3.5.3 Programme design

The first question in the programme design sub-section asked whether coaches included Olympic style weightlifting exercises in their prescribed training programme. Twenty six of 30 coaches indicated that they implemented Olympic style weightlifting exercises.

The next four questions within this sub-section were related to recovery time periods afforded between 1) an Olympic weightlifting style strength training session (eg featuring clean, snatch, hang clean) and a high quality rowing session 2) a general strength training session (eg squat, bench press, bent over row, shoulder press) and a high quality rowing session, 3) a Olympic weightlifting style strength training session and a competitive rowing race, 4) a general strength training session and a competitive rowing race. Responses to these four questions are displayed in table 4a.4.

Table 4a.4 Recovery time afforded between strength training and rowing training and competition

Question	Same day	Same day-24 h	24 h	24-36 h	36 h	36-48 h	36-48- >48 h	48 h	48- >48 h	48- >48 h	>48 h
Recovery time period allowed between a Olympic weightlifting style strength training session and a high quality rowing session	3	-	11	2	7	-	-	3	-	-	-
Recovery time period allowed between a general strength training session and a high quality rowing session	5	2	12	3	4	-	-	3	-	-	-
Recovery time period allowed between a Olympic weightlifting style strength training session and a competitive rowing race	-	-	-	-	1	1	1	6	2	-	16
Recovery time period allowed between a general strength training session and a competitive rowing race	-	-	-	-	3	1	1	7	-	-	17

The sixth question in this sub-section asked coaches about the extent to which they agreed that strength and power influence 2000 m rowing performance. Twenty-five coaches indicated they strongly agreed, whereas 5 coaches reported they agreed and only one coach indicated they disagreed.

The next question asked the coaches to identify, in order of importance, the five weightlifting training exercises that are most important in their programmes. Results from this question are listed in table 4a.5.

Table 4a.5 Coaches rank order of the 5 most important weightlifting exercises within their training programme

Order of importance	Exercises (number of coaches responding)
1	Cleans (19) Squat (8) Leg press, tubing around hull shell, front squat (1)
2	Squat (14) Clean or clean & jerk (3) Cleans and snatches, deadlift, hang clean below knee (2) Bench pull, bench press, core stability exercises, leg press, lunges or split squat, rowing with lightened gearing to develop movement speed, snatch (1)
3	Deadlift, bench pull (7) Bent over row, leg press (3) Snatch, squat (2) Deadlift (elevated to increase range), inverted row, lunges, front squat, power clean, Romanian deadlift (1)
4	Bench pull (5) Bench press, squat, uni lateral exercises (3) Core stability, leg press, Romanian deadlift (2) Bent over row, clean, deadlift, elevated deadlift, hang clean, overhead squat, power snatch, press ups and pull ups (1)
5	Bench press, bench pull (5) Pull up or lateral pull down (4) Deadlift (3) Core, uni lateral exercises (2) Clean compound, cleans and snatches, pull up and bench press, Romanian deadlift or stiff leg deadlift, shoulder press, snatch, snatch pull (1)

The seventh question in this sub-section asked coaches whether they use periodisation to structure training programmes and 29 of 31 coaches indicated that they used periodisation. Coaches' comments in response to this question included; "Important to plan training sessions around competitions to allow athletes to peak at the right times", "To create fine balance between exercise and recovery, super-compensation and fatigue", "Allows for peaking at right time and recovery to be programmed", "To prevent plateaus in strength & power".

The final question in this section enquired how coaches determined the load (weight) rowers' use during typical strength training exercises. Responses were content analysed into five categories including (a) repetition maximum and max testing, (b) subjectively from athlete and coach experience, (c) accelerometer testing, (d) periodisation and phase of training, (e) miscellaneous. Table 4a.6 depicts these higher-order themes, the total number of coaches whose responses made up the theme, and select raw data within each higher-order theme.

Table 4a.6 Determination of training loads

Higher-order themes	Number of responses	Select raw data representing responses to this question
Repetition maximum and max testing	19	Based on previous 1 RM testing. Determination of 3 RM, 5 RM. Max weight tests.
Subjectivity from athlete and coach experience	6	Knowledge of athlete. By experience - mine and athletes. Athlete experience and maturity.
Miscellaneous	5	Communication between *English Institute of Sport support staff of athletes. Self determined as a function of boat speed, faster rowers increase drag proportionally anyway. Sets and repetitions.
Accelerometer testing	2	Accelerometer testing.
Periodization and phase of training	2	Periodization. Depends on phase.

*The English Institute of Sport (EIS) is a nationwide network of sport science and sports medical support services, funded by the U.K government to foster the talents of elite athletes within England.

4a.3.6 Speed development

Nineteen of 32 coaches who responded to the survey reported incorporating some type of speed development work in their programme. Responses were content analysed and resulted in the creation of seven higher-order themes, including (a) rowing on the water, (b) ergometer training, (c) plyometrics, (d) strength training, (e) circuits and endurance weights, (f) interval training, (g) miscellaneous. Table 4a.7 depicts these higher-order themes, the total number of coaches whose responses made up the theme, and select raw data within each higher-order theme.

Table 4a.7 Training methods used by coaches for speed development

Higher-order themes	Number of responses	Select raw data representing responses to this question
Rowing on the water	12	1) lightened oar length / gearing 2) training in larger crew boats (eg 2 doubles combine as a quad). Bursts on water. Racing starts / 100-m sprints on water (10x100-m).
Ergometer training	7	Sprinting on the ergometer. 10-30 second ergometer. Light ergometer.
Plyometrics	6	Plyometrics/complex training (more for power than pure speed). Plyometric training. Plyometrics.
Strength training	5	70-80% loading, snatches, repeated fast lifting of 5 repetitions(ish). Olympic lifts. Mainly strength development as a platform to then perform more power/speed-strength exercises as space is limited in where we train.
Circuits and endurance weights	4	Endurance weights. Circuit training. Circuits.
Interval training	3	Interval training. Intervals.
Miscellaneous	2	Power training. Dynamic exercises and less repetitions.

4a.3.7 Plyometrics

Sixteen of 32 coaches reported using plyometrics. The second question asked coaches why they prescribed plyometrics. Six coaches reported prescribing plyometrics as a means of improving power. Five coaches reported prescribing plyometrics to improve speed. Two coaches prescribed plyometrics to recruit high threshold muscle fibres. Other responses included “dynamics”, “strength-power work”, and “dynamic strength development”.

The third question in this section focused on the phases of the year plyometrics were used, figure 4a.3 shows responses to this question. The fourth question determined how coaches integrated plyometrics into their prescribed training programme. Responses were content analysed and resulted in the creation of five higher-order themes, including (a) complex and contrast training, (b) part of circuit training, (c) add to weights session, (d) after strength training, (e) miscellaneous. Table 4a.8 lists the higher-order themes, total number of coaches whose responses make up the theme, and representative raw data within each higher-order theme. The final question in this section asked the coaches to identify the types of plyometric exercises regularly used in their programme. Results from this question are shown in figure 4a.4.

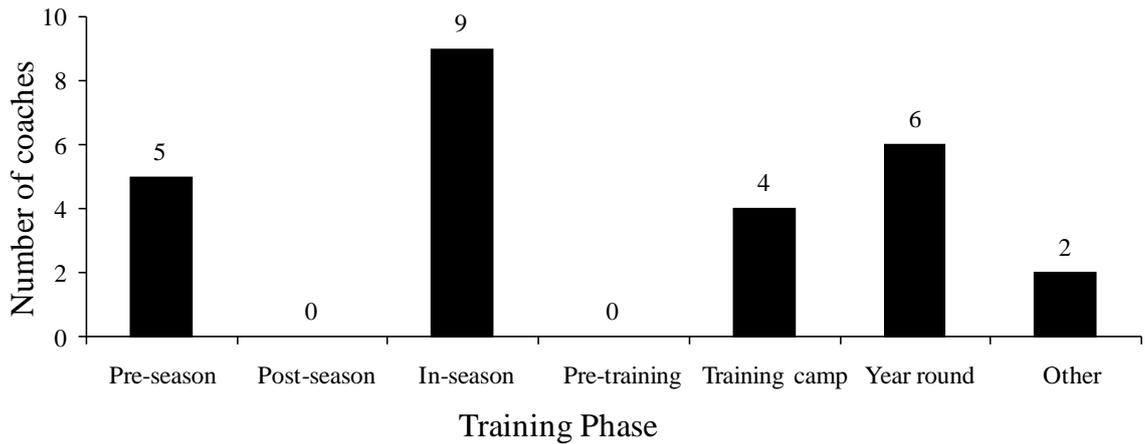


Figure 4a.3 The phase of training in which coaches prescribed plyometric training

Table 4a.8 Methods of integration of plyometrics into prescribed training programme

Higher-order themes	Number of responses	Select raw data representing responses to this question
Complex and contrast training	5	Use in gym sessions in combination with heavy lifting. Contrast training, in the sessions at beginning
Part of circuit training	3	Part of circuit training, no specific sessions at present. Body weight circuits.
Add to weights session	2	As an exercise in the gym session. Add to weights session.
After strength training	2	At the end of a program of weights.
Miscellaneous	4	To supplement ergometer training. Once a week.

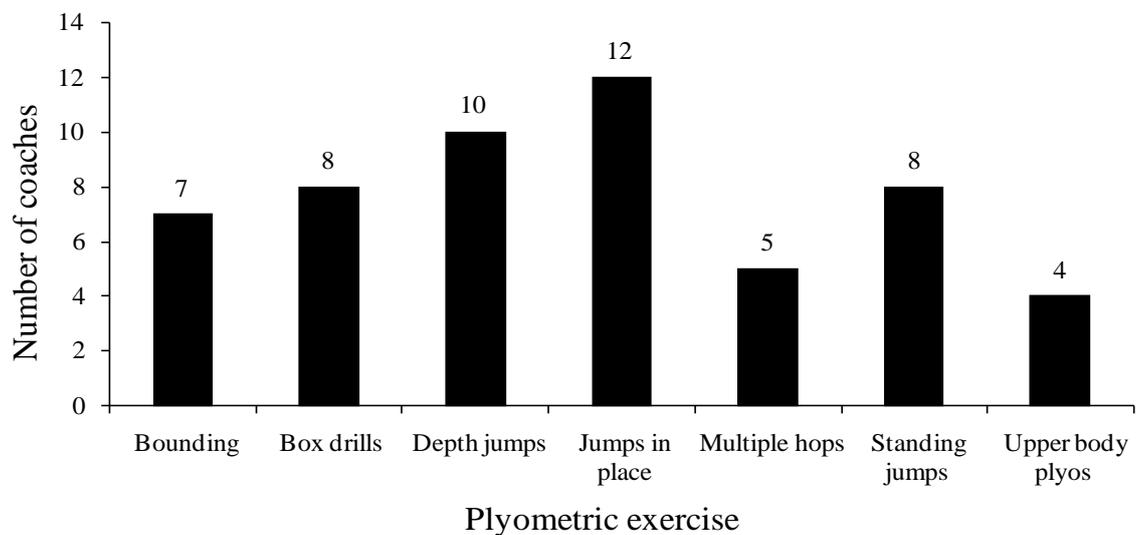


Figure 4a.4 Types of plyometric exercises regularly prescribed by coaches

4a.3.8 Flexibility development

Thirty one of 32 coaches indicated that their rowers perform some type of flexibility training. All coaches indicated rowers performed static stretching, 22 reported using dynamic stretching and 18 indicating proprioceptive neuromuscular facilitation (PNF) stretching. Five coaches stated rowers performed other flexibility methods such as; “partner-assisted”, “vibration-myofascial”, “myofascial release-foam roller”, “active isolated” and “through full range of motion in lifting”.

Coaches were asked to indicate when athletes were encouraged or required to perform flexibility exercises (in relation to this question practice refers to ‘rowing practice’ and workout refers to ‘strength training workout’), the duration of a typical flexibility session, and the duration that athletes were encouraged to hold a static stretch. Results from these questions are presented in figures 4a.5-4a.7.

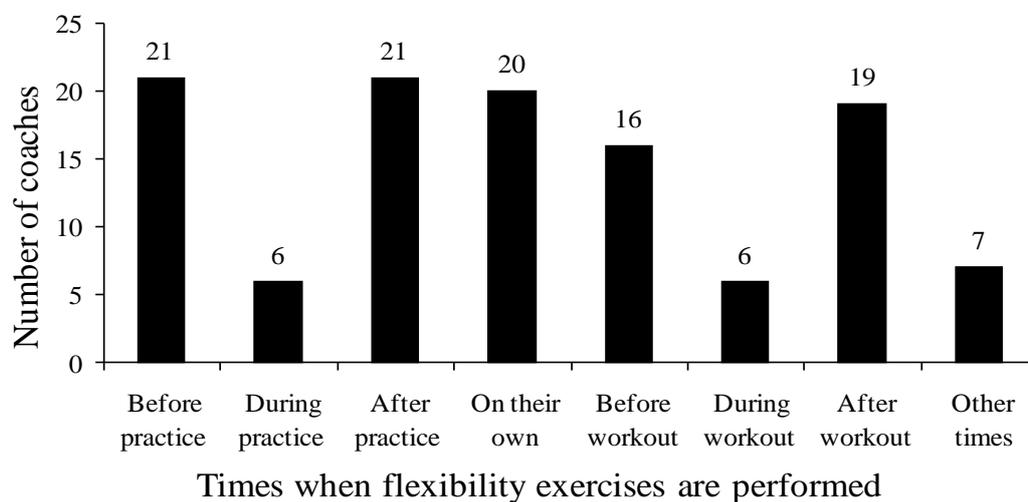


Figure 4a.5 Times when athletes were encouraged or required to perform flexibility exercises

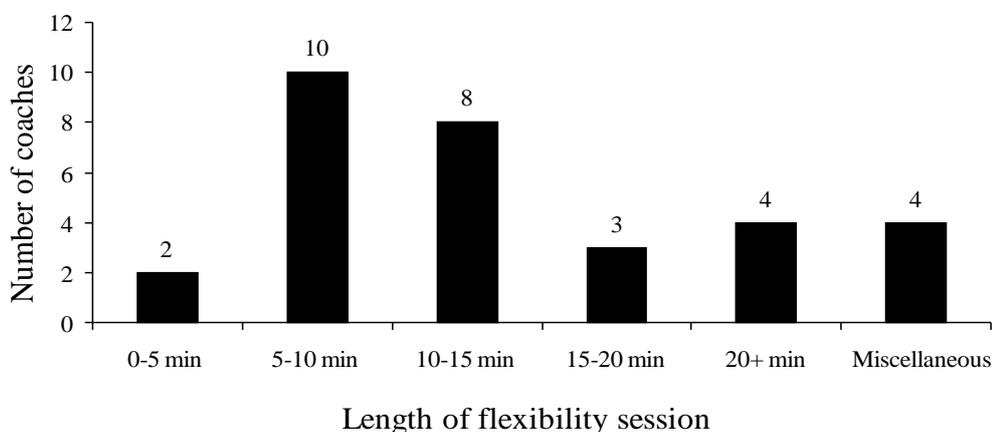


Figure 4a.6 Length (minutes) of a typical flexibility session prescribed by coaches

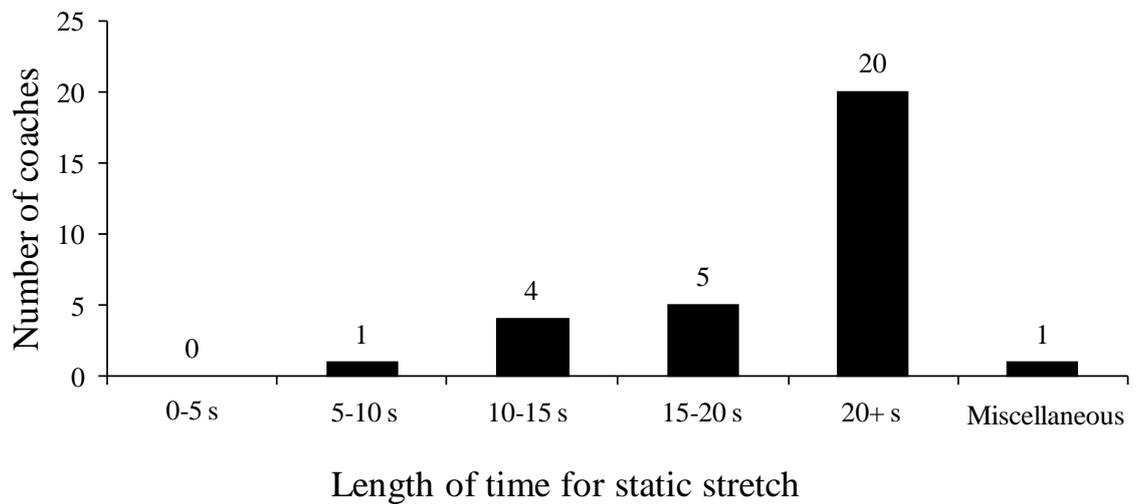


Figure 4a.7 Amount of time (seconds) coaches encourage rowers to hold a static stretch

4a.3.9 Unique aspects of the programme

The answers to the question concerning what were the unique aspects of the prescribed physical conditioning programme were content analysed into six higher order themes. These themes included, (a) individualise, (b) coaching quality, (c) variety of training, (d) pre-hab and core, (e) endurance strength, (f) miscellaneous. Table 4a.9 lists these higher-order themes, total number of coaches whose responses make up each theme, and select representative raw data supporting each higher-order theme.

The second question of this section enquired what coaches would like to do differently with their physical conditioning programmes. Responses were content analysed and resulted in the creation of seven higher-order themes, themes included, (a) change emphasis of current programme, (b) nothing, (c) plyometrics, (d) more strength training, (e) circuits and endurance weights, (f) more rowing and aerobic conditioning, (g) miscellaneous. Table 4a.10 lists the higher-order themes, total number of coaches whose responses make up the theme, and representative raw data within each higher-order theme.

Table 4a.9 Unique aspects of coaches prescribed physical conditioning programme

Higher-order themes	Number of responses	Select raw data representing responses to this question
Miscellaneous	8	Emphasis on high volume of specific training to maximize technical and physiological development. Specific distance training on the ergometer, technical work on the water. The weight training should mainly be geared to connect the athlete better. The limbs are strong from rowing training.
Individualize	6	Tailoring to anaerobic and aerobic improvement based on individual performance. That we individually assess each rower then prescribe the most beneficial mode for him to train to achieve his goals, our programs are not one size fits all. Personal programs, one to one coaching.
Coaching quality	6	Lifting coaching quality. Use of English Institute of Sport knowledge. None- what we do is quad practice, solid and well coached.
Variety of training	4	Variety of water/ergometer/weights & cross training. Variety of exercises. Variety.
Pre-habilitation and core	3	Trunk strengthening. Focus on improving the mobility of the T-spine, then integrating into rotation patterns. Lots of pre-habilitation work.
Endurance strength	3	Endurance strength -60 repetitions with medium weight. 200+ squat jumps/leg press/bench pulls. Power endurance lifting circuit.

Table 4a.10 What coaches would like to do differently with their physical conditioning programmes

Higher-order themes	Number of responses	Select raw data representing responses to this question
Miscellaneous	7	A track. More autonomy to program, chief coaches, have a lot of decisions. Keep the continuity through to world championships!!!
Change emphasis of current program	4	A much more cross-training based off-season program. Less volume of ergometers, more flexibility/mobility work. Add more variety to training.
Nothing	4	Nothing at present. Nothing.
Plyometrics	3	Encourage plyometric sessions. Add in more plyometric based sessions if had space to do so. Have more space! So we can include more med ball / speed / plyometrics and get some platforms so we can perform more Olympic lifting movements.
More strength training	3	More off season weights (hypertrophy). More lifting. As group gets older add in weights for strength and power.
Circuits and endurance weights	3	More endurance strength weight training. introduce circuit training for endurance inc core and plyometrics (not enough time). Resistance circuits.
More rowing / aerobic	2	More rowing. More aerobic training of medium intensity.

4a.3.10 Comments

The final section of the survey allowed coaches the opportunity to make further comments regarding their prescribed training programme. The responses of the nine coaches who filled out this section were content analysed into three higher order themes: (a) comments of training programme difficulties and limitations, (b) comments of programme description, (c) miscellaneous.

The higher order theme ‘comments of training programme difficulties and limitations’ consisted of comments such as “Many of the rowers (or other athletes) come to me with big postural issues and a lot cannot perform basic movement patterns correctly. This often means a lot of time is wasted in the first year of conditioning having to correct these faults rather than focusing on improving performance”. The theme of ‘comments of programme description’ included responses such as “This university programme – is complex and complicated as we cater for; under 23 world medallists to World Class Start athletes (Great Britain rowing talent identification programme) to school rowers to complete novices”. The theme of ‘Miscellaneous’ consisted of comments such as “Let’s see how it goes in Beijing!!” (a reference to the approaching Olympic Games).

4a.4 Discussion

This is the first comprehensive survey of strength and conditioning practices occurring within rowing. To the author’s knowledge it is also the first qualitative assessment of coaches’ strength and conditioning practices for any sport within the United Kingdom. A total of 32 coaches responded to the questionnaire. This is the highest number of questionnaire responses obtained in a survey describing coaches’ strength and conditioning provision to one specific sport. Studies conducted on practices of strength and conditioning coaches, involved with a specific sport, in Northern America have elicited between 20 and 26 responses (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). There have been other surveys involving strength and conditioning coaches which have analysed a total of four sports (Sutherland & Wiley, 1997), the total number of responses for this study was 74, with the largest proportion being from American Football coaches (n = 23). Durell *et al.* (2003) conducted a survey of 137 NCAA strength and conditioning coaches, however analysis was not associated with any specific sport. The survey response rate was lower than similarly designed studies involving American sports (69-87 %) (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005), but this was likely to be due to the increased follow up mailings that occurred

with these surveys. In this study extensive follow up mailing of the survey to non-responders was not performed as the response number ($n = 32$) was deemed sufficient for analysis. In the present study, 22 of 32 (69 %) coaches indicated working with either national or Olympic level athletes. Therefore the data displayed is a reflection of practices that occur towards the elite end of rowing. However caution should be taken in the interpretation of the obtained findings since training prescribed to athletes by coaches is not always matched with what is performed by athletes. Elite netball players have shown a reported adherence of 66 % to a nine week endurance training program (Palmer *et al.*, 2005). In addition trained rowers who were prescribed a 12 week mixed intensity endurance training program adhered to ~ 70 % of the prescribed training zones (Ingham *et al.*, 2008). Therefore the findings should be looked upon as to what strength and conditioning training is commonly prescribed rather than what is actually performed by the athletes.

In terms of physical testing, coaches surveyed in this study tested on average between four and five parameters of fitness. The most commonly assessed parameter of fitness was cardiovascular endurance which was assessed by 24 of 30 (80 %) coaches. This differs from coaches from the NBA, NFL and MLB where 60 %, 46 % and 24 % respectively assessed cardiovascular endurance (Ebben & Blackard, 2001; Ebben *et al.*, 2005; Simenz *et al.*, 2005). However, the result is similar to that found amongst NHL coaches where 78 % assessed cardiovascular endurance (Ebben *et al.*, 2004a). The likely reason why cardiovascular endurance is more commonly assessed by rowing coaches is because the aerobic energy contribution has been reported to provide 67-86 % of total metabolism during a 2000 m race (Secher, 1982; Riechman *et al.*, 2002). In contrast the North American sports previously studied are more heavily dependent on anaerobic metabolism (Glaister, 2005). Assessment of body composition was much less prevalent amongst rowing coaches (47 %) compared to North American strength and conditioning coaches (83-100 %) (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). This may appear somewhat surprising as a low percentage body fat has been associated with success in lightweight rowing (Slater *et al.*, 2005), but no relation has been found to exist between skinfold thickness and ability in heavyweight rowers (Bourgois *et al.*, 2000). In heavyweight rowers a reduced emphasis on the measurement of body composition is less surprising as body mass is typically supported by a sliding seat in the boat (Secher, 1982). Because of this support, body fat in rowers does not put rowers at the same disadvantage that it would put athletes who carry their own body mass, for example runners (Mikulic, 2008). Since a positive relationship has been found to exist

between body mass and rowing performance (Secher, 1982; Bourgois *et al.*, 2000; Mikulic, 2008) and the fact that it is challenging to combine a high muscle mass with leanness (Slater *et al.*, 2005), it is maybe unsurprising that body composition assessment is not routinely performed by coaches.

Twenty six of the 30 coaches 87 %, who prescribed strength training, indicated that they implemented Olympic style weightlifting exercises. This is considerably more than reported by MLB strength and conditioning coaches (14 %) but similar to strength and conditioning coaches working in the NFL (88 %), NHL (91 %) and NBA (95 %) (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). Olympic weightlifting style strength training has been found to improve vertical jump performance in high school American football players (Channell & Barfield, 2008) and 10 m sprint speed in healthy young males (Tricoli *et al.*, 2005). In addition Olympic weightlifting exercises such as power cleans, hang cleans and snatches are recommended for basketball, baseball and ice hockey (Marlow, 2002; Pollitt, 2003; Tamborra, 2008). The clean and the squat were considered the most important weightlifting exercises prescribed within rowers training programme. The clean and the squat were also seen as the two most important weightlifting exercises by strength and conditioning coaches of the NBA, the NFL, and the NHL (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Simenz *et al.*, 2005). Major League Baseball strength and conditioning coaches regarded the squat as the most important strength exercise and lunges as the second most important exercise (Ebben *et al.*, 2005). It is not surprising that the clean and squat exercises are valued across a range of sports since they have both been found to relate to numerous measures of sports specific functional performance including sprint and jump ability (Peterson *et al.*, 2006; Hori *et al.*, 2008). Biomechanical electromyography analysis has shown that muscle groups are active in combination during the rowing stroke, and therefore rowers should perform whole body strengthening exercises that involve co-ordination between the upper and lower body (Rodriguez *et al.*, 1990). In addition, previous published strength and conditioning guides for rowing have recommended whole body strengthening exercises such as cleans, squats and deadlifts (Ivey *et al.*, 2004; McNeely *et al.*, 2005). Furthermore, a strength training programme based around these styles of exercises has been found to improve performance time, total power and power per stroke during a 2000 m rowing ergometer test in both novice and varsity rowers. Therefore, based on these findings, it would seem that the majority of the coaches responding to the survey are correct in their prescription of suitable strength training exercises for rowers.

Twenty-nine of 30 (97 %) coaches reported periodising their programmes. These data are similar to the practices of NBA (90 %), NHL (91 %) and MLB (83 %) coaches than NFL (69 %) coaches (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). Periodised strength training programmes have resulted in greater improvements in strength, power and body composition when compared to a linear strength training programme in collegiate American Football players (Kraemer, 1997). A 12 week periodised strength programme has resulted in gains of over 30 % and 15 % in the squat and bench press respectively in Baseball players (Szymanski *et al.*, 2004). With regards to strength training frequency, the majority of coaches indicated that rowers perform strength training either two (26 %) or three (33 %) times per week during the off-season and either two (27 %) or three (27 %) or two to three (27 %) times during the in-season. Ivey *et al.* (2004) guidelines recommended between two to three strength and power training sessions per week. In comparison, strength training during the in-season and off-season in the NFL, NHL, MLB and NBA tends to be performed two and four days per week, respectively (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). During the in-season the majority of coaches (11 of 26) reported that they typically prescribed under eight repetitions for strength training exercises. Previously Ivey *et al.* (2004) have advised prescription of three to eight repetitions on strength and power exercises for female collegiate rowers, and McNeely *et al.* (2005) have recommended rowers use low repetitions and loads of 85-95 % of 1 RM for strength training exercises. In support of these recommendations, Ebben *et al.* (2004b) found that a strength training programme consisting of lower repetitions (5-12 repetitions) resulted in greater improvements in rowing performance than a programme consisting of higher repetitions (15-32 repetitions) in female varsity rowers. Furthermore, rowing performance has been shown to be highly correlated with maximal strength and power (Secher, 1975; Russell *et al.*, 1998; Ingham *et al.*, 2002; Riechman *et al.*, 2002; Yoshiga & Higuchi, 2003a; Battista *et al.*, 2007). Performance of strength training with high loads and low repetitions has been shown to be the most effective means of eliciting gains in maximal strength (Campos *et al.*, 2002). In light of these research findings the survey results suggest that the majority of coaches prescribe the appropriate loading for strength exercises for rowers.

Coaches were asked what recovery period they afforded between strength training sessions (general strength session and an Olympic weightlifting based session) and a high quality rowing training session or a rowing race. Coaches tended to allow 24 h between either type of strength training session specified and a high quality rowing session.

However, it has been reported that elite rowers train 1100-1200 h per year, which is just over 3 h a day (Fiskerstrand & Seiler, 2004), with two training sessions occurring daily, for seven days a week (Hagerman *et al.*, 1996). Therefore periods of less than 24 h recovery between strength training and quality rowing training will occur frequently. Most coaches allowed over 48 h rest between either type of strength training session specified and a rowing race. Speed development training was conducted by 26 of 32 (81 %) coaches. This is a lower proportion than documented for NFL (100 %), MLB (100 %), NBA (100 %) and NHL (96 %) athletes (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). The most popular method of training for speed development was rowing sprints on the water. Sixteen of 32 (50 %) coaches prescribed plyometrics to rowers. This percentage is considerably lower than previously reported in NBA coaches (100 %) MLB coaches (95 %) NHL coaches (91 %) and NFL coaches (73 %) (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). The lower prevalence of speed development and plyometric training for the rowers is perhaps not surprising as absolute speed, short term power production and anaerobic ability have a greater importance for the other sports (Williford *et al.*, 1994; Burr *et al.*, 2007; Castagna *et al.*, 2008).

All coaches who reported prescribing flexibility training (97 %) reported performing static stretching. This result is similar to previous studies; for example all MLB strength and conditioning coaches, 91 % of NHL strength and conditioning coaches, 85 % of NFL strength and conditioning coaches and 100 % of NBA strength and conditioning coaches reported using static stretching (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). Seventy-one percent of coaches reported using dynamic stretching and 58 % indicated using PNF stretching. Prescription of dynamic stretching amongst studies of North American coaches ranged from 54 % to 90 % and PNF stretching ranged from 68 % to 75 % (Ebben & Blackard, 2001; Ebben *et al.*, 2004a; Ebben *et al.*, 2005; Simenz *et al.*, 2005). Flexibility has been associated with a lower incidence of back pain and injury in rowing (McGregor *et al.*, 2002), a greater pitching velocity within baseball (Stodden *et al.*, 2005), a reduced incidence of Patellar tendinopathy in basketball (Cook *et al.*, 2004), a lower prevalence of musculo-tendinous strains in American Football (Cross & Worrell, 1999), and stretching has been recommended to prevent muscle strains in ice hockey (Dick, 1993). Therefore it is not surprising that prescription of flexibility training is common practice.

From analysis of survey data several key research findings emerged. Physical testing was commonly conducted amongst coaches with cardiovascular endurance and muscle strength and power being frequently assessed. For strength training prescription Olympic weightlifting was widely practiced, and almost all coaches employed a periodised training plan. Twenty-four hours recovery tended to be afforded between strength training and rowing training whereas over 48 h was allowed between strength training and racing. Plyometrics were prescribed by half the respondents while rowing sprints on the water was the most popular method of training for speed development. Static stretching was prescribed by all the coaches whose rowers performed flexibility training and dynamic stretching was found to be more frequently practiced than PNF stretching.

4a.5 Practical applications

This study describes the strength and conditioning practices of British based rowing coaches and strength and conditioning coaches who work with rowers. Since 22 of the 32 (69 %) coaches surveyed work with either Olympic or National standard rowers, coaches now have a source of data describing strength and conditioning practices particularly with respect to the elite end of the sport. Coaches who work with rowers and or endurance based sports at all levels can use this review of strength and conditioning practices as a resource to diversify and improve their practices. Future researchers could use data within this survey to design experimental protocols examining the effect of current or new strength and conditioning practices on various aspects of rowing performance.

4b. Strength and conditioning practices in rowing: perspectives of two elite coaches

4b.1 Introduction

The primary reasons for performing the interviews of two rowing coaches were to explore themes that occurred from the questionnaire data in more detail. Additionally, the information presented here gives further strength to the overall descriptive conclusions drawn on strength and conditioning practices occurring within British rowing. This allows for increased external validity in the subsequent design of rowing based intervention studies.

4b.2 Methods

Semi-structured interviews of two coaches working with British rowing were conducted. Please refer to 3.2.2 for more detail.

4b.3 Coach information

Two coaches, both of whom were working with Olympic rowers were interviewed. One of whom was the country's lead strength and conditioning practitioner involved with rowing. The other coach was an international rowing coach. The strength and conditioning coach worked with senior rowing squads; heavyweight / lightweight men and heavyweight / lightweight women and had been involved with the delivery of strength and conditioning to elite rowers for four years. The rowing coach specialised in working with senior lightweight male rowers and had been involved in the coaching of elite rowers for eleven years.

4b.4 Strength training prescription

4b.4.1 Frequency of strength training

The rowing coach stated that during the pre-season (minimal competitions) the lightweight rowers will perform three strength training sessions a week. However, during the summer he revealed that it was hard to maintain this continuity.

Rowing coach; *“In the summer the work we do on the water’s quite intensive there’s a high power / strength component to it and also we are racing quite frequently every three weeks and the recovery and preparation means that we can’t quite maintain our strength training, but three sessions when we can”*.

The coach revealed that strength training was largely scheduled on base endurance days. This was so rowers could perform strength training *“not particularly pre-exhausted”*, and he gave the example of planning a strength training session two hours after a 20 km row.

Rowing coach; *“We would generally try and avoid putting a strength training session in on work days but it’s not always possible”*.

The strength and conditioning coach indicated that the frequency of strength training sessions will differ amongst squads.

Strength and conditioning coach; *“Typically two to three, they differ slightly in the format depending on the squad. For example the men typically do two strength sessions a week plus a circuit. The women do two strength sessions and the lightweights do three strength”*.

4b.4.2 Strength training programme design

In terms of strength training prescription both coaches emphasised the importance of Olympic lifting exercises and whole body strength exercises and discussed the effectiveness of these exercises in modelling the rowing stroke.

Rowing coach; *“The core lifts have stood the test of time, in terms of deadlift, power clean, front squat, back squat, snatch, the hang variants of the snatch and the clean and then there is derivatives of that in terms of stiff leg / straight leg deadlifts. The lifts that work the kinetic chain are working in rowing of hamstring, glute, back but in the vertical plain rather than horizontal plain”*.

Strength and conditioning coach; *“Exercise selection is fairly straight forward because of the movement patterns in the sport. The importance of the Olympic lifts, whether its power cleans or power snatches, the typical whole-body strength lifts front / back squats, deadlifts, Romanian deadlift, different variations, single leg exercises whether its step ups, lunges, Bulgarian squats, pistol squats”*.

Both coaches mentioned that the bench press and bench pull were used for the development of upper body strength. Coaches were in agreement that three to five sets of

an exercise were commonly prescribed. The rowing coach stated that three to six repetitions per set were performed, whereas the strength and conditioning coach shared how repetitions performed vary across phases.

Rowing coach; *“Typically with the senior men we’ll work down from 10s in terms of general prep, down to 5s and 3s in max strength phases, back up towards 8s for some of the power endurance type work.”*

The rowing coach was of the opinion that despite rowing being characterised as a strength-endurance type of sport, it is vitally important that strength training should generally be performed with low repetitions with a high load.

Rowing coach; *“To accelerate that boat from a dead / standing start to maximum speed, which happens in about eight strokes in our sport obviously requires firstly an enormous strength component, for the first few strokes, and then switching to a power component and if there is one area of the race where strength training impacts it’s that first part”.*

He continued to mention that often in rowing training, a relatively high force would be developed for strokes, which would condition specific muscular endurance required for rowing above any gym based strength training.

4b.4.3 Whether coaches would like to change anything regarding the current delivery of strength and conditioning

The rowing coach stated he would not change anything regarding the current delivery of strength and conditioning to the rowers he coached. However, he felt that if he did wish to make changes within the rowers’ strength and conditioning programme this could be easily achieved via good communication links with the strength and conditioning coaches. The strength and conditioning coach did not directly mention anything that he would change in the current delivery of strength and conditioning. However, he did mention that the coaching team were at a “*cross-roads*” in terms of questioning what is optimal for the sport. He highlighted that the top rowing coaches understood the preparation of rowers far better than anyone else and said he thought it was often an “*over-sight*” for the strength and conditioning coach to try and dictate the strength and conditioning programme.

4b.4.4 How the strength and conditioning programme is manipulated for different types of rower

Both coaches indicated that the programme was manipulated to suit the needs of different types of rower. The rowing coach highlighted the differences in strength training prescription among different groups of rower.

Rowing coach; *“The lightweight men’s crew we try and avoid hypertrophy so we will pitch straight into strength training. I think it’s generally held that women need more upper body strength. Juniors need more strength development across the board, but they need it through the kinetic chain areas”*.

The coach then made reference to the crew he was coaching at the time of the interview.

Rowing coach; *“I’m coaching two guys, we have the core lifts the same, we individualise it because one of them needs more upper body strength”*.

The strength and conditioning coach stressed that developmental rowers, particularly those recruited through the talent identification system, are often lacking in postural integrity and mobility to get into the correct positions for rowing despite possessing a decent level of strength.

Strength and conditioning coach; *“So they tend to be relatively strong but they may lack the postural integrity or the mobility to get into the right positions”*.

4b.5 Perceptions / opinions of the benefit of strength training to rowing

4b.5.1 The effects coaches believe strength training has on rowing performance

The strength and conditioning coach believed that strength training was an important and influential aspect of training for rowing and referred to the strength required to produce adequate force to the oar.

Strength and conditioning coach; *“Looking at some of the biomechanical figures the forces they produce at the handle are sometimes over 100 kg for the men and the average force is anywhere between 30 kg and 60 kg. Therefore the athlete has to be strong enough to replicate that”*.

He also referred to how strength training can be used to work on weaknesses within an individual’s stroke.

Strength and conditioning coach; *“If they think the trunk is a weak link or their upper body is a weak link, the gym provides an environment to try to develop that one aspect”*.

The rowing coach stressed that strength training was a crucial aspect of training for rowing and mentioned various reasons for this.

Rowing coach; *“To maintain a high force per repetition component to our sport, to get off the start quickly and basically to make sure that the rowers are strong and stable and balanced and supported so we’re avoiding injury as well”*.

Rowing coach; *“In the gym it’s a chance for the guys to get to see each other moving, it’s also a chance for me, usually I’m 60-70 m away on the bank, I can watch you doing a power clean, I can get a bit closer to see your movement patterns as well”*.

4b.5.2 The importance of Olympic lifting as a method of strength training

Both the coaches believed that Olympic lifting was an important method of strength training for rowers. In terms of specificity of movement, the two coaches were of the opinion that the power clean closely models the rowing stroke.

Strength and conditioning coach; *“Even the (rowing) coaches would probably say that the power clean would be the most sports specific type lift. There is a number of technical aspects to do with the lifts in terms of the first pull, holding the trunk and just extending the knees, which is exactly the same as what they want in the boat. Then there’s the fact of completing that explosive pull with the arms as long as possible straight rather than breaking the arms early”*.

Rowing coach; *“The coaching points are the same, you listen to the lead strength and conditioning coach about people getting a connection to the bar before they drive through, we talk about getting a connection to the blade before you push through. I would say one word specificity, in terms of the neural component”*.

The strength and conditioning coach also mentioned that from a postural point of view, frequently the errors that a rower makes in the boat will be exactly the same as they make in the gym whilst performing Olympic lifting.

4b.5.3 The stages of a 2000 m race that coaches thought benefited from strength and power

Both coaches indicated that the start of a 2000 m race was heavily influenced by strength and power.

Rowing coach; *“First ten strokes, first 100 m, first 250 m”*.

However, both coaches mentioned that a rower’s level of strength and power would influence their ability throughout the whole race.

Strength and conditioning coach; *“Arguably I would say through the whole race, because someone’s postural integrity and their ability to actually hold positions and connect is going to be related to what they do in the gym, also the relationship between someone’s power they produce and what their maximum relative power is, so obviously the stronger and more powerful someone is the more powerful their going to be for each rep they produce”*.

The strength and conditioning coach further mentioned that the end of the race was also heavily impacted by strength and power since high forces are required at this stage.

4b.5.4 Views on whether the top elite rowers are also the physically strongest

Interestingly the two coaches had differing opinions on whether the top elite rowers were also the ones who were able to lift the most weight on commonly performed strength training exercises. The rowing coach indicated that the strongest rowers in the gym sometimes don't convert this to rowing force in the water.

Rowing coach; *"They lift that massive bar but they don't fire properly, the blade doesn't go through the water properly. So no would be the answer. There may even be an inverse trend actually thinking about it"*.

The strength and conditioning coach's view contrasted to that of the rowing coach on this issue.

Strength and conditioning coach; *"Arguably yes, if I look at the men's squad for example the average for the men's four, which is the top boat, would be more than the average of the total men's squad would be"*.

However, the strength and conditioning coach did caution that exceptions to this rule did exist, where athletes will perform really well in the gym but cannot convert that performance to the boat. It was also of his opinion that there was a maximum level for strength development, and further progression of strength and fast twitch fibres beyond this level then becomes detrimental to performance.

4b.6 Recovery from strength training

4b.6.1 Recovery time period afforded between strength training and rowing competition and whether this is perceived as sufficient

The strength and conditioning coach indicated that rowers will lift up to a week before World Cup races. The rowing coach stated that strength training generally ceases seven days before World Cup races and three weeks before Olympic Games and World Championships. However, he did mention that for national trials, lifting will occur within closer proximity of racing.

Rowing coach; *"You might find us lifting before our own trials because we can't taper off for everything"*.

Both coaches indicated that although actual gym style strength training would cease well in advance of international racing, other types of more rowing specific resistance / strength and power training would continue until closer to competition.

Rowing coach; *“The weights come off and there’s a lot more starts, there’s a lot more sprint work and that serves three purposes; it probably continues our strength development, it maintains our strength, and it probably ensures there’s some transference as well”*

The rowing coach indicated that he felt a sufficient recovery period was afforded between intense strength training and racing, however the strength and conditioning coach commented it would be hard to say whether the period was sufficient because of the more specific strength / power training performed closer to competition.

4b.6.2 Recovery time periods afforded between strength training and rowing training and whether they are perceived as sufficient

The strength and conditioning coach highlighted the point that the rowers will typically train three times a day. He commented that the male rowers would perform strength training usually as their first session between 7.30 am to 9 am in the morning. After this they would perform their second session; a rowing session, at around 10.30 am or 11 am. He did mention that a lot of the rowing based sessions are long duration steady-state aerobic workouts. However, he also stated that there are instances where the coach has selected a higher intensity training session, and gave the example of power strokes on the water. He expressed that the rowers have performed sub-optimally in this type of session due to lack of recovery from the strength training session performed hours earlier.

Strength and conditioning coach; *“There has been instances where the coach has maybe put a higher intensity session in, should it be power strokes on the water and they obviously haven’t been able to deliver in that session because they haven’t been fully recovered from the weights session”*.

When asked whether the recovery period following strength training is sufficient for peak performance during rowing training, the strength and conditioning coach commented that the rowers would complete their three daily training sessions by 3 pm and after discussions with physiologists there were *“question marks”* over whether this was optimal for recovery. He alluded that if the third session was to be scheduled in the evening then this may lead to more complete recovery. However, he did mention, that by having three sessions time-scaled close to each-other, although this is physiologically harder, it may prepare the rowers better for being able to perform. He indicated that this is the sort of question they were currently trying to address through research.

Strength and conditioning coach; *“Some of the research that their hoping to look at moving forward as in to if they spread the day out and try and get optimum recovery between sessions, does that actually give them better results than doing what they do at the minute, whenever they know what they do at the minute actually does produce medallists”*.

The rowing coach stated that 24-36 h was afforded between intense strength training and high quality rowing training and that he thought this period although not ideal for recovery, was sufficient and adequate and commented.

Rowing coach; *“If we prioritised everything we would never get anywhere”*.

The rowing coach mentioned that in the summer when discontinuity exists within the training programme often issues of ‘soreness and stiffness’ arise following intensive strength training sessions. He added that this can also cause technique flaws within the rowing stroke. The strength and conditioning coach’s perspective was that his fellow rowing coaches understood the recovery demands elicited by an intense strength training session. It was his opinion that rowing athletes respond differently following strength training than other groups of athletes.

Strength and conditioning coach; *“I think for me the real golden nugget in the whole thing, is the fact that rowing athletes don’t respond the same as other athletes and the fact that most of the strength training theory is based on maybe American football players, sport science students and isn’t based on gold medal winning rowers”*.

He also added that rowers would recover quicker following strength training session than more anaerobic based athletes giving the example of a sprinter.

4b.6.3 Coaches’ views on recovery demands for Olympic lifting based strength training vs. general strength training

The strength and conditioning coach was of the opinion that Olympic lifting based strength training poses an increased demand on fast twitch muscle fibres than more general strength training. He added that an Olympic lifting based session will have more of a neural demand compared to a higher rep resistance training session where the demand is more metabolic and fatiguing to intermediate and slow twitch muscle fibres. He stated that he would choose the type of strength training session to schedule based on the nature of the endurance training scheduled on the same day.

Strength and conditioning coach; *“So typically if I’m on a training camp and I know that, that day they have some pretty tough aerobic sessions to do, I will try and put a high-intensity session in to work at the other end of the spectrum, so an Olympic lifting type session”*.

The rowing coach was also of the opinion that Olympic lifting based strength training requires increased recovery.

Rowing coach; *“It possibly should be because there’s obviously a lot of recruitment across the whole body on the Olympic lifts, there’s a lot more skill, there’s a lot more neural stress because there’s a high speed component to it. I think in an ideal world we would say yes it needs more, but we rarely give it that”*.

4b.6.4 Strategies employed to aid recovery

The strength and conditioning coach stated that recovery strategies were implemented on an individual basis. He stated that any strategies used are primarily set by the physiologists working with the squad. Contrast bathing, ice baths, compression clothing and nutritional strategies were methods that some rowers chose to use. He alluded that strategies were outlined to rowers by the physiologist and the rowers then chose to use what they feel works for them. In terms of dietary interventions he mentioned there is consultation with both a doctor (medical screen) and nutritionist before any intervention was chosen. The rowing coach mentioned that some rowers will recover better than others, and for the ones who don’t recover as well, strategies are looked into. As with the strength and conditioning coach the rowing coach mentioned the input from nutritionists and physiologists.

Rowing coach; *“The physiologists look after people’s hydration, the nutritionists look after people’s dietary recovery and we’ve done quite a lot of work lately on sleep”*.

4b.6.5 The specific strategies / markers employed to monitor recovery

Both coaches referred to morning monitoring of psychophysiological parameters taking place every day on training camps.

Strength and conditioning coach; *“On training camp the physiologist will do morning monitoring every day and look at various different measures; heart rate, hydration, a mood state questionnaire and urea levels. Their also in the process of looking at hormonal profiling and cortisol levels”*.

The rowing coach mentioned that on a day to day basis there is always a physiologist available to conduct monitoring should the coach wish for it. He stated that differing symptoms of tiredness / under-recovery occurred within rowers.

Rowing coach; *“One guy when he gets tired might get mouth ulcers and spotty, another guy when he gets over-tired doesn’t sleep”*.

He stressed the importance of rowers admitting to when they felt over-tired, to which the coach thought was *“almost more important”* than physiological measure results such as urea.

4b.7 Fitness testing

4b.7.1 The physical tests that are commonly used to monitor rowers' progress and the fitness variables measured

In response to questioning concerning the physical tests used to monitor rowers progress the strength and conditioning coach mainly alluded to strength and power tests conducted.

Strength and conditioning coach; *“On the men’s side we do 1 RMs on power clean, bench press and bench pull”*.

On the contrary he eluded that for the women’s programme the head coach prefers to use a 12 rep test for squats and power cleans assessing power endurance using the Ballistic measurement system (Fitness Technology, Australia). The strength and conditioning coach described how *“more sports specific strength measures”*, such as the 250 m ergometer sprint and ten power strokes are also used. He alluded that it is sometimes challenging to regularly carry out these strength and power based assessments and that the more endurance based tests such as the 2000 m, 5000 m or 30 minute tests which occur on a *“weekly, fortnightly or monthly basis”*, take precedent over the more anaerobic tests. The rowing coach gave a more in-depth overview of the overall physical testing procedures. He expressed that aerobic endurance was *“probably”* the most constantly measured variable and he viewed this as the most important variable to assess. The test used most frequently to assess aerobic endurance is a 6 km ergometer test fixed at 18 s.min⁻¹; where blood lactate levels are maintained under 2 mmol.L⁻¹, it was reported that this test was performed twice a week. He then described how rowers’ strength was monitored.

Rowing coach; *“For strength we monitor frequently in the gym to see what people are lifting, we tend to do a 250 m ergo once a week after a weights session or as part of a weights session, again that’s specific power training, and it gives us a monitor there”*.

Interestingly the rowing coach revealed that the overall physical testing programme has shifted to more of a field testing approach as opposed to lab testing.

Rowing coach; *“We moved away now from gas analysis. Our testing has become more field testing rather than lab testing and has become more sports specific rather than laboratory white coat physiology”*.

He indicated that ergometer testing was generally carried out in November, January and March. Five kilometre long distance trials on the water were conducted in October, December and February. With the criterion test; a 2000 m single sculls test taking place in March. However, he indicated that monitoring of rowers’ performance was a constant on-going process.

Rowing coach; *“We do, a lot of monitoring, we monitor 18 km, 24 km on the ergo. Monitoring power output against blood lactate in a sub-maximal way we do step testing. We’re monitoring paddling speeds out there (water) against blood lactate”*.

4b.7.2 Whether the training programme is manipulated on the basis of fitness test results

The strength and conditioning coach indicated that it is a big challenge to make individualised changes to the general training programme on the basis of fitness test results.

Strength and conditioning coach; *“My experience working with senior squads is the fact that the coach doesn’t want a great degree of individualisation across a squad. All senior women and senior men will have a programme that comes out that everyone will follow on week to week basis. The coaches aren’t that comfortable with the fact that well this person will do one programme, and it will be totally different from what someone else will do”*.

From a strength and conditioning perspective he indicated that the majority of rowers do the key lifts but then there is some opportunity for individualised prescription.

Strength and conditioning coach; *“If someone happens to be weaker in the upper body they may have some additional work to do or from a core perspective if they know their weak through their back extensors they may have more extension type exercises in there”*.

In addition he reported that there is increased opportunity to manipulate the training programme *“off the back of tests”* with the lightweight squad compared to the heavyweight men or women. The rowing coach stated that for strength training the training programme could be manipulated on an individual basis.

Rowing coach; *“You talk strength training no question, because there’s different ways to access and help people”*.

However, he expressed the difficulty of individualising the core rowing training programme because of the squad system that is in place.

Rowing coach; *“It’s very difficult to individualise a programme because we’re in a team sport. The things we’re testing are generally based on aerobic capacity / aerobic endurance and if people aren’t aerobically strong enough we have one way of dealing with it which is to carry out more steady state, endurance training”*.

He also quoted a statement from the chief coach of the women’s squad.

Rowing coach; *“We do the step tests and the step tests are good but if you have a great step test what are you going to do; you’ll train harder, if you have a bad step test what you going to do; you train harder”*.

4b.8 Overall training programme structure

The content of this section comes exclusively from the rowing coach interview.

4b.8.1 *How is the annual training plan set out*

The rowing coach emphasised that training was not split into distinct phases but rather the training was kept consistent.

Rowing coach; *“A lot of sports talk about pre-season, in-season, we are aerobic capacity, aerobic capacity, aerobic capacity, our training model is pretty consistent all year round”*.

He emphasised that aspects of fitness are worked concurrently at once and that the relative proportion of work on each aspect changes along the course of the training cycle. He then mentioned the intensity of the rowing training performed.

Rowing coach; *“We probably complete 70-80 % of it; utilisation training below rate 22, below 81 % boat speed. What will happen is the quality of that will increase, the guys will get more out of the boat at 22 the rates will start to come up and eventually you end up doing something like 50-60 % aerobic training and then we’re doing the other 40-50 % is a little bit more at the top end of things”*.

4b.8.2 *The structure of a typical week of training in the pre-season (out of competition) phase*

The rowing coach provided a detailed description of the content of a week’s training.

Rowing coach; *“We train seven days a week. We would probably complete 24-27 hours of training. The split between land and water training would be something like 50/50, there would be about 200-250 km rowing in there or ergo work including the mileage on the ergo. The days would probably go; three sessions Monday, three sessions Tuesday, two sessions Wednesday a half day, and then go three Thursday, three Friday, two Saturday and Sunday would be one long row, so there is some recovery planned in there. We would probably lift on a Monday, Wednesday, Friday, we would put a core stability / trunk strengthening session in there somewhere. In terms of intensity proportion probably 70-80 % of that aerobic training would be what we call utilisation level 2, which would be stroke rate 17-19, 40-50 km on the boat very sustainable work”*.

He described how the training stress and adaptation were not caused from any individual session but a culmination of the weekly training volume.

Rowing coach; *“People aren’t getting out of the boat and falling over, it’s at the end of the week their tired, and when they get their day off every 10 days we then try and grow them back from there”*.

The training week would occasionally involve short rowing bouts at 2000 m race pace which served to familiarise rowers with the pace sensation of a 2000 m race amidst the majority of the training which was performed at a lower intensity.

Rowing coach; *“The intensity tends to be fairly low rate but we might just put in there a 500 m at race pace here and there, just to keep reminding their bodies actually it’s about a 6 minute race”*.

4b.8.3 The frequency that rest periods / days scheduled in the training programme

The coach indicated that in the winter (pre-season) a rest day was given every 10 days. However, he referred to how rest days can sometimes cause problems.

Rowing coach; *“Some of them even still train they’ll spin on the bike or something because they feel bad if they stop, and we do get more problems with people after a rest day actually, people come in they get more injuries more illness and more bad performances after a rest day”*.

During this ten day period there would also be three half days and he stated that if more recovery time was perceived to be required then more could be scheduled. He emphasised that the recovery time across the crew was dictated according to the requirements of the strongest rower.

Rowing coach; *“We tend to try and go at the pace of the strongest guy, because you’ve got to be tough to do this and learn to recover, but if people are falling over, not so much falling over with fatigue, but if we start to have a run of injuries, then we need more time, we need to back off”*.

The coach then described how rest periods were scheduled into the training programme during the summer, where there is an increased number of competitions and emphasis on quality training.

Rowing coach; *“In the summer with the women and lightweights we’re tending to work quite religiously now 6 days on 1 day off. We tend to build a Sunday in off, it’s not just for physical fatigue but it’s mentally very tough. The quality of what they’re doing out there in the summer because they are so motivated and technically we’re getting a lot of work on, it’s different to the winter where the skill isn’t so good and its working, and I think head coach is finding it now as well to give them one day every seven days, plus a half day on a Wednesday and a half day on a Saturday”*.

4c. Chapter summary

Table 4c.1 Summary of themes and sub-themes resulting from the questionnaire responses and interviews

Themes / Sub-themes	Questionnaire	Interviews
<p>Strength training Prescription</p> <p><i>Weekly frequency</i></p> <p><i>Sets and repetitions</i></p> <p><i>Key identified exercises</i></p> <p><i>Programme design</i></p>	<p>Even number of responses indicating 2 or 3 sessions.</p> <p>In-season: sets of under 8 repetitions Off-season: sets of over 8 repetitions 3-5 sets repeatedly emphasised.</p> <p>1. Clean 2. Squat 3. Deadlift 4. Bench pull 5. Bench press.</p> <p>29 / 31 coaches indicated using a periodised training plan.</p>	<p>Rowing coach: lightweight squad; 3 sessions when possible. Strength and conditioning coach: 2 to 3 depending on squad.</p> <p>Rowing coach: 3-5 sets of 3-6 repetitions. Strength and conditioning coach: 3-5 sets of 3-10 repetitions.</p> <p>Both coaches: Olympic lifts, squats, deadlifts, bench pull, bench press.</p> <p>Strength and conditioning coach: Strength training plan divided into phases.</p>
<p>Recovery from strength training</p> <p><i>Recovery afforded between a strength training session and rowing training</i></p> <p><i>Recovery afforded between a strength training session and rowing race</i></p>	<p>24 h (11 responses) and 36 h (7) most commonly cited for Olympic weightlifting style session. 24 h (12) or Same day (5) for a general strength training session.</p> <p>> 48 h (16) and 48 h (6) most commonly cited for Olympic weightlifting style session. > 48 h (17) or 48 h (7) for a general strength training session.</p>	<p>Strength and conditioning coach: 90-120 min. Rowing coach: 24-36 h. Both coaches: Increased recovery demand following Olympic lifting based strength training.</p> <p>Both coaches: One week.</p>
<p>Fitness testing</p> <p><i>When testing was performed</i></p> <p><i>Aspects of fitness tested</i></p>	<p>Testing conducted pre-season (28) and in-season (29).</p> <p>Cardiovascular endurance (24), Muscular power (21), Muscular strength (21), Anaerobic capacity (17).</p>	<p>Rowing coach: Ergometer testing generally carried out in November, January and March. 5000 m water trials in October, December and February 2000 m water trial in March.</p> <p>Strength and conditioning coach: Precedent for assessment of endurance capacity through 2000 m, 5000 m and 30 minute tests. 'Sports specific strength measures' of 250 m ergometer sprint and 10 power strokes. 1 RM on power clean, bench press and bench pull. Rowing coach: aerobic endurance 'probably' the most constantly measured variable. For strength / power assessment: monitoring of gym lifting and 250 m ergo sprint once a week.</p>

This descriptive analysis of the strength and conditioning practices within British Rowing featured a questionnaire study involving 32 responses and interviews of a British rowing coach and strength and conditioning coach who provided support to elite international British rowers. With 22 of the questionnaire responses being from coaches who indicated that they worked with either national- or Olympic level athletes, combined with the

opinions of the two international rowing coaches, cumulatively this analysis is reflective of practices occurring toward the elite end of rowing. Table 0c.1 lists key themes and sub-themes which were derived from the questionnaire study and interviews. In relation to the theme of strength training prescription, responses from the questionnaire generally matched those arising from the interviews. To summarise reported practices, a periodised plan of strength training is prescribed, featuring 2-3 training sessions per week, which feature Olympic weightlifting style exercises and multi-joint strength exercises performed across multiple sets with low to moderate repetition ranges.

For the theme of recovery from strength training both the coaches expressed that strength training ceased a week before a rowing race, similarly the majority of the survey responders indicated allowing over 48 h recovery between strength training and a rowing race. The coaches had differing opinions on the recovery periods afforded between strength training and rowing training. The strength and conditioning coach commented that when a high-intensity session, giving the example of power strokes on the water, had been scheduled after strength training, reduced performance in this style of session has sometimes occurred due to insufficient recovery from the preceding strength training bout. He further expressed there were doubts from colleague physiologists over whether the regular practice of completing three daily training sessions by 3 pm was optimal for recovery. However, he did allude to the robustness of elite rowers to deal with this level of training stress in comparison to other athletes. In contrast the rowing coach stated that 24-36 h was afforded between intense strength training and rowing training which he deemed was a sufficient recovery period. Although he later commented how 'soreness and stiffness' arising from strength training has caused technique flaws within the rowing stroke. The most frequent response from the survey was 24 h recovery between strength training and rowing training, with a tendency to allow less recovery time following general strength training. This is in agreement with the opinions of both interviewed coaches who indicated that Olympic lifting posed increased demand on the central nervous system and Type 2 muscle fibres in comparison to more general higher rep strength training. In relation to fitness testing administered, the two interviewee coaches indicated precedence for ergometer and water based endurance tests which paired with the most popular assessed fitness aspect of cardiovascular endurance from the surveys. A majority of the survey responders also indicated prescribing strength and power tests, both the interviewed coaches also alluded to the regular undertaking of sports specific strength measures such as 250 m ergometer sprint and power stroke tests as well as more traditional tests of strength such as 1 RM testing on power clean, bench press and bench pull.

**5. Reproducibility of performance and
physiological measures and
assessment of pacing during 2000 m
rowing ergometry**

5.1 Introduction

This PhD thesis features three intervention studies involving various exercise tests and physiological measures such as assessments of strength and power, markers of muscle damage and 2000 m rowing ergometer performance with related physiological measures. The establishment of the reproducibility of these measures was required in order to determine whether a change between repeated trials was likely due to random error or to the intervention.

Strength and power tests have been shown to be strongly correlated with rowing performance (Ingham *et al.*, 2002; Battista *et al.*, 2007; Nevill *et al.*, 2011) and are commonly used by coaches and practitioners to assess the anaerobic power producing ability of rowers (Chapter 4; McNeely *et al.*, 2005). Numerous rowing studies have featured assessment of maximum voluntary contraction (MVC) of the leg extensors (Chance *et al.*, 1992; Parkin *et al.*, 2001) and vertical jumping ability (Kramer *et al.*, 1993; Tse *et al.*, 2005; Battista *et al.*, 2007). Although the reproducibility of MVC of the leg extensors (Viale *et al.*, 2007; Zech *et al.*, 2008) squat jump and counter movement jump (Markovic *et al.*, 2004; Casartelli *et al.*, 2010) have been previously reported, these studies did not utilise rowers, therefore the consistency of repeated performances amongst rowers in these tests is not yet established. Hopkins (2000) suggests that ideally the reproducibility of a given test should be established within the population of interest in regard to the research being undertaken. Furthermore, the reproducibility of the rowing power stroke test has not been established in any population, despite this test being a highly specific anaerobic test for rowing with numerous research studies featuring this test (Hartmann *et al.*, 1993; Ingham *et al.*, 2002; Izquierdo-Gabarren *et al.*, 2011).

Various indirect markers of training stress have been used for research concerning monitoring the training of rowers (Maestu *et al.*, 2005b). Creatine kinase (CK) is an enzyme which catalyses the exchange of high-energy phosphate bonds between phosphocreatine and adenosine diphosphate produced during muscle contraction (Brancaccio *et al.*, 2007). In relation to training practice, serum CK levels increase as a consequence of an increased permeability or breakdown of the muscle cell sarcolemma which can occur from strenuous exercise (Epstein, 1995; Friden & Lieber, 2001). Serum CK, has been used as a marker of training stress in response to acute strength training and endurance training sessions performed by rowers (Kokalas *et al.*, 2004) and also used to monitor rowers over a prolonged period such as over the course of competitive season (Urhausen *et al.*, 1987) and during a training camp (Steinacker *et al.*, 1993). Basal levels of CK have shown high variability [typical error (TE) = 19 %] therefore the effects of

imposed exercise interventions on CK levels must be interpreted with caution (Hartmann & Mester, 2000). Assessment of limb girth measurements and soreness ratings via visual analogue scales have previously been carried out in rowing based research (Bourgois *et al.*, 2000; Stutchfield & Coleman, 2006; Kerr *et al.*, 2007; Grindstaff *et al.*, 2010). Both assessment of limb girths and perceived soreness have been shown to possess good reproducibility over repeated measures (Labs *et al.*, 2000; Bijur *et al.*, 2001; Rosier *et al.*, 2002), therefore proving to be simple and useful tests that can be used in the monitoring of rowers.

Pacing strategy relates to the pattern by which energetic resources, mechanical power output or speed is distributed during a bout of exercise (Stone *et al.*, 2011). A growing body of evidence exists with regard to the pacing strategy used by trained rowers performing a 2000 m rowing ergometer test or on-water race (Schabort *et al.*, 1999; Soper & Hume, 2004; Garland, 2005; Brown *et al.*, 2010). Traditionally a reverse J shaped pacing strategy has been observed for 2000 m rowing (Soper & Hume, 2004; Garland, 2005; Brown *et al.*, 2010). This strategy is characterised by a high power output during the initial phase, followed by a decrease in power output in the middle of the event culminating with an end-spurt in the final stages, which is completed with a higher power output than the middle phase but lower than the initial phase (Abbiss & Laursen, 2008). The reverse J shaped strategy is firmly established for on-water rowing races (Hagerman, 1994; Garland, 2005; Brown *et al.*, 2010), however, there is conflicting evidence regarding the pacing strategy during 2000 m ergometer rowing. Researchers have reported a positive pacing strategy, characterised by a fast start and gradual decline in speed throughout the event (Abbiss & Laursen, 2008) in national level rowers and high school rowers (Schabort *et al.*, 1999; Brown *et al.*, 2010) whereas a reverse J shaped strategy has been recorded in both elite and well-trained rowers (Soper & Hume, 2004; Brown *et al.*, 2010).

Physiological responses are comparable between 2000 m trials whether performed on-water or using an ergometer, which may partly explain the pacing strategy similarities. A previous study indicated no differences between oxygen consumption ($\dot{V}O_2$), heart rate and peak blood lactate [Lac^-], although aerobic contribution to total energy production during on-water rowing is higher in comparison to ergometer trials (87 % vs. 84 %) (de Campos Mello *et al.*, 2009). Although there is conflicting evidence regarding pacing during 2000 m rowing ergometry, the test itself has proved to have good reproducibility across repeated trials. Schabort *et al.* (1999) and Soper & Hume (2004) had trained male rowers perform three 2000 m trials and found the TE for mean power during the test to be 2.0 % and 1.8 % respectively. However, participants in these studies were relatively

young; ~ 16 years old (Schabort *et al.*, 1999) and ~ 19 years old (Soper & Hume, 2004) and the mean 2000 m performance times produced; 6:51-6:56 and 6:58 min:s, are considerably slower than times reported from trained club standard rowers of a similar body mass taking part in research studies (6:33.7 to 6:34.5 min:s) (Ingham *et al.*, 2007; 2008). The rowing experience and performance level of the rowers used in the studies by Schabort *et al.* (1999) and Soper & Hume (2004) might not be representative of trained senior club rowers and therefore the results obtained may not be transferrable to this population. In addition, the smallest practical effect, which allows for qualification of the probability of a practical change in performance occurring (Batterham & Hopkins, 2006), has not been reported for 2000 m rowing ergometer performance. Calculating the smallest practical effect is necessary to distinguish whether real changes have occurred over time for subsequent testing periods (Hopkins, 2000).

Recently several authors have investigated the reproducibility of power and metabolic responses during cycling time trials (Corbett *et al.*, 2009; Stone *et al.*, 2011; Thomas *et al.*, 2012). These authors have analysed performance and physiological variables per phase of the event, which allows for intricate analysis of varying trends in pacing and their causality from the analysis of metabolic responses. Interestingly, Corbett *et al.* (2009) and Thomas *et al.* (2012) have shown that pacing strategy is modified from the trial 1 to trials 2 and 3, with accompanying changes in energy liberation characteristics in the study by Corbett *et al.* (2009). These authors theorised that the changes in pacing following trial 1 were consistent with the concept of an intelligent, complex regulatory system described by the Central Governor Model (CGM), where information gained from the first trial is used to change the exercise template on subsequent bouts, either consciously or subconsciously (Noakes *et al.*, 2004; St Clair Gibson & Noakes, 2004; St Clair Gibson *et al.*, 2006). In relation to rowing, Schabort *et al.* (1999) also reported changes in pacing strategy from trial 1 to trials 2 and 3, however the authors did not carry out any cardiorespiratory analysis during the trials. Therefore physiological interpretation of their observed findings was restricted. Coupled with the lack of cardiorespiratory analysis, there is no research assessing surface electromyography (EMG) across a range of anatomical sites for research assessing reproducibility during repeated 2000 m rowing trials. Evaluation of the reliability of EMG during such dynamic endurance exercise is essential to determine the appropriateness of its use for research investigating such exercise (Fauth *et al.*, 2010).

This study had two principal aims; firstly to investigate the reproducibility of strength and power performance, markers of muscle damage, 2000 m rowing ergometer performance and related physiological parameters across three repeated trials in trained club rowers. Secondly, to investigate the pacing strategy adopted and distribution of energetic resources across three 2000 m tests. It was hypothesised that 2000 m ergometer performance would be consistent across repeated trials; however typical error would be greater than previously reported for this test due to the participants wearing unfamiliar respiratory gas exchange equipment that is required for physiological analysis. It was anticipated that a reverse J-shaped pacing strategy would be demonstrated during the three 2000 m trials.

5.2 Methods

5.2.1 Participants

Fourteen male well-trained competitive club rowers volunteered to take part in the study. Mean age [\pm standard deviation (SD)] of the participants was 22.8 (5.1) years, stature 1.86 (0.05) m, body mass 85.6 (8.3) kg, 2000 m rowing ergometer time 6:33.9 (0:09.5) min:s, rowing experience 7.1 (5.1) years. All participants had extensive prior experience at performing 2000 m ergometer tests before their involvement in the study. Participants were informed of the experimental procedures and any potential risks involved and gave their written informed consent to participate in the study. The study was approved by the Research Ethics Committee of the School of Life Sciences at Northumbria University.

5.2.2 Experimental protocol

The study followed a repeated measures design to determine the consistency of assessments of strength and power, markers of muscle damage and pacing and metabolic responses during 2000 m rowing ergometry in trained rowers. Each participant performed three laboratory testing sessions interspersed by 3-7 days between each session, each session followed the same protocol which is described below. Participants were asked to arrive at the laboratory in a hydrated state having abstained from exercise on the day of testing and strength training in the 72 h before testing. On the first testing session body mass and stature were measured. A capillary blood sample was taken from the finger for assessment of CK (only sessions 2 and 3) and [Lac⁻]. Participants perceived soreness rating and limb girths were also assessed. Electrodes were then attached to seven anatomical sites for EMG analysis. Following this, participants completed a five min warm-up on a rowing ergometer, before undertaking a protocol of strength and power tests which involved;

assessment of maximal voluntary contraction force of the leg extensors, three individual static squat jumps and counter movement jumps, and five maximal rowing power strokes on the rowing ergometer. A face mask was then placed on the participants for analysis of expired breath-by-breath respiratory gas exchange parameters which were to be collected during the 2000 m test. The participants were then instructed to warm-up for a further five min on the rowing ergometer after which they performed the 2000 m test. Heart rate [beats per min ($\text{b}\cdot\text{min}^{-1}$)] was recorded every 10 s during the test while immediately after the test, participants provided a rating of perceived exertion (RPE) and capillary blood samples were taken before the test and at 1-, 3-, 5- and 7 min after for the assessment of blood lactate.

5.2.3 Experimental test battery

5.2.3.1 Maximal voluntary contraction (MVC)

Maximal voluntary contraction force of the right leg knee extensors was determined using a strain gauge (MIE Medical Research Ltd, Leeds, UK). Please refer to section 3.4.1 for more detail.

5.2.3.2 Static squat jump (SSJ) and counter movement jump (CMJ)

An optical measurement system (Optojump Next, Microgate, Bolzano, Italy) was used for assessment of jump performance. Three independent SSJ and CMJ trials were conducted; the highest trial was recorded for data analysis. Please refer to section 3.4.2 for more detail.

5.2.3.3 Power strokes (PS)

Maximal stroke power was assessed air-braked rowing ergometer (Concept 2 Model C, Concept 2 Ltd, Wilford, Notts, UK). Please refer to section 3.4.3 for more detail.

5.2.3.4 2000 m rowing ergometer test

The test was performed on an air-braked rowing ergometer (Concept 2 Model C, Concept 2 Ltd, Wilford, Notts, UK). Please refer to section 3.5 for more detail.

5.2.3.5 Surface electromyography analysis (EMG)

Surface EMG was recorded from seven anatomical sites; gastrocnemius (GA), biceps femoris (BF), gluteus maximus (GM), erector spinae (ES), vastus medialis (VM), rectus abdominis (RA) and latissimus dorsi (LD) respectively, and measured during power strokes and the 2000 m test using a 16 channel wireless telemetric system (Myon, Myon AG, Barr, Switzerland). Mean rectified EMG recorded during each 500 m stage of the 2000 m test was normalised against the mean rectified EMG recorded during the five

power strokes, and subsequently expressed as a percentage. Please refer to section 3.5.7 for more detail.

5.2.3.6 Force analysis

Handle force was recorded during the power strokes and 2000 m test via a load cell (RLTO500kg, RDP Electronics Ltd, Wolverhampton, UK) located in series between the handle and drive chain. The handle force characteristics assessed for power strokes were maximal instantaneous force and power and mean force and power, characteristics assessed during the 2000 m test were mean handle force and power. Please refer to section 3.5.8 for more detail.

5.2.3.7 Rating of perceived soreness

Participants' level of perceived muscle soreness was assessed via a 10 cm long visual analogue scale. Please refer to section 3.6.1 for more detail.

5.2.3.8 Limb girths

Limb girth measurements were taken from the mid-thigh, mid-calf and upper arm. Please refer to section 3.6.2 for more detail.

5.2.4 Blood analysis

Capillary blood samples were collected as outlined in section 3.7. This was used for the analysis of blood lactate [Lac^-] (section 3.7.1) and CK (section 3.7.2).

5.2.5 Statistical analysis

Descriptive statistics are presented as mean (\pm SD) unless otherwise stated. Statistical analyses were conducted using SPSS 16.0 (Chicago, IL, USA) with the alpha level for significance set at $p < 0.05$. One-way ANOVA tests with three repeated measures were used to investigate between trial differences in 2000 m whole trial performance with accompanying physiological measures and also strength and power test performance and markers of muscle damage. Typical error as a percentage (TE %) [90 % confidence intervals (CI)] for the aforementioned assessments was derived from log transformed data and established using a spreadsheet (Hopkins, 2007a). In assessing the variability of performance tests and physiological measures, low and moderate TE have been defined as under 2 % (Hopkins *et al.*, 2001; Stone *et al.*, 2011) and between 3-10 % (Stone *et al.*, 2011) respectively. Smallest practical effect was calculated for each performance test and marker of muscle damage from the product of 0.3 [which represents the smallest standardised change in mean for a group of trained participants; Hopkins *et al.* (2009)] multiplied by the between-participant standard deviation across the three trials.

To describe any differences in the pacing strategy, the test data was divided into 4x 500 m stages. A 3x4 (trial x stage) repeated measures ANOVA was used to investigate differences in pacing strategy, which featured assessment of contributions from aerobic (P_{aer}) and anaerobic metabolism (P_{anaer}) to mean power (P_{tot}), $\dot{V}O_2$ ($\text{L}\cdot\text{min}^{-1}$), stroke rate [(strokes per min ($\text{s}\cdot\text{min}^{-1}$))], handle force and power and EMG. Assumptions of sphericity were assessed using Mauchly's test of sphericity, with any violations adjusted by use of the Greenhouse-Geisser ($_{\text{GG}}$) correction. If a significant main effect across time was shown then post-hoc differences across trials were analysed with use of the LSD correction. Effect size (ES) was calculated for any non-statistically significant result trends ($p = 0.051-0.10$) in accordance to procedures suggested by Hopkins (2003). In accordance with these procedures interpretation of observed effect sizes are as follows; trivial < 0.2 , small 0.2-0.6, moderate 0.6-1.2, large 1.2-2.0, very large > 2.0 (Hopkins, 2003).

5.3 Results

5.3.1 Reproducibility of measures

For the 2000 m test there were no differences between any of the assessed performance or physiological measures (Table 5.1). In addition, the mean TE (%) across trials 1-3 for 2000 m and related physiological variables was low to moderate (range: 1.4-7.6 %) with the exception of peak $[\text{Lac}^-]$ (Table 5.1). In relation to the stages of the 2000 m test, TE (%) was greatest during the initial 500 m stage of the test (Table 5.2) and higher in the second stage compared to stages three and four. On inspection the higher overall TE (%) between trials 2-3 is attributable to greater variation during the initial 500 m stage since TE for the final three stages of the test was similar between trials 1-2 and 2-3. For 2000 m time the smallest practical effect was calculated as 2.9 s, expressed in relation to mean power this value equated to 8 watts.

Table 5.1 Mean (SD) for whole trial performance and physiological measures during each trial and associated typical error as a % (90 % CI) for trials 1-2, 2-3 and as a mean across all trials

	Trial 1	Trial 2	Trial 3	TE T1-T2 (%)	TE T2-T3 (%)	Mean TE (%)
Time (S)	402.5 (9.6)	403.9 (9.4)	401.7 (10.0)	0.6 (0.5-0.9)	0.9 (0.7-1.4)	0.8 (0.7-1.1)
Power (W)	347 (24)	343 (24)	348 (26)	1.8 (1.4-2.7)	2.9 (2.2-4.4)	2.4 (2.0-3.4)
Handle power (W)	365 (26)	360 (27)	363 (28)	2.3 (1.8-3.5)	2.8 (2.1-4.2)	2.6 (2.1-3.6)
Handle force (N)	182 (10)	185 (15)	178 (13)	6.2 (4.7-9.4)	8.8 (6.6-13.3)	7.6 (6.2-10.6)
Stroke rate (s.min ⁻¹)	30 (1)	30 (1)	30 (2)	2.8 (2.1-4.1)	3.1 (2.3-4.6)	2.9 (2.4-4.0)
Peak $\dot{V}O_2$ (L. min ⁻¹)	6.03 (0.62)	5.96 (0.62)	6.04 (0.62)	4.1 (3.1-6.2)	4.5 (3.4-6.7)	4.3 (3.5-6.0)
$\dot{V}O_2$ (L. min ⁻¹)	5.09 (0.50)	5.01 (0.41)	5.03 (0.51)	4.2 (3.2-6.3)	5.8 (4.4-8.7)	5.1 (3.9-7.7)
$\dot{V}CO_2$ (L. min ⁻¹)	5.78 (0.62)	5.62 (0.56)	5.58 (0.46)	4.6 (3.5-6.9)	5.1 (3.9-7.7)	4.9 (4.0-6.8)
RER	1.13 (0.04)	1.12 (0.05)	1.12 (0.08)	2.3 (1.7-3.4)	2.4 (1.8-3.6)	2.3 (1.9-3.2)
Peak HR (b.min ⁻¹)	192 (6)	190 (6)	191 (6)	1.5 (1.1-2.3)	1.2 (0.9-1.8)	1.4 (1.1-1.9)
HR (b.min ⁻¹)	182 (6)	179 (6)	180 (6)	1.7 (1.3-2.5)	1.7 (1.3-2.5)	1.7 (1.4-2.3)
Peak blood lactate (mmol. L ⁻¹)	18.6 (3.8)	16.3 (3.5)	17.2 (3.1)	7.5 (5.7-11.4)	14.5 (10.9-22.3)	11.5 (9.3-16.2)
RPE	17 (1)	17 (1)	17 (1)	4.1 (3.1-6.1)	5.0 (3.8-7.5)	4.5 (3.7-6.3)

Table 5.2 Typical error as a % (90 % CI) for trials 1-2, 2-3 and mean across all trials for successive 500 m stages during the 2000 m ergometer test

	Trial 1-2	Trial 2-3	Mean TE
0-500 m	4.3 (3.2-6.4)	7.6 (5.8-11.5)	6.2 (5.0-8.6)
500-1000 m	4.1 (3.1-6.1)	4.1 (3.1-6.2)	4.1 (3.4-5.7)
1000-1500 m	3.1 (2.4-4.7)	2.6 (2.0-3.9)	2.9 (2.4-4.0)
1500-2000 m	2.9 (2.2-4.3)	3.1 (2.4-4.7)	3.0 (2.5-4.2)

The TE (%) for rectified EMG across seven anatomical sites for each stage of the 2000 m test is shown in table 5.3. RA displayed the lowest mean TE (%) for rectified EMG across each 500 m stage of the test (13.2-15.9 %) and GM showed the highest (38.3-44.8 %). There were no differences between the strength and power tests which showed a low to moderate mean TE (3.0-5.9 %) (Table 5.4). No differences existed between trials for the assessed markers of muscle damage. Mean TE (%) was low for limb girths (1.7-2.2 %), moderate for soreness (7.8 %) and high for CK (21.0 %) (Table 5.4).

Table 5.3 Typical error as a % (90 % CI) for trials 1-2, 2-3 and mean across all trials for rectified EMG during successive 500 m stages of the 2000 m ergometer test for seven anatomical sites

Muscle	n =	Stage	TE T1-T2 (%)	TE T2-T3 (%)	Mean TE (%)
Gastrocnemius	10	0-500 m	42.3 (29.3-78.7)	15.9 (11.4-27.5)	31.1 (23.9-48.8)
	10	500-1000 m	36.9 (25.7-67.6)	15.6 (11.2-26.9)	27.7 (21.4-43.2)
	10	1000-1500 m	41.7 (29.0-77.5)	18.1 (12.9-31.4)	31.4 (24.1-49.4)
	10	1500-2000 m	38.7 (27.0-71.4)	12.8 (9.2-22.0)	28.0 (21.6-43.7)
Rectus abdominis	12	0-500 m	13.9 (10.2-22.4)	12.5 (9.2-20.1)	13.2 (10.4-18.6)
	12	500-1000 m	19.3 (14.1-31.4)	11.8 (8.7-18.9)	15.9 (12.6-23.2)
	12	1000-1500 m	15.2 (11.1-24.5)	12.9 (9.5-20.7)	14.1 (11.1-20.8)
	12	1500-2000 m	14.9 (10.9-24.0)	13.9 (10.2-22.4)	14.4 (11.4-20.8)
Biceps femoris	12	0-500 m	10.9 (8.1-17.5)	18.5 (13.5-30.0)	15.1 (11.8-21.3)
	12	500-1000 m	14.4 (10.6-23.1)	17.4 (12.8-28.3)	16.0 (12.5-22.6)
	12	1000-1500 m	11.9 (8.8-19.1)	16.2 (11.9-26.3)	14.2 (11.2-20.0)
	12	1500-2000 m	8.6 (6.4-13.7)	19.0 (13.9-30.9)	14.6 (11.4-20.6)
Gluteus maximus	11	0-500 m	51.3 (35.8-93.4)	21.7 (15.6-36.8)	38.3 (29.5-58.7)
	11	500-1000 m	56.4 (39.2-104.0)	23.7 (17.1-40.4)	42.0 (32.3-64.7)
	11	1000-1500 m	57.0 (39.6-105.2)	19.8 (14.3-33.4)	41.0 (31.6-63.1)
	11	1500-2000 m	64.0 (44.1-119.9)	18.6 (13.4-31.1)	44.8 (34.4-69.3)
Latissimus dorsi	12	0-500 m	16.1 (11.8-26.0)	15.7 (11.5-25.4)	15.9 (12.6-23.1)
	12	500-1000 m	12.6 (9.3-20.3)	21.8 (15.9-35.8)	17.7 (14.0-25.8)
	12	1000-1500 m	11.3 (8.3-18.0)	22.1 (16.1-36.4)	17.4 (13.7-25.3)
	12	1500-2000 m	14.2 (10.4-22.9)	18.9 (13.8-30.7)	16.7 (13.2-24.2)
Erector spinae	10	0-500 m	8.5 (6.1-14.3)	13.3 (9.5-22.8)	11.1 (8.6-16.1)
	10	500-1000 m	9.7 (7.0-16.5)	19.8 (14.1-34.6)	15.4 (11.9-22.6)
	10	1000-1500 m	13.0 (9.4-22.4)	23.6 (16.7-41.8)	18.9 (14.5-27.9)
	10	1500-2000 m	14.1 (10.1-24.2)	24.6 (17.4-43.6)	19.9 (15.2-29.3)
Vastus medialis	11	0-500 m	38.8 (27.5-68.7)	15.5 (11.2-25.8)	28.8 (22.4-44.5)
	11	500-1000 m	31.3 (22.3-54.3)	16.8 (12.2-28.1)	24.8 (19.1-36.6)
	11	1000-1500 m	40.4 (28.5-71.8)	17.5 (12.7-29.3)	30.5 (23.7-47.1)
	11	1500-2000 m	33.6 (23.8-58.6)	16.1 (11.7-26.8)	25.9 (20.2-39.7)

Table 5.4 Mean (SD) for strength and power tests and markers of muscle damage during each trial and associated typical error as a % (90 % CI) for trials 1-2, 2-3 and as a mean across all trials and smallest practical effect (SPE). * = TE (%) for Soreness expressed relative to 0-10 scale

	Trial 1	Trial 2	Trial 3	TE T1-T2 (%)	TE T2-T3 (%)	Mean TE (%)	SPE
MVC (N)	581 (83)	582 (79)	578 (83)	6.1 (4.6-9.2)	5.6 (4.3-8.5)	5.9 (4.8-8.2)	24
SSJ (cm)	32.3 (5.1)	32.2 (5.3)	32.2 (5.6)	4.9 (3.7-7.3)	5.2 (3.9-7.8)	5.0 (4.1-7.0)	1.6
CMJ (cm)	34.9 (6.1)	34.0 (5.4)	34.1 (6.0)	4.0 (3.1-6.1)	5.2 (3.9-7.8)	4.7 (3.8-6.5)	1.7
PS (W)	529 (44)	527 (43)	523 (40)	3.5 (2.7-5.2)	2.4 (1.8-3.6)	3.0 (2.5-4.2)	13
PS handle force max (N)	1133 (120)	1139 (107)	1106 (101)	3.0 (2.3-4.5)	3.7 (2.8-5.5)	3.4 (2.7-4.7)	33
PS handle force mean (N)	235 (13)	242 (13)	230 (14)	4.0 (3.0-6.0)	5.6 (4.2-8.4)	4.9 (4.0-6.8)	4
PS handle power max (W)	2688 (334)	2731 (311)	2637 (288)	3.6 (2.7-5.4)	4.1 (3.1-6.1)	3.8 (3.1-5.3)	93
PS handle power mean (W)	541 (46)	544 (47)	535 (39)	3.6 (2.8-5.5)	2.8 (2.1-4.2)	3.3 (2.7-4.5)	14
Soreness	0.9 (0.9)	1.1 (1.1)	1.0 (1.4)	7.4 (5.6-11.0)*	8.2 (6.3-12.2)*	7.8 (6.4-10.8)*	0.3
CK (U/L)	N/A	185 (130)	176 (103)	N/A	21.0 (15.6-32.7)	21.0 (15.6-32.7)	35
Arm girth (cm)	32.0 (2.3)	31.8 (2.4)	31.9 (2.1)	2.3 (1.7-3.3)	2.0 (1.6-2.9)	2.1 (1.8-2.9)	0.7
Thigh girth (cm)	57.2 (3.1)	57.2 (3.2)	57.2 (2.7)	1.8 (1.4-2.5)	1.7 (1.3-2.5)	1.7 (1.4-2.3)	0.9
Calf girth (cm)	37.4 (2.2)	37.9 (2.5)	37.8 (2.4)	2.3 (1.8-3.3)	2.1 (1.7-3.1)	2.2 (1.8-3.0)	0.7

5.3.2 Pacing of the 2000 m test

There were significant within trial differences for P_{tot} ($F_{(GG)2,13} = 57.63$, $p < 0.001$), P_{aer} ($F_{(GG)2,13} = 156.57$, $p < 0.001$), P_{anaer} ($F_{(GG)2,13} = 166.81$, $p < 0.001$) (Figure 5.1), handle force ($F_{(GG)2,13} = 58.24$, $p < 0.001$) and handle power ($F_{(GG)2,13} = 59.54$, $p < 0.001$) (Figure 5.2). In relation to pacing strategy, pairwise comparisons revealed that a fast start was adopted by participants during the first 500 m stage with power output [391 (27) W] being significantly greater than the three latter 500 m stages [stage two: 336 (24) W, stage three: 320 (24) W, stage four: 336 (34) W]. The mean power during the third 500 m stage was found to be significantly lower than in stages two and four. This pattern displayed by mean power in respect to the 4x 500 m component stages was also followed by handle force and power. In relation to P_{aer} , stage one possessed the lowest power [207 (17)], with no differences between the following three stages [258-261 (21-23) W]. For P_{anaer} , stage one possessed the highest power [184 (25) W], while stage three featured the lowest power

output [60 (21) W], with no differences in power between stages two [78 (20) W] and four [74 (29) W]. There were within trial differences for $\dot{V}O_2$ ($F_{(GG)2,13} = 178.18, p < 0.001$). Oxygen uptake was lower during the initial 500 m of the test (4.26 (0.37) L.min⁻¹) compared to the remaining 1500 m (5.27 (0.44) L.min⁻¹, 5.32 (0.46) L.min⁻¹, 5.34 (0.48) L.min⁻¹ for stages two, three and four respectively). Differences in stroke rate existed between 500 m stages during the 2000 m test ($F_{2,13} = 40.18, p < 0.001$), with the rate being highest during the first stage (32 (1) s.min⁻¹), before significantly decreasing to 29 (1) s.min⁻¹ during stages two and three and then significantly increasing to 30 (1) s.min⁻¹ during the final stage (Figure 5.1).

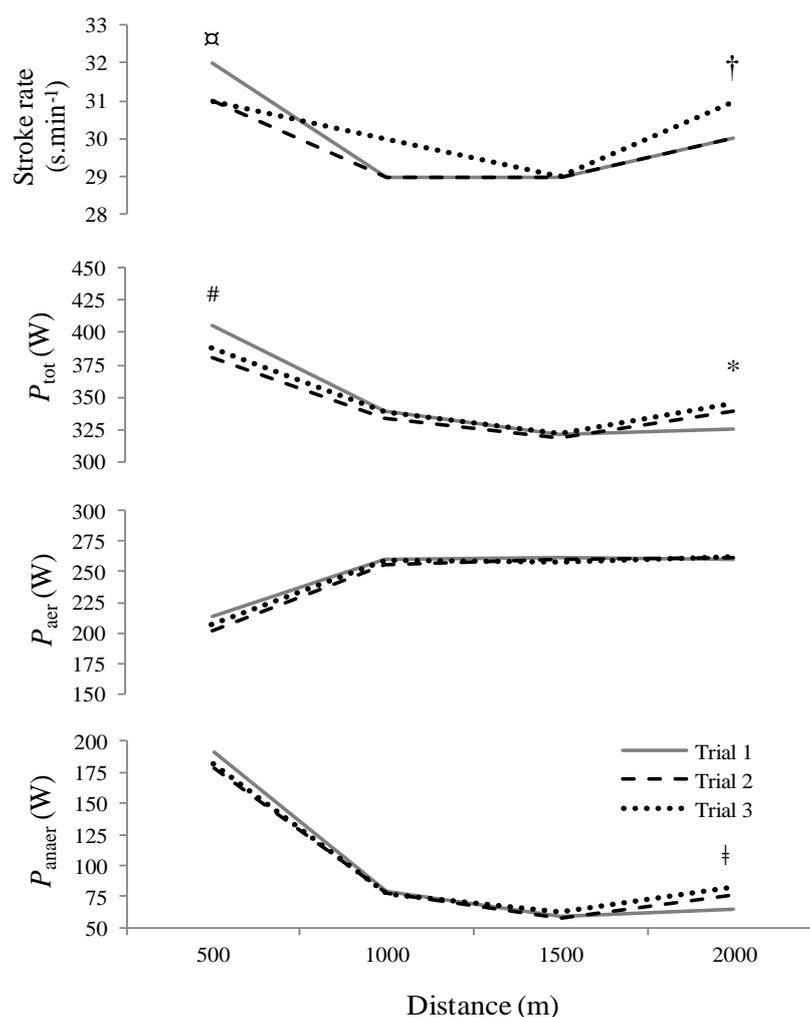


Figure 5.1 Serial pattern of stroke rate (s.min⁻¹) and anaerobic and aerobic contributions to total power (W) during repeat 2000 m trials. * Trial 1 significantly different ($p < 0.05$) than trials 2 and 3. # Significant difference ($p < 0.05$) between trials 1 and 2 and trend for difference ($p < 0.10$) between trials 1 and 3. † Significant difference ($p < 0.05$) between trials 1 and 3 and trend for difference ($p < 0.10$) between trials 1 and 2. α Trial 1 significantly different ($p < 0.05$) than trial 2. † Significant difference ($p < 0.05$) between trials 1 and 3 and trend for difference ($p < 0.10$) between trials 2 and 3.

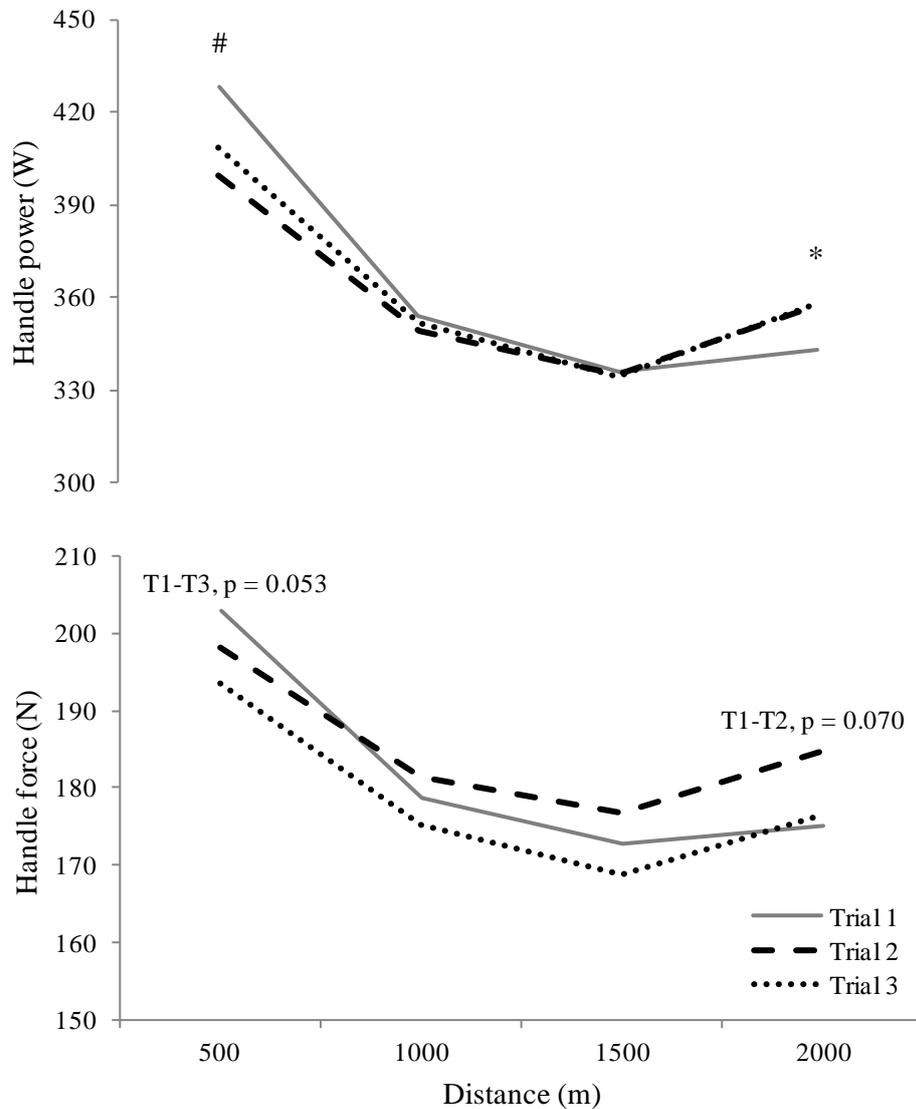


Figure 5.2 Serial pattern of handle force (N) and handle power (W) during repeat 2000 m trials. * Trial 1 significantly different ($p < 0.05$) than trials 2 and 3. # Significant difference ($p < 0.05$) between trials 1 and 2 and trend for difference ($p < 0.10$) between trials 1 and 3. Trends for difference ($p < 0.10$) displayed on handle force figure.

There were significant trial * stage effects for P_{tot} ($F_{(GG)2,13} = 5.83$, $p = 0.006$), P_{anaer} ($F_{(GG)2,13} = 3.36$, $p = 0.032$) (Figure 5.1), handle force ($F_{(GG)2,13} = 5.56$, $p = 0.003$) and handle power ($F_{(GG)2,13} = 5.97$, $p = 0.003$) (Figure 5.2). Mean power for the initial 500 m stage in trial 1 demonstrated a higher value [405 (35) W] compared to trial 2 [381 (32) W, $p = 0.002$] and a trend toward a higher value than trial 3 [388 (32) W, $p = 0.078$, $ES = 0.50$]. There was a concomitant increase in power during the final 500 m for trials 2 [339 (35) W] and 3 [345 (36) W] relative to trial one [325 (32) W] ($p < 0.01$), indicating the presence of an end-sprint in trials 2 and 3. The changes between trials for P_{anaer} somewhat mirrored those of P_{tot} ; there was a trend for P_{anaer} to be higher during stage one for trial 1 in

comparison to trial 2 [192 (35) W vs. 178 (23) W, $p = 0.091$, $ES = 0.47$]. However, during stage four, P_{anaer} was lower for trial 1 [65 (28) W] than trial 2 [77 (31) W, $p = 0.063$, $ES = 0.41$] and 3 [82 (38) W, $p = 0.012$]. There were trends for handle force to be higher during stage one for trial 1 in comparison to trial 3 (203 (13) N vs. 193 (14), $p = 0.053$, $ES = 0.67$) and lower during stage four for trial 1 in comparison to trial 2 (175 (13) N vs. 185 (19), $p = 0.070$, $ES = 0.47$) while handle power mirrored the pattern of P_{tot} between the trials. A significant trial * stage effect was present for stroke rate ($F_{2,13} = 3.04$, $p = 0.010$) (Figure 5.1). For stage one, stroke rate was significantly higher during trial 1 compared to trial 2 [32 (1) W vs. 31 (1) W, $p = 0.007$], whereas for stage four stroke rate was higher for trial 3 [31 (1) W] than both trials 1 [30 (1) W, $p = 0.015$] and 2 [30 (2) W, $p = 0.065$, $ES = 0.59$].

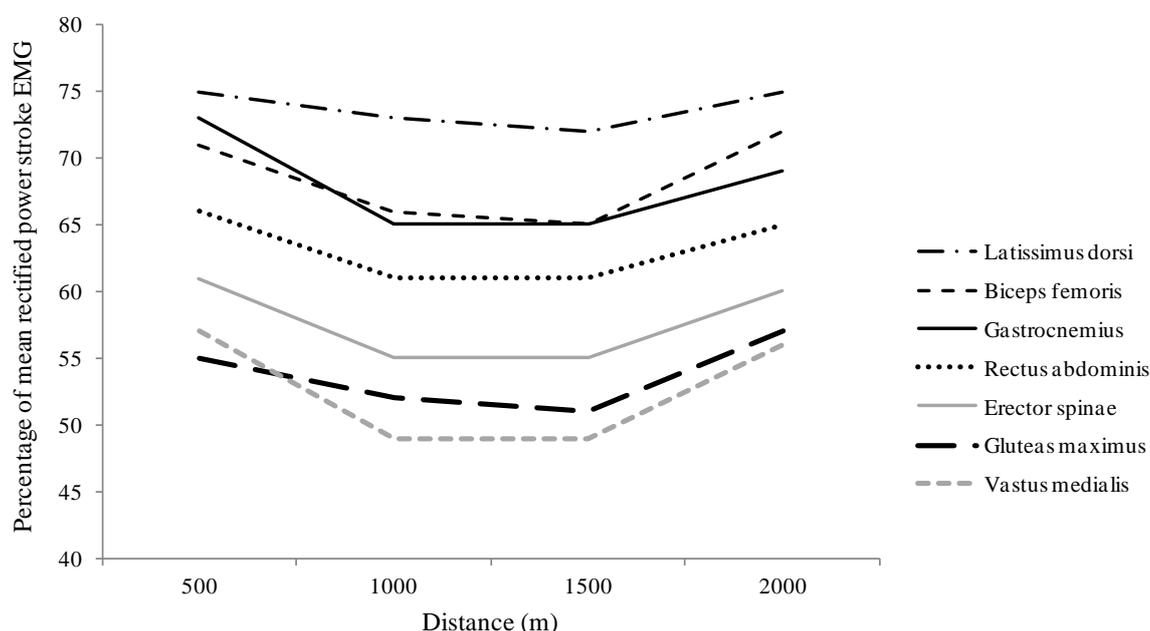


Figure 5.3 Serial pattern of EMG for all seven anatomical sites. EMG for each 500 m stage is expressed as a percentage of the mean rectified EMG value recorded across the five power strokes. The mean values for the three 2000 m trials are shown per 500 m stage for each site

There were significant within trial differences for rectified EMG for BF ($F_{(GG)2,11} = 4.92$, $p = 0.029$), GM ($F_{(GG)2,10} = 6.48$, $p = 0.019$) and VM ($F_{(GG)2,10} = 11.69$, $p = 0.002$) while trends for differences existed for GA, RA and ES ($p = 0.051-0.10$). In relation to stages of the 2000 m test the pattern was for a decrease in EMG during stages two and three compared to stages one and four (Figure 5.3). There were no between trial differences in EMG at any of the sites.

5.4 Discussion

The principal aims of this study were to investigate the reproducibility of strength and power performance, markers of muscle damage, 2000 m rowing ergometer performance and related physiological parameters across three repeated trials and secondly, to investigate the pacing strategy adopted and distribution of energetic resources across three 2000 m tests in trained club rowers.

The TE for 2000 m mean power recorded from trials 1 to 2 (1.8 %), 2 to 3 (2.9 %) and overall (2.4 %), indicates good reproducibility across repeated trials. Typical error was slightly higher to that reported during 2000 m ergometry by Schabort *et al.* (1999) and Soper & Hume (2004), which concurs with the experimental hypothesis. The assessed physiological measures in the present study demonstrated good to moderate reproducibility (mean TE = 1.4-7.6 %) with the exception of $[\text{Lac}^-]$ (11.5 %). These findings are similar to those reported by Stone *et al.* (2011) and Thomas *et al.* (2012) who had trained cyclists perform repeated time trials and found low to moderate variability in physiological measures (1.2-8.0 %) but greater variability in $[\text{Lac}^-]$ (9.6-17.7 %). Swart and Jennings (2004) have concluded that changes in $[\text{Lac}^-]$ concentration should be interpreted with caution as the changes do not track training status or exercise intensity with sufficient precision to have a practical application. Across the three, trials mean $\dot{V}\text{O}_2$ values recorded were higher ($\sim 5.0 \text{ L}\cdot\text{min}^{-1}$) than previously reported in rowers of a similar standard [~ 4.5 - $4.6 \text{ L}\cdot\text{min}^{-1}$; de Campos Mello *et al.* (2009); Russell *et al.* (1998)], however the participants in the current study possessed a higher body mass therefore larger absolute $\dot{V}\text{O}_2$ values could be expected. Peak lactate levels recorded in the present study (16 - $19 \text{ mmol}\cdot\text{L}^{-1}$) were towards the upper limit at what has been reported following 2000 m ergometer tests [11 - $19 \text{ mmol}\cdot\text{L}^{-1}$; Shephard (1998)], indicating the participants were sufficiently motivated to perform the ergometer tests with maximal effort.

To the author's knowledge this is the first study to report contributions of aerobic and anaerobic metabolism to total power per segment of a 2000 m rowing trial. The within trial serial changes of P_{aer} and P_{anaer} followed a pattern that would be expected given the pacing characteristics of the 2000 m test. The initial 500 m of 2000 m rowing trials has consistently been found to be the most powerful phase (Brown *et al.* 2010; Garland, 2005; Schabort *et al.* 1999; Soper and Hume, 2004) and unsurprisingly featured the greatest anaerobic energy liberation. In accordance with the reverse J shaped pacing model; P_{anaer} decreased during stage three allowing a reserve of anaerobic energy to be utilised in stage four (Abbiss and Laursen, 2008). The concomitant maintenance of P_{aer} and hence $\dot{V}\text{O}_2$

within a narrow range during stages two, three and four indicates that the peak for oxidative energy liberation was achieved in the second stage. These findings concur with those of Corbett *et al.* (2009) who found that variations in power output during a 2000 m cycling time trial were caused by altering the pattern of anaerobic energy distribution.

The mean TE for rectified EMG during the 2000 m test across the seven anatomical sites ranged from 11.1-44.8 %. This represents slightly lower variation in EMG than has been previously shown across a variety of muscles during a dynamic exercise protocol involving jumping and sprinting (mean TE = 20.1-49.3 %) (Fauth *et al.*, 2010). Furthermore, EMG variation during slow paced simple dynamic exercises has been shown to range between TE = 11.0-51.5 % (Knutson *et al.*, 1994; Bolgla & Uhl, 2007) therefore EMG can be used with a good degree of confidence for research involving rigorous dynamic exercise. There was low to moderate variation across trials in the strength and power tests and markers of muscle damage (mean TE = 1.7-7.8 %) with the exception of CK (21.0 %), which showed similar variability that previously reported by Nicholson *et al.* (1985) (TE = 19 %). Therefore the majority of tests and markers can be used with confidence when monitoring training progress and stress and conducting research interventions with rowers, obtained values for CK should be interpreted with caution.

In relation to power output, the smallest practical effect was 8 W equivalent to 2.3 %, which was slightly lower than the mean TE across the three trials of 2.4 %. Therefore an improvement in 2000 m performance of 2.5 % or 9 W would be regarded as a meaningful change in performance as this is greater than both the TE and smallest practical effect. This meaningful change value, expressed in relation to 2000 m completion time, is equivalent to 3.2 s. With use of methods described by Hopkins (2000) the sample size requirements for a study using a particular protocol can be estimated from knowledge of the typical error and smallest practical effect. Using the equation proposed by Hopkins, the data presented in the current study indicate a minimum sample size requirement of ten participants to detect 80 % power in a crossover or simple test-retest design. If a control group is used, then the minimum requirement is 38 participants.

For the first trial, participants followed a positive pacing strategy where power output was highest during stage one, then declined on average by 66 W during stage two and then by a further ~ 20 W for stages three and four. The results indicate that an adjustment in pacing strategy was made following this first trial. This was characterised by a reduction in power output during the initial 500 m for trials 2 and 3, which conserved anaerobic energy that was subsequently expended during the final 500 m and afforded a higher power output, which led to an end-spurt during trials 2 and 3. Handle power

similarly expressed these between trial differences, while handle force showed the general differences in pacing strategy from trials 1 to 2 and 3. However, differences in handle force between trials were expressed as trends ($p = 0.053-0.070$), probably as a consequence of the comparative insensitivity of this measure (mean TE = 7.6 %), compared to handle power. This strategy is characterised as a reverse J shaped model of pacing and its use is established in on-water rowing races (Hagerman, 1994; Garland, 2005; Brown *et al.*, 2010). The end-spurt phenomenon occurs as the endpoint approaches and the risk of premature fatigue reduces, reflected in the considered energetic reserve the athlete maintains for the majority of the race in order to reduce the hazard of catastrophic failure (de Koning *et al.*, 2011). The rowers in the present study had extensive experience at performing 2000 m tests within training; therefore it was assumed that they would have an established model of pacing for this test. However, the participating rowers did not have prior experience of performing physiological research, therefore this presented an unfamiliar environment for the performance of the 2000 m tests. The respiratory apparatus and other factors (time in training cycle) consistently affected the 2000 m performance of participants, with mean performance time increased by ~ 9 s across the three trials compared with reported personal best times for the 2000 m test. Rowers produce high ventilation rates (Volianitis & Secher, 2009) and so will be sensitive to any restriction to breathing. That said the rowers produced maximal or near maximal efforts [RPE 17(1)] in the experimental trials based on physiological responses. Given that subjects may not produce maximal efforts under laboratory conditions (Hopkins *et al.*, 1999) and were not tapering for competition at the time of the study justifies the observed variation to be acceptable. In relation to the planning of rowing based intervention studies, it is important for researchers to consider the changes in pacing strategy that can occur across repeated 2000 m ergometer trials independent of any enforced intervention. When considering the results from the current study and those from Schabort *et al.* (1999), whose participants also adopted a different pacing strategy in trials 2 and 3 following trial 1, it is imperative that one familiarisation trial is completed when carrying out intervention studies featuring a 2000 m row.

There was no adjustment in pacing profile from trials 2 to 3, indicating that sufficient prior experience was gained in the first trial to allow the participants to adopt an assumed optimal strategy for the subsequent trials. However, despite these shifts in pacing strategy from trial 1 there was no difference in performance time across the three trials. This is in contrast to findings by Schabort *et al.* (1999) who showed that changes in pacing strategy for a 2000 m row following trial 1, were matched with performance improvements in trials

2 and 3. However, the findings are in agreement with Corbett, Barwood & Parkhouse (2009) who found no performance improvements in 2000 m cycling performance despite participants changing from a positive pacing strategy in trial 1 to a reverse J shaped strategy in trials 2 and 3. Thomas *et al.* (2012) also reported a progressively blunted start in repeated trials when assessing the reproducibility of 20 km cycling, although a reverse J shaped pacing strategy was present for all trials. The current findings are in accordance with the concept of an intelligent regulatory pacing mechanism, as described as the Central Governor Model (Noakes *et al.*, 2004; St Clair Gibson & Noakes, 2004; St Clair Gibson *et al.*, 2006). Since the data suggest that feedback gained from the first trial was utilised to modify the exercise template, either consciously or subconsciously to decrease the power produced during stage one on trials 2 and 3. The higher power produced during stage one for trial 1 likely caused levels of discomfort due to metabolite accumulation, heightening afferent feedback and informed the pacing algorithm (Baden *et al.*, 2005) for subsequent trials. This adjustment in pacing led to a decrease in stage one power for trials 2 and 3.

Even though there were differences in power in respect to stages one and four between trial 1 compared to 2 and 3, there were no differences in EMG during any stage between trials. In respect to the change in pacing strategy from trial 1, where participants consciously produced a lower power output in stage one during trials 2 and 3, it could have been predicted that a lower neural drive would have accompanied this self-regulated reduction in power. The inherent lack of sensitivity in the measurement of EMG (mean TE = ~ 11-45 %) may have negated such changes from being displayed, since the changes in power output across stages between trials were clear however ultimately still small (4-6 %). In respect to the within trial pattern of EMG; stages two and three possessed lower values than stages one and four, which displayed similar values for all muscle sites. This indicates that stages one and four possessed equal neural output and conscious effort (Maestu *et al.*, 2006), although stage four resulted in a lower power output than stage one. This is likely due to increased levels of fatigue in the exercising musculature during stage four in comparison to stage one (Abbiss & Laursen, 2008).

5.5 Conclusion

In conclusion, assessments of strength and power, markers of muscle damage and performance and physiological responses during 2000 m rowing ergometry were found to be consistent over three trials in well-trained rowers. Therefore the assessments can be confidently used in the physiological monitoring of rowers or rowing based intervention studies. The variability of CK, [Lac⁻] and EMG was higher than other assessed measures

although the inherent error was comparable to previously published investigations. Caution should be taken when carrying out physiological intervention studies involving the 2000 m ergometer test, with participants who are unaccustomed to such environments, since changes in pacing strategy were shown to exist from trial 1 to trials 2 and 3. Therefore, a habituation trial is recommended, as a single trial appears to provide sufficient prior experience for a reproducible pacing strategy thereafter. The results indicate that an improvement in mean power during 2000 m ergometer performance of 2.5 % or 9 W signifies a real and practical change in performance and that subtle changes in pacing strategy might be related to changes in anaerobic energy metabolism.

**6. Recovery of rowing sprint
performance after high-intensity
strength training**

6.1 Introduction

Olympic weightlifting is a form of strength training that is used by a wide variety of athletes to enhance performance (Tricoli *et al.*, 2005) and is commonly practiced amongst rowers (Chapter 4; Ivey *et al.*, 2004). Olympic weightlifting involves the performance of explosive eccentric muscle actions (Chiu & Schilling, 2005), yet such actions might potentially lead to a degree of muscle damage and transient reduction in muscle function if the training bout is extensive. To the author's knowledge, data have not been reported in the literature showing the impact of muscle damage resulting from strength training featuring Olympic weightlifting exercises on subsequent physical performance. A potential reason for this lack of data is due to the high level of skill required to practice Olympic weightlifting competently and safely which limits the available participant numbers. Perhaps to circumvent this issue, researchers have instead investigated the effect of plyometric / jump protocols (Semark *et al.*, 1999; Marginson *et al.*, 2005; Twist & Eston, 2005; Skurvydas *et al.*, 2006; Skurvydas *et al.*, 2008; Twist *et al.*, 2008; Davies *et al.*, 2009b) which involve eccentric actions similar to those encountered when performing Olympic weightlifting (Canavan *et al.*, 1996) and barbell squats (Raastad & Hallen, 2000; Byrne & Eston, 2002a; 2002b; French *et al.*, 2008), which are frequently used in training by Olympic weightlifters and a wide variety of other athletes (Drechsler, 1998).

The performance of these aforementioned jump and squat protocols has produced considerable muscle damage and significant performance decrements in measures of functional ability including: counter movement jump height (Byrne & Eston, 2002a; Marginson *et al.*, 2005; Skurvydas *et al.*, 2006; French *et al.*, 2008; Skurvydas *et al.*, 2008), squat jump height (Raastad & Hallen, 2000; Byrne & Eston, 2002a; Marginson *et al.*, 2005), isometric strength (Byrne & Eston, 2002a; 2002b; Marginson *et al.*, 2005; Skurvydas *et al.*, 2008), cycling peak power (Byrne & Eston, 2002b; Twist & Eston, 2005), 10 m and 20 m run sprint time (Twist & Eston, 2005; Davies *et al.*, 2009b; Twist & Eston, 2009) and uni-lateral balance performance (Twist *et al.*, 2008). It has been argued that the lack of relation between the functional tests performed and the athletic history of the chosen participants serves to decrease the applied relevance and external validity of the findings involved (Atkinson & Nevill, 2001; Byrne *et al.*, 2004). Yet, the majority of studies reported in the literature have continued to measure non-sports specific functional performance (in relation to the recruited participants) in the presence of muscle damage (Raastad & Hallen, 2000; Byrne & Eston, 2002a; 2002b; Marginson *et al.*, 2005; Skurvydas *et al.*, 2006; Skurvydas *et al.*, 2008; Twist *et al.*, 2008).

The overall training load of rowers is generally high in volume, with some rowers engaging in more than 20 h of training per week (Steinacker *et al.*, 1998). Therefore it is important that they recover sufficiently following training in order to train effectively in future training sessions, and also to limit the likelihood of injury occurrence (Maestu *et al.*, 2005b). The performance of strength training, in addition to regular rowing based training, creates further exercise stress to recover from, and as previously mentioned, Olympic weightlifting is a form of strength training which is commonly practiced amongst rowers (Chapter 4; Ivey *et al.*, 2004). Since there is no research addressing functional performance following a bout of Olympic weightlifting-style strength training the planning of such exercise bouts within a training programme has to be based on anecdotal reports and the experience of coaches and rowers. Findings from a recent questionnaire (Chapter 4a) showed that approximately 90 % of rowing coaches indicated that high quality rowing training was typically performed on the same day or up to 36 h after strength training. If a high quality rowing session, or more importantly a rowing race, were performed before adequate recovery from a strength training session then peak performance is unlikely to be achieved.

To the author's knowledge this is the first study to elucidate the effect of a high-intensity strength training session that features Olympic weightlifting exercises on functional performance which is representative of the participants' actual sport. It was hypothesised that performance decrements will occur in both rowing sprint performance and counter movement jump following a bout of high-intensity strength training.

6.2 Methods

6.2.1 Participants

Ten male club standard rowers were recruited from Durham University Rowing Club and Tees Rowing Club [mean (\pm standard deviation (SD)), 20.4 (2.8) y, 86.7 (9.9) kg, 1.93 (0.06 m)]. Prior to the study, participants completed at least 12 weeks (twice a week) of supervised Olympic weightlifting-style strength training. They were informed of the experimental procedures and any potential risks involved and gave their written informed consent to participate in the study. The study was approved by the ethical committee of the School of Social Sciences and Law at Teesside University. The participants were asked to abstain from alcohol 24 h preceding laboratory testing sessions and strength training sessions and caffeine before arriving at the laboratory on each of the testing days, this was

confirmed through self-report on the days of testing and strength training. In the weeks preceding testing, participants performed a 250 m rowing ergometer test and a counter movement jump test. These tests familiarised participants with the content of the experimental protocol.

6.2.2 250 m rowing ergometer sprint test reproducibility

In order to ascertain any changes in 250 m performance following the strength training the reproducibility of the test without any imposed intervention must be established. Six male club rowers [mean (SD), 19.5 (2.7) y, 83.6 (10.0) kg, 1.89 (0.07) m] performed the 250 m ergometer test on three occasions. Performance was consistent across trials [Power output (W): Mean typical error % (90 % confidence intervals) = 1.6 (1.2-2.7)] with the smallest practical effect calculated as 16 W or 0.5 s.

6.2.3 Procedures

On the first testing day participants arrived at the laboratory having abstained from all exercise for 48 h and strength training for 120 h. Participants' body mass and stature were then measured. Participants then performed four maximal counter movement jumps (CMJ), interspersed with 30 s recovery between jumps. Participants then performed a five min warm-up on a rowing ergometer which was followed by the 250 m test. Immediately after the test was completed participants attributed a rating of perceived exertion (RPE) for how physically demanding they found the test. Twenty four hours after the baseline measures, earlobe capillary blood was taken for assessment of creatine kinase (CK). Participants perceived soreness rating and limb girths were also assessed. Participants then performed the strength training session (ST). One hour following the ST, soreness and girth measurements were repeated. Participants returned to the lab 24, 48 and 72 h following ST, and a blood sample for assessment of CK was taken and then perceived soreness rating and limb girths were assessed. The participants then completed the CMJ and 250 m rowing ergometer test. See figure 6.1 for a schematic diagram describing the experimental design.

Pre study	Participants abstained from all exercise for 48 h and strength training for 120 h
Day 1	Baseline Trial: CMJ, 250 m
Day 2	Creatine kinase, Soreness, Limb girths
	Strength training session
	1 h post ST: Soreness, Limb girths
Day 3	Creatine kinase, Soreness, Limb girths
	Follow up 24 h: CMJ, 250 m
Day 4	Creatine kinase, Soreness, Limb girths
	Follow up 48 h: CMJ, 250 m
Day 5	Creatine kinase, Soreness, Limb girths
	Follow up 72 h: CMJ, 250 m

Figure 6.1 Schematic diagram describing experimental design

6.2.4 Experimental test battery

Reproducibility of the following exercise tests and markers of muscle damage were assessed in chapter 5.

6.2.4.1 Counter movement jump (CMJ)

The Just Jump measurement system was used for assessment (Just Jump, Probotics, Huntsville, AL, USA). Four independent CMJ trials were conducted; the highest trial was recorded for data analysis. Please refer to section 3.4.2 for more detail.

6.2.4.2 250 m rowing ergometer sprint (250 m)

The test was performed on an air-braked rowing ergometer (Concept 2 Model D, Concept 2 Ltd, Wilford, Notts, UK) with a drag factor of 140. Participants were required to hold a rate of 30 strokes per minute ($s \cdot \text{min}^{-1}$) during the 250 m test. A fixed stroke rate was chosen as it was thought that allowing for a free stroke rate over a short duration test would lead to discrepancies in the reliability of the data, and secondly a rate of 30 $s \cdot \text{min}^{-1}$ has been used in previous research which featured a short duration rowing test (Ingham *et al.*,

2002). Immediately after the test was completed, participants gave a rating of perceived exertion (RPE) for how physically demanding they found the test. The scale ran from 6 indicating no exertion to 20 indicating exhaustion (Borg, 1970). The 250 m test was chosen as it was thought that it could be performed on consecutive testing days without causing the build up of residual fatigue. Additionally, short duration rowing tests, such as the five power stroke test, and 30 s ergometer sprint test have been found to correlate strongly ($r = 0.87-0.95$) with 2000 m rowing test performance (Ingham *et al.*, 2002; Riechman *et al.*, 2002), therefore it is assumed likely that the results from the 250 m test would provide an indication of 2000 m test performance.

6.2.4.3 Rating of perceived soreness

Participants' level of perceived muscle soreness was assessed via a 10 cm long visual analogue scale. Please refer to section 3.6.1 for more detail.

6.2.4.4 Limb girths

Limb girth measurements were taken from the mid-thigh, mid-calf and upper arm. Please refer to section 3.6.2 for more detail.

6.2.5 Strength training session

A strength training session featuring various multi-joint barbell exercises was performed by participants as described in table 6.1. Please refer to section 3.3 for more detail.

Table 6.1 Strength training session and mean and (SD) of 1 RM achieved by the participants on the exercises featured

Exercise	Sets x reps	% 1 RM / weight used	1 RM achieved [kg]
Snatch	4x5	85 %	52.5 (7.5)
Clean	4x5	85 %	77.5 (12.5)
Back squat	4x5	85 %	100 (17.5)
Romanian deadlift	3x8	75 % of squat 1 RM	-
Bench press	3x5	85 %	65 (15)
Bent over row	3x5	85 %	70 (10)
Weighted sit-ups	3x15	10 kg	-

Mean (SD) rounded to nearest 2.5 kg increment

6.2.6 Blood analysis

Capillary blood samples were collected as outlined in section 3.7. This was used for the analysis of CK (Section 3.7.2).

6.2.7 Statistical analysis

Data presented in the results section is written as mean (\pm SD), unless stated otherwise. Changes in assessed measures were analysed using repeated measures ANOVA tests. The alpha level for significance was set at $p < 0.05$ for all analysed data. Assumptions of sphericity were assessed using Mauchly's test of sphericity, with any violations adjusted by use of the Greenhouse-Geisser ($_{GG}$) correction. If a significant main effect across time was shown then post hoc differences across trials were analysed with use of the LSD correction. Where significant differences were shown in the markers of muscle damage and performance tests, then Pearson product moment correlations were conducted on the changes in the data.

In addition, the smallest practical effect was calculated for measures exhibiting significant changes. Defining the smallest practical effect allows for qualification of the probability of a practical change in performance occurring (Batterham & Hopkins, 2006). Smallest practical effect was calculated for each dependent variable from the product of 0.3 [which represents the smallest standardised change in mean for a group of trained participants; Hopkins *et al.* (2009)] multiplied by the between-participant standard deviation across the three re-test reliability trials of the group of participants in chapter 5. From using the smallest practical effect value magnitude and inference of the change in each dependent variable was then analysed according to procedures developed by (Hopkins, 2007b). From these procedures, 90 % confidence intervals (CI) for the changes in dependent variables from pre to post intervention are calculated. In addition, practical likelihoods of harm or benefit caused to each dependent variable from the independent variable (intervention) are established based on percentage boundaries; 0 to 0.5 % indicated most unlikely; 0.5 % to 5 % indicated very unlikely; 5 % to 25 % indicated unlikely; 25 % to 75 % indicated possibly; 75 % to 95 % indicated likely; 95 % to 99.5 % indicated very likely; and > 99.5 % indicated most likely (Hopkins, 2007b).

6.3 Results

Perceived muscle soreness increased significantly following the bout of strength training ($F_{4,9} = 26.6$, $p < 0.001$). Scores were elevated above baseline values at all time points (Figure 6.2). The practical inference was that the ST was 'most likely' to result in

increased soreness at 1 h, 24 h and 48 h and ‘likely’ to result in increased soreness at 72 h. There was a significant main effect across time for creatine kinase activity ($F_{(GG)3,9} = 13.1$, $p = 0.001$). Creatine kinase was significantly increased from 245 (192) U/L at baseline to 513 (311) U/L at 24 h with values returning to baseline at 48 h. The 90 % CI indicated that at 24 h post ST the likely increase in CK for the population in relation to baseline values was 146 to 390 U/L. The practical inference was that the ST was ‘most likely’ to result in raised CK at 24 h. There were no significant changes in limb girths at any time point with measurements at each site; Arm (31-31.7 cm across trials), Calf (38.7-39.2 cm) and Thigh (56.5-57.1 cm) remaining consistent throughout trials.

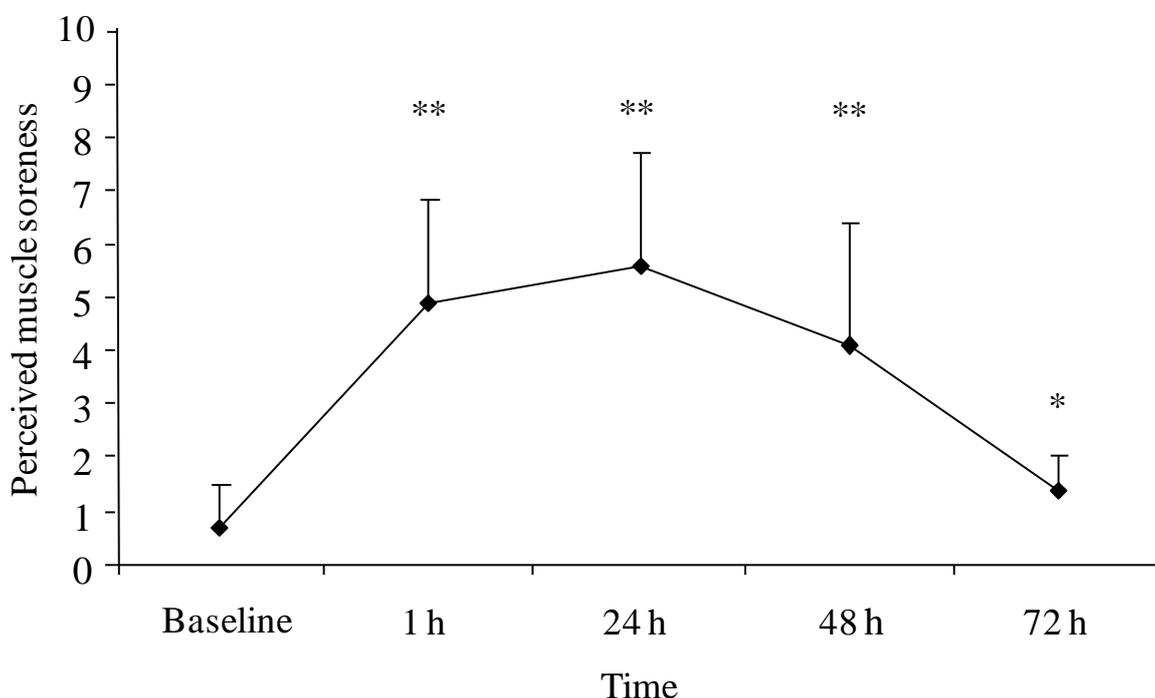


Figure 6.2 Change in perceived muscle soreness (scale: 0 - 10) following high-intensity strength training. Values are expressed as mean (SD) (n = 10). ** Significantly higher than baseline ($p < 0.01$). * Significantly higher than baseline ($p < 0.05$).

There was a significant main effect for 250 m sprint time to change over time ($F_{3,9} = 8.2$, $p = 0.001$). At 24 h the mean time to complete the 250 m sprint was 44.6 (1.4) s, the 90 % CI indicated that the length of time to complete the sprint at 24 h post ST in the population was likely to be 0.3 to 0.7 s slower than baseline [44.1 (1.5 s)] (Figure 6.3). The practical inference was that the ST would ‘possibly’ cause a decrease in performance at this time point. However, at 48 h and 72 h sprint performance was not significantly different to baseline levels [44.2 (1.5) s and 44.1 (1.5) s respectively]. There was a change in 250 m sprint RPE over time ($F_{3,9} = 4.8$, $p = 0.008$), with attributed values for the 24 h [17 (1)] and

48 h [17 (2)] trials being higher than for the baseline trial [16 (1)]. The practical inference was that the ST was ‘very likely’ and ‘likely’ to result in increased RPE during the 250 m sprint at 24 h and 48 h respectively. From baseline to 24 h there was a significant correlation between the changes in 250 m and RPE ($r = 0.64$, $p = 0.023$), however there were no significant correlations between the changes in CK or soreness and 250 m.

There was a significant main effect across time for CMJ height ($F_{3,9} = 3.7$, $p = 0.023$). At 48 h post ST, mean CMJ was 48.6 (8.4) cm, the 90 % CI indicated that jump height could decrease from 0.7 to 4.1 cm in relation to the baseline trial [46.2 (7.2) cm]. According to the practical inference this represented a ‘likely’ decrease in jump performance.

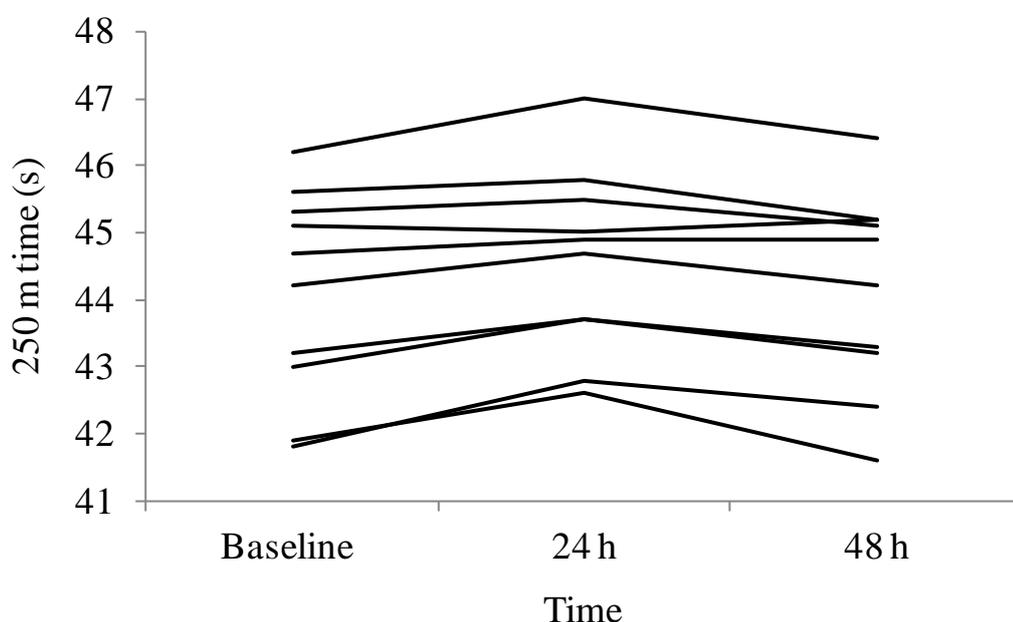


Figure 6.3 Individual participant (n = 10) changes in 250 m rowing sprint time at 24 h and 48 h following high-intensity strength training

6.4 Discussion

This was the first study to investigate the impact of a strength training session featuring Olympic weightlifting exercises on subsequent dynamic exercise performance. The results showed that 250 m rowing sprint and CMJ performance were decreased following strength training.

In this study, 250 m rowing ergometer performance was reduced at 24 h after the ST. The decrease in rowing sprint performance (1.1 %) was smaller than reported by other authors who have investigated sprint performance following muscle damaging exercise. Davies *et al.* (2009b) and Twist & Eston (2005) recorded 4.4 % and 3 % decreases

respectively in run sprint performance and Byrne & Eston (2002b) reported a 17 % decrease in cycling ergometer sprint peak power. However, the small decrease in performance was consistent amongst participants, indeed from magnitude of change based analysis it was deemed that there was a 'possible' chance that this change was harmful to performance (Hopkins, 2007b). Therefore this small but predictable decrease in rowing sprint performance is something that rowers and coaches should consider when scheduling short duration / power orientated time trials or training sessions. A potential cause of the decrement in rowing sprint performance is selective damage to type II muscle fibres caused from the ST. Eccentric exercise has been shown to cause preferential damage to type II muscle fibres (Jones *et al.*, 1986). Previous authors who have used eccentric muscle action based damaging protocols have cited this as a probable cause of subsequent reduced power producing ability (Byrne & Eston, 2002b; Marginson *et al.*, 2005; Twist & Eston, 2005). It is likely that the overall eccentric muscle loading caused by the ST was lower than the eccentrically biased protocols as used by previous authors. However, certain exercises featured within the ST such as the clean and snatch lifts feature eccentric actions similar to those encountered when jumping (Canavan *et al.*, 1996) and the eccentric action when performing the Romanian deadlift is emphasised (Brandon & Cleather, 2007), this coupled with a high load (85 % 1 RM) on most of the featured exercises translates to a significant magnitude of eccentric muscle loading during the ST.

Rating of perceived exertion in response to the 250 m test was found to significantly increase at 24 h and 48 h post-ST, previous authors have recorded increases in RPE during endurance exercise following the performance of general strength training (Scott *et al.*, 2003) and high volume barbell squats (Davies *et al.*, 2008). The change in RPE from baseline to 24 h was also found to significantly correlate with the change in 250 m sprint time. Twist & Eston (2009) have proposed that the increased pain sensation resulting from muscle damaging exercise led to a self limiting work intensity and pacing during a subsequent five min cycling effort. They found that RPE was unchanged during a 5 km time trial despite less distance being covered during the second 5 km time trial following a muscle damaging protocol which perhaps signifies an attempt by the participants to work within tolerable limits. This could explain why the significant rise in RPE at 24 h occurred even though participants' performance on the 250 m sprint was decreased in relation to the baseline test. However, research suggests that performance in sprint type events lasting less than 60 s is optimal when athletes perform maximally from start to finish (Smith & Hill, 1991; Corbett, 2009), although not all athletes employ this strategy (Wilberg & Pratt, 1988) therefore it is questionable whether self-limiting pacing

would affect performance in the current study since the test was completed in approximately 44 s.

One reason for the small decrement in 250 m performance despite evidence of moderate muscle damage might be due to what is known as the 'repeated bout effect'. The repeated bout effect refers to when a novel bout of eccentric exercise induces skeletal muscle damage, but repeating the same exercise within several weeks results in significantly less damage and is characterised by a smaller reduction and faster recovery of parameters of muscle function (Nosaka *et al.*, 2001). Both Nosaka *et al.* (2001) and Lavender & Nosaka (2008) have found this effect to occur with repeated resistance training. The majority of the studies which have assessed functional anaerobic type performance in the presence of muscle damage (Semark *et al.*, 1999; Byrne & Eston, 2002a; 2002b; Marginson *et al.*, 2005; Twist & Eston, 2005; Skurvydas *et al.*, 2006; French *et al.*, 2008; Skurvydas *et al.*, 2008; Twist *et al.*, 2008) have featured high-intensity exercise challenges often with a focus on eccentric loading (for example high volume plyometric jumps and barbell squats). Since these protocols would likely be novel to the featured participants the extent of the functional decrement experienced after the protocols would be large since there would be no protective repeated bout effect. Raastad & Hallen (2000) are the only previous authors to directly specify that their participants had experience of performance of the chosen damaging protocol. Likewise, in the current study all the participants performed strength training on a regular basis and sessions commonly featured the exercises and loading demands prescribed in the ST. Therefore the participants had the protection of the repeated bout effect when performing the ST. Perhaps unsurprisingly the time-course of functional decrement recorded by Raastad & Hallen (2000) and in the current study was shorter compared to many of these aforementioned studies where the featured participants were not previously familiarised with the muscle damaging protocols.

The changes in perceived muscle soreness and plasma CK provide evidence that muscle damage was present following the ST. However, limb girths were unaffected following strength training, this indicates that the muscle damage was not severe enough to induce oedema and swelling which is associated with the inflammatory response that occurs as a result of muscle damage (Clarkson *et al.*, 1992). This finding of no change in limb girths despite elevated CK, soreness and decreases in functional performance following a bout of muscle damaging exercise, has been shown previously in participants who had been regularly exposed to a damaging exercise bout (Davies *et al.*, 2009b). The CK value peaked at 24 h post exercise and is in agreement with previous studies which

have reported elevated CK values at 24 h following high volume barbell squat protocols (Byrne & Eston, 2002b; French *et al.*, 2008), a general strength training session (McBride, 1995) and after a protocol of drop jumps (Davies *et al.*, 2009b). Perceived soreness rating was significantly elevated for 72 h following ST, with the peak value occurring at 24 h and these findings are similar to responses following other strength training protocols (Rawson *et al.*, 2007; French *et al.*, 2008; Hackney *et al.*, 2008). More prolonged increases in CK (Twist & Eston, 2005; Skurvydas *et al.*, 2006; Skurvydas *et al.*, 2008; Tofas *et al.*, 2008) have been found to exist following plyometric exercise protocols than in comparison to the ST. Therefore it is likely that the ST elicited less muscle damage than the jump based damaging protocols used in these studies. The increased damage resulting from jump based protocols may be due to the greater overall eccentric loading featured in these protocols compared to the ST (Jamurtas, 2000).

There was a significant decrease in CMJ height 48 h following ST. This finding supports those obtained by previous authors who reported significant decrements in CMJ lasting from 24-72 h following performance of high volume barbell squats (Byrne & Eston, 2002a; French *et al.*, 2008) and plyometric jumps (Marginson *et al.*, 2005; Skurvydas *et al.*, 2006). However, the decrement in CMJ performance in the present study (4.9 %) was less than reported by the aforementioned authors who reported decrements between 8.5 % to 15 %. The damaging protocols used in the aforementioned studies were far more leg dominant than our chosen protocol. These authors used high volume jump and squat protocols which would have focused muscle damaging effects on the lower body muscles, which are primarily used for the performance of a CMJ (Crowther *et al.*, 2007), this contrasts to the present study where a whole body strength training session was used. While the Olympic weightlifting exercises included in the ST featured eccentric actions which are similar in nature to those encountered when jumping (Canavan *et al.*, 1996), the volume of repetitions on these exercises was lower compared to the number of jumps featured in the plyometric protocols. It is likely that the ST session would cause whole body functional decrement rather than localised lower body impairment. Therefore it is not surprising that leg dominant protocols resulted in greater CMJ height decrements.

6.5 Conclusion

A high-intensity strength training session, which was typical in nature to the type undertaken by rowers, resulted in symptoms of muscle damage which persisted for 48 h. In addition, 250 m rowing sprint and counter movement jump were significantly decreased at 24 h and 48 h respectively following the bout of strength training. Due to the familiarity of

the muscle damaging exercise protocol, it is likely that the repeated bout effect protected participants from exaggerated decrements in functional performance that have been shown to result following novel exercise challenges. The findings have implications for coaches and athletes in regards to the scheduling of sports / event specific training or testing following strength training. Specifically in rowing, optimal performance may be compromised if scheduled ≤ 24 h after high-intensity strength training.

7. Does a bout of strength training affect 2000 m rowing ergometer performance and rowing-specific maximal power 24 hours later?

7.1 Introduction

Research suggests that rowers perform strength training with a loading between 85 % to 95 % of their one repetition maximum (Chapter 4; McNeely *et al.*, 2005). Heavy load resistance training such as this has been shown to produce more pronounced and longer lasting decrements in parameters of muscle function including muscle power, maximal voluntary contraction, peak torque and electrically evoked force, than moderate load resistance training (Raastad & Hallen, 2000; Linnamo *et al.*, 2005; Paschalis *et al.*, 2005a). Despite the strenuous nature of the strength training performed by rowers there is a lack of research investigating the impact of acute strength training on rowing or endurance performance in general. Scott *et al.* (2003) are the only authors to assess the impact of a bout of strength training, featuring free weight barbell exercises, on subsequent endurance exercise. They found that participants reported significantly higher rating of perceived exertion (RPE) values during a 30 min sub-maximal run performed 24 to 30 h after the strength training session in comparison to a baseline trial. The participants in the Scott *et al.* (2003) study were described as ‘physically active’, taking part in ≥ 3 running sessions a week. Using such participants rather than athletes, who train specifically to compete in a particular sport or event, limits the applicability of the findings obtained in relation to the athletic setting (Marcora & Bosio, 2007).

Various studies have assessed the impact of muscle damaging exercise challenges (commonly a series of jumps or prolonged downhill running) on subsequent cycling or running endurance performance. This research has generally involved either assessment of physiological responses during sub-maximal exercise (Gleeson *et al.*, 1995; Calbet *et al.*, 2001; Braun & Dutton, 2003; Scott *et al.*, 2003; Paschalis *et al.*, 2005b; Chen *et al.*, 2007; Chen *et al.*, 2008) or incremental tests to volitional exhaustion (Gleeson *et al.*, 1998; Davies *et al.*, 2008; Davies *et al.*, 2009a). However, the use of these endurance protocols has been questioned on the basis that they possess low ecological validity since the featured protocols do not simulate or model the demands imposed throughout a typical endurance cycling or running event (Schabert *et al.*, 1998; Atkinson & Nevill, 2001). In terms of athletic performance, a more reliable and externally valid means of assessing endurance performance involves protocols in which athletes are required to complete a fixed amount of work or to cover a given distance in the shortest possible time (time trials) or to complete a maximal amount of work in a specific time period (Schabert *et al.*, 1998; Atkinson & Nevill, 2001; Hopkins *et al.*, 2001). Marcora & Bosio (2007) and Twist and Eston (2009), reported ~ 4 % decreases in the distance run in 30 min and the distance cycled in 5 min, respectively, following muscle damaging protocols involving plyometric

jumps. Despite the exercise tests being more applicable to the athletic setting than those previously discussed, the participants in these studies were not trained endurance athletes. In light of this issue, Marcora & Bosio (2007) cautioned that their results could not confidently be applied to high level athletes, since this population might be less susceptible to exercise induced muscle damage due to the repeated bout effect (McHugh, 2003). The repeated bout effect refers to when a novel bout of eccentric exercise induces skeletal muscle damage, but repeating the same exercise within several weeks results in significantly less damage and is characterised by a smaller reduction and faster recovery of parameters of muscle function (Nosaka *et al.*, 2001). Authors have found this effect to occur with repeated bouts of resistance training (Nosaka *et al.*, 2001; Lavender & Nosaka, 2008), jump training (Marginson *et al.*, 2005; Miyama & Nosaka, 2007) and downhill running (Rowlands *et al.*, 2001).

A more complete understanding of the effects of acute strength training on endurance performance is important, particularly for endurance based sports where strength training is routinely performed. This is because bouts of strength training result in subsequent decrements in sports specific muscle function, notably power producing ability (Chapter 6; Raastad & Hallen, 2000; Byrne & Eston, 2002a; 2002b; French *et al.*, 2008). Findings from a recent questionnaire (Chapter 4a) found that approximately 90 % of rowing coaches programme rowing training on the same day or up to 36 h after strength training. This finding indicates a belief amongst coaches that rowers are able to perform high-load strength training and subsequently perform meaningful rowing training in close proximity to one another. However, a strength training session, similar to that habitually performed by rowers, led to a decrease in 250 m rowing sprint performance at 24 h with accompanying symptoms of muscle damage and decreases in jump height (Chapter 6). Since short duration rowing tests have been shown to correlate with 2000 m rowing performance [$r = 0.87-0.95$; Ingham *et al.* (2002); Riechman *et al.* (2002)], there is the potential that 2000 m rowing performance would be negatively affected by prior strength training undertaken in close proximity.

Therefore the aim of this study was to determine the effect of a bout of high-intensity strength training on 2000 m rowing ergometer performance and rowing specific maximal power. It was hypothesised that concurrent performance decrements would occur in 2000 m rowing ergometer performance and rowing specific maximal power following a bout of high-intensity strength training.

7.2 Methods

7.2.1 Participants

Eight club standard rowers were recruited from Tees Rowing Club [mean (\pm standard deviation (SD)), age: 23.6 (6.8) y, body mass: 85.4 (9.8) kg, stature: 1.88 (0.06) m, 2000 m ergometer time: 6:35.2 (0:12.4) min:s. The participants possessed a similar 2000 m ergometer time to those recruited by Ingham *et al.* (2007) (2000 m: 6:34.5 min:s) who were described as ‘club standard’ rowers. To put the standard of the recruited rowers into context, Ingham *et al.* (2007) found eight Olympic champion rowers to have a 2000 m time of 5.53.4 min:s. All participants had at least one year of experience at regularly performing structured strength training and prior to the study, all participants completed at least 12 weeks (two sessions a week) of supervised Olympic weightlifting-style strength training. During this ≥ 12 week period the participants maintained their habitual rowing training and did not perform any additional strength training. They were informed of the experimental procedures and any potential risks involved and gave their written informed consent to participate in the study. The study was approved by the ethical committee of the School of Social Sciences and Law at Teesside University. The participants were asked to abstain from alcohol 24 h preceding laboratory testing sessions and strength training sessions and caffeine before arriving at the laboratory on each of the testing days, this was confirmed through self-report on the days of testing and strength training.

7.2.2 Experimental protocol

Throughout their involvement in the research participants maintained their regular rowing training and avoided strength training, apart from the sessions given before the two follow up trials (24 h and 48 h). Participants were asked to abstain from exercise on the day of testing and arrive at the laboratory in a hydrated state. All participants were habituated to tests prior to the first testing day, this involved performing each of the power tests at the start of their supervised strength training sessions in the four weeks prior to testing. Participants were asked to abstain from strength training in the 72 h before baseline testing. On the first testing day body mass and stature were measured. Participants then completed a 5 min warm-up on a rowing ergometer, followed by five individual static squat jumps (SSJ) and five individual counter movement jumps (CMJ), interspersed with 30 s recovery between each jump. After the jumps, participants performed five maximal rowing power strokes (PS) on the rowing ergometer. The participants were then instructed to warm-up for a further 5 min on the rowing ergometer after which they performed the 2000 m test. Heart rate was recorded every 30 s during the test. Immediately after the test was completed,

participants provided a rating of perceived exertion (RPE) for how physically demanding they found the test. Capillary blood samples were taken before and at the end of the test and at 1-, 3-, 5- and 7 min of recovery for the assessment of blood lactate [Lac⁻].

Four to six days after the baseline measures, participants returned to the laboratory. A capillary blood sample was taken from the finger for assessment of creatine kinase (CK) and lactate dehydrogenase (LDH). Participants perceived soreness rating and limb girths were also assessed. The participants then performed the strength training session (ST). Two hours following the ST, capillary blood was drawn for assessment of CK and LDH, and soreness and girth measurements were repeated. In addition, at this time-point the anaerobic (SSJ, CMJ, PS) power tests were again completed. Participants were then randomly assigned to perform follow up measures at either 24 h or 48 h after the ST. For follow up measures, capillary blood was collected for assessment of baseline [Lac⁻], CK and LDH, and perceived soreness and limb girths were also assessed. The participants then repeated the testing protocol described for the first testing day. Four to six days following completion of the first follow up trial, participants repeated the ST and then performed follow up testing at 24 h or 48 h after in a counter-balanced manner. The study followed a within participant design, since the same group of participants performed all three 2000 m trials. See figure 7.1 for a schematic diagram describing the experimental design.

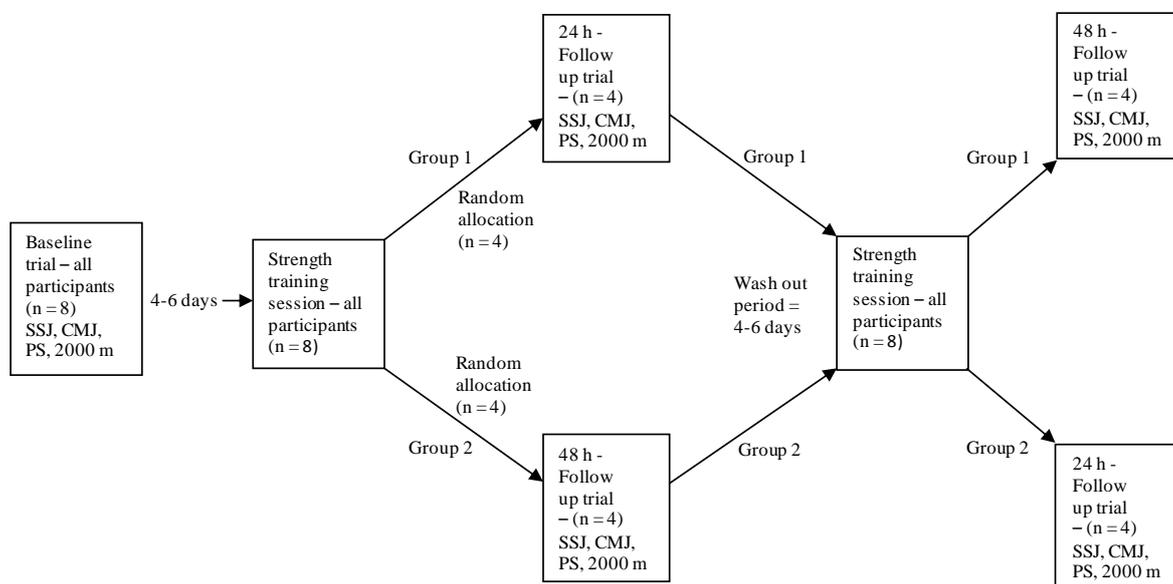


Figure 7.1 Schematic diagram describing experimental design

7.2.3 Experimental test battery

Reproducibility of the following exercise tests and markers of muscle damage were assessed in chapter 5.

7.2.3.1 Static squat jump (SSJ) and counter movement jump (CMJ)

The Just Jump measurement system was used for assessment (Just Jump, Probotics, Huntsville, AL, USA). Five independent SSJ and CMJ trials were conducted; the highest trial was recorded for data analysis. Please refer to section 3.4.2 for more detail.

7.2.3.2 Power strokes (PS)

Maximal stroke power was assessed using an air-braked rowing ergometer (Concept 2 Model D, Concept 2 Ltd, Wilford, Notts, UK). Please refer to section 3.4.3 for more detail.

7.2.3.3 2000 m rowing ergometer test (2000 m)

The test was performed on an air-braked rowing ergometer (Concept 2 Model D, Concept 2 Ltd, Wilford, Notts, UK). Please refer to section 3.5 for more detail.

7.2.3.4 Rating of perceived soreness

Participants' level of perceived muscle soreness was assessed via a 10 cm long visual analogue scale. Please refer to section 3.6.1 for more detail.

7.2.3.5 Limb girths

Limb girth measurements were taken from the mid-thigh, mid-calf and upper arm. Please refer to section 3.6.2 for more detail.

7.2.4 Strength training session

A strength training session featuring various multi-joint barbell exercises was performed by participants as described in table 7.1. Please refer to section 3.3 for more detail.

Table 7.1 Strength training session and mean (SD) of 1 RM achieved by the participants on the exercises featured

Exercise	Sets x reps	% 1 RM / weight used	1 RM achieved [kg]
Snatch	4x5	85 %	60 (5)
Clean	4x5	85 %	82.5 (7.5)
Back squat	4x5	85 %	110 (15)
Romanian deadlift	3x8	75 % of squat 1 RM	-
Bench press	3x5	85 %	80 (7.5)
Bench pull	3x5	85 %	82.5 (5)
Weighted sit-ups	3x15	15 kg	-

Mean (SD) rounded to the nearest 2.5 kg increment

7.2.5 Blood analysis

Capillary blood samples were collected as outlined in section 3.7. This was used for the analysis of $[\text{Lac}^-]$ (Section 3.7.1), CK (Section 3.7.2) and LDH (Section 3.7.3).

7.2.6 Statistical analysis

Data are presented as mean (\pm SD), unless stated otherwise. Due to the large inter-participant variability in serum CK and LDH levels (Xue & Yeung, 1994; Nosaka & Clarkson, 1996) recorded values were log transformed using a spreadsheet produced by (Hopkins *et al.*, 2009) and subsequent statistical analysis was conducted on the transformed data. Absolute means for CK and LDH values are presented in the results section. For all other measures, raw data values were used for statistical analysis. Changes in assessed measures were analysed using repeated measures ANOVA tests. The alpha level for significance was set at $p < 0.05$ for all data. Assumptions of sphericity were assessed using Mauchly's test of sphericity. If a significant main effect across time was shown then post hoc differences across trials were analysed with use of the LSD correction. Where significant differences were shown in the markers of muscle damage and performance tests, then Pearson product moment correlations were conducted on the changes in the data. Pearson product moment correlations were also performed between 2000 m performance and SSJ, CMJ and PS at baseline, 24 h and 48 h.

In addition, the smallest practical effect was calculated for measures exhibiting significant changes. Defining the smallest practical effect allows for qualification of the

probability of a practical change in performance occurring (Batterham & Hopkins, 2006). Smallest practical effect was calculated for each dependent variable from the product of 0.3 [which represents the smallest standardised change in mean for a group of trained participants; Hopkins *et al.* (2009)] multiplied by the between-participant standard deviation across the three re-test reliability trials of the group of participants in chapter 5. From using the smallest practical effect value, magnitude and inference of the change in each dependent variable was then analysed according to procedures developed by (Hopkins, 2007b). From these procedures, 90 % confidence intervals (CI) for the changes in dependent variables from pre- to post- intervention are calculated. In addition practical inferences of harm or benefit caused to each dependent variable from the independent variable (intervention) were drawn using the approach identified by (Batterham & Hopkins, 2006). These inferences were based on percentage boundaries which indicate the chances in percent of harm or benefit occurring to a dependent variable as a consequence of the intervention; 0 to 0.5 % indicated most unlikely; 0.5 % to 5 % indicated very unlikely; 5 % to 25 % indicated unlikely; 25 % to 75 % indicated possibly; 75 % to 95 % indicated likely; 95 % to 99.5 % indicated very likely; and > 99.5 % indicated most likely (Hopkins, 2007b).

7.3 Results

7.3.1 Markers of muscle damage

There was a significant main effect across time for perceived muscle soreness ($F_{3,6} = 5.06$, $p = 0.010$). Perceived soreness rating was significantly raised above baseline at 2 h and 24 h, while a trend for increased soreness existed at 48 h (Figure 7.2). There was a significant main effect across time for log transformed CK values ($F_{3,7} = 12.05$, $p < 0.001$). Values were significantly raised above baseline [145 (54) U/L] at all time-points [2 h: 210 (57) U/L, 24 h: 413 (205) U/L, 48 h: 205 (50) U/L] (Figure 7.2). Practical inferences indicated that CK levels and perceived soreness ratings were ‘very’ to ‘most’ likely to increase at all assessed time-points. There was a significant main effect across time for log transformed LDH activity ($F_{3,6} = 3.205$, $p = 0.048$). A significant rise in LDH occurred at 2 h post ST in relation to baseline [1130 (253) U/L vs. 863 (210) U/L] with the practical inference that the ST was ‘very likely’ to result in raised LDH levels at this time-point. There were no significant changes in limb girths at any time point with measurements at each site; arm (32.3-32.7 cm across trials), calf (36.8-37 cm) and thigh (55.3-56.1 cm) remaining consistent throughout trials.

7.3.2 Exercise test measures

7.3.2.1 Anaerobic power tests

There were significant main effects over time for SSJ height ($F_{3,7} = 11.96$, $p < 0.001$) and CMJ height ($F_{3,7} = 8.83$, $p = 0.001$). Baseline values for SSJ and CMJ were 47.4 (3.9) cm (90 % CI: 44.8 – 49.9 cm), and 51.7 (4.4) cm (90 % CI: 48.8 – 54.6 cm), respectively. Jump height significantly decreased at 2 h [SSJ: 42.9 (4.3) cm (90 % CI: 40.0 – 45.8 cm), CMJ: 47.1 (4.1) cm (90 % CI: 44.4 – 49.9 cm)], 24 h [SSJ: 44.0 (2.8) cm (90 % CI: 42.1 – 45.8 cm), CMJ: 48.8 (2.6) cm (90 % CI: 47.0 – 50.5 cm)] and 48 h [SSJ: 45.1 (4.0) cm (90 % CI: 42.4 – 47.7 cm), CMJ: 49.0 (4.4) cm (90 % CI: 46.1 – 52.0 cm)] following ST (Figure 7.2). It was inferred that decreases in SSJ were ‘very likely’ to occur at 2 h and 24 h and ‘likely’ to occur at 48 h and decreases in CMJ height were ‘very likely’ to occur at 2 h and ‘likely’ to occur at 24 h and 48 h. There were significant correlations between changes in CMJ and CK from baseline to 48 h ($r = 0.66$, $p = 0.037$), and changes in SSJ and soreness from baseline to 2 h ($r = -0.68$, $p = 0.048$). There were no other significant correlations between changes in jump performance and markers of muscle damage.

There was a significant main effect over time for PS to change following ST ($F_{3,7} = 3.66$, $p = 0.029$). In relation to baseline peak power output (PPO) during the PS [551 (59) W (90 % CI: 511 – 590 W)] significant decreases in PPO occurred at 2 h [523 (58) W (90 % CI: 485 – 562 W)], 24 h [525 (40) W (90 % CI: 498 – 552 W)] and 48 h [534 (59) W, (90 % CI: 494 – 574 W)]. (Figure 7.2). The practical inference was that the ST was ‘very likely’ harmful to stroke power at 2 h, ‘likely’ harmful to stroke power at 24 h, and ‘possibly’ harmful to stroke power at 48 h.

7.3.2.2 2000 m rowing ergometer test

Baseline 2000 m rowing time was 99.1 % of the participants’ personal best performance for the test. There were no changes in performance time for the 2000 m rowing ergometer test across trials, with the changes in the mean between baseline and both 24 h (2.2 s) and 48 h (1.4 s) being within the calculated smallest practical effect and typical error (3.2 s) established for this test in chapter 5. Resting [Lac⁻] was found to be significantly higher at 48 h compared to baseline ($p < 0.05$), although no differences existed in either peak or change in [Lac⁻]. There were no other significant differences in physiological measures across trials (Table 7.2). There was a significant correlation between 2000 m time and PS power at baseline ($r = -0.81$, $p = 0.015$) and 48 h ($r = -0.77$, $p = 0.024$) but no significant correlations between 2000 m time and jump height at any time-point.

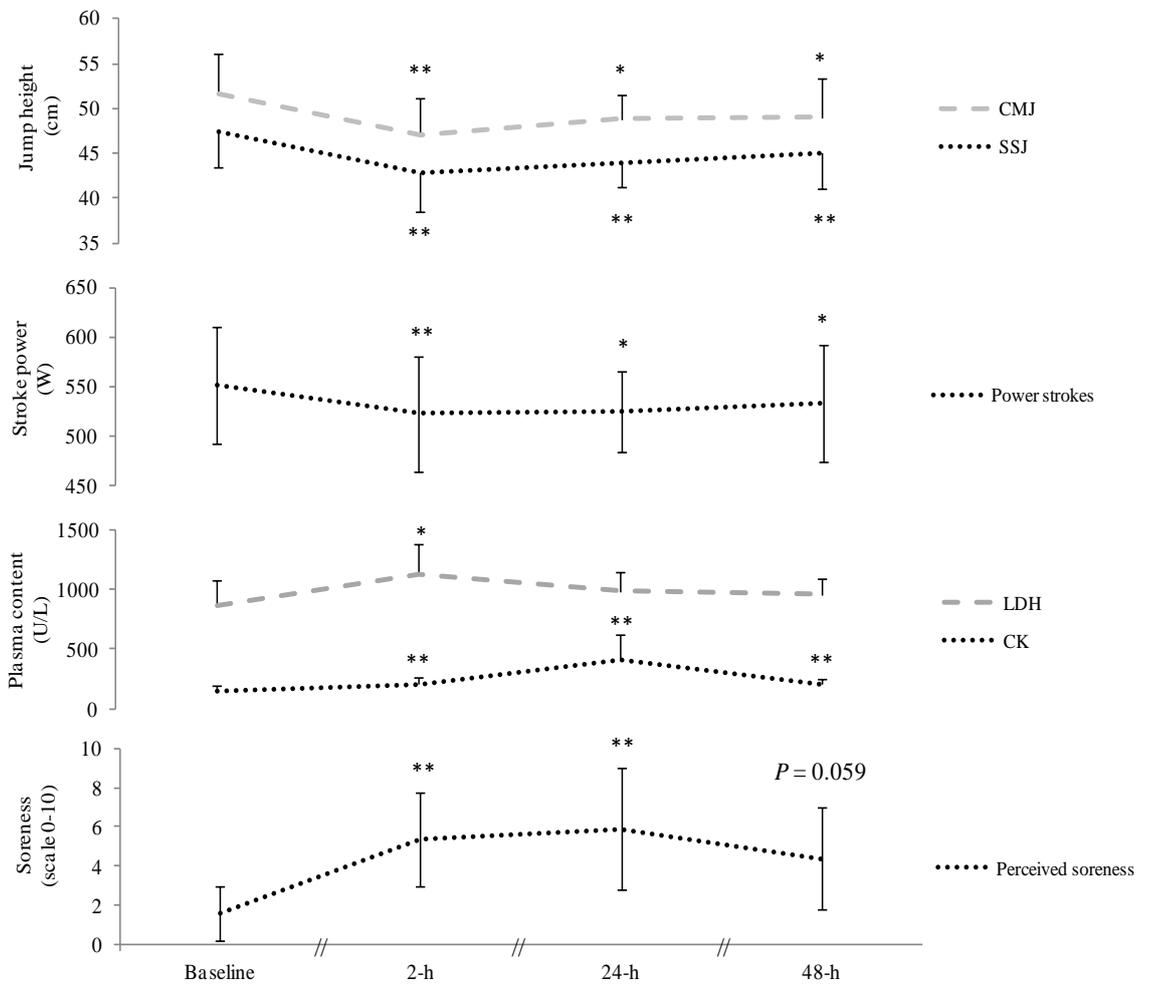


Figure 7.2 Changes in markers of muscle damage and anaerobic power tests following high-intensity strength training. The upper panel describes change in static squat jump (SSJ) and counter movement jump (CMJ) height following high-intensity strength training (n = 8). The second panel describes change in rowing stroke power following high-intensity strength training (n = 8). The third panel describes changes in creatine kinase (CK) and lactate dehydrogenase (LDH) activity following high-intensity strength training (CK n = 8; LDH n = 7). The lower panel describes change in soreness (scale: 0-10) following high-intensity strength training (n = 7). For all panels; ** Significantly higher than baseline ($p < 0.01$). * Significantly higher than baseline ($p < 0.05$).

Table 7.2 Changes in 2000 m rowing ergometer performance following high-intensity strength training

	Baseline	24-h	48-h
Completion time (min:s) (n = 8)	6:38.6 (0:11.9)	6:40.8 (0:09.3)	6:40.0 (0:09.1)
Mean heart rate (b.min ⁻¹) (n = 8)	181 (8)	179 (8)	181 (9)
Peak heart rate (b.min ⁻¹) (n = 8)	189 (8)	188 (8)	190 (8)
Baseline blood lactate (mmol.l ⁻¹) (n = 6 [#])	1.5 (0.3)	1.9 (0.7)	1.9 (0.3*)
Peak blood lactate (mmol.l ⁻¹) (n = 6 [#])	12.6 (1.7)	13.2 (2.5)	13.1 (3.2)
Change in blood lactate (mmol.l ⁻¹) (n = 6 [#])	11.2 (1.5)	11.4 (2.6)	11.2 (3.2)
RPE (6-20 Scale) (n = 8)	19 (2)	18 (2)	18 (2)

Values are expressed as mean (SD), * Significantly different from baseline ($p < 0.05$). # Valid measurements could not be obtained from two of the participants.

7.4 Discussion

This is the first study to investigate the impact of a bout of high-intensity strength training on event-specific performance in trained endurance athletes. The results showed that following strength training, 2000 m rowing ergometer performance was not significantly altered despite significant decreases in rowing specific maximal power.

The increases in perceived muscle soreness, plasma CK and LDH provide evidence that muscle damage was present following the ST. The CK values were significantly raised in relation to baseline at all time-points (up to 48 h) following the ST. This is a similar response to strength training bouts featuring multi-joint free weight exercises such as squats, deadlifts and lunges (Raastad & Hallen, 2000; Hoffman *et al.*, 2010). Lactate dehydrogenase levels were also significantly increased but only at 2 h post ST, which is in agreement with Machado *et al.* (2011) who also observed raised LDH levels shortly after the completion of whole-body strength training. Perceived soreness rating was significantly elevated at 2 h and 24 h following ST, and it was inferred that soreness was ‘very likely’ to be increased at 48 h. These findings are similar to responses following other strength training protocols (Scott *et al.*, 2003; French *et al.*, 2008; Hoffman *et al.*,

2010).

Following the ST there were significant reductions in rowing stroke power and jump height which persisted for 48 h. The percentage decrease in performance for the anaerobic power tests across the assessed time-points were 10 %, 7 %, 5 % for SSJ, which were similar to the decrements of 9 %, 6 %, 5 % for CMJ, while the decrements in PS were smaller (5 %, 5 %, 3 %). However, the 90 % CI demonstrate that decrements in performance on these tests vary widely between participants. This indicates that when rowers perform power testing / training sessions, there is likely to be a wide variation in the acute responses (\leq 48 h) following intense strength training across a crew. The decrements in jump height in this study were smaller than have been recorded following protocols of high volume barbell squats and plyometric jumps (9-17 %; (Marginson *et al.*, 2005; Skurvydas *et al.*, 2006; French *et al.*, 2008). The larger decrements in jump height in these studies are not surprising since the squat and plyometric protocols employed were more 'leg-dominant' than the whole-body strength training used in the present study. The greater overall recruitment of the lower body musculature would translate to exaggerated damage in these muscles, which are primarily used for the performance of SSJ and CMJ (Crowther *et al.*, 2007). Interestingly, in comparison to our ST, higher intensity but lower volume bouts of multi-joint strength training have resulted in a smaller decrement in SSJ performance in trained participants (Raastad & Hallen, 2000) and lower CK levels in rowers (Kokalas *et al.*, 2004). These findings indicate that the volume of strength training is a key determinant of the extent of the subsequent impairment of muscle function.

Performance time for the 2000 m ergometer test and related measures of heart rate, RPE and [Lac⁻] were unaffected following strength training. This finding is contrary to that reported by other authors who have investigated short term endurance performance (< 8 min) following muscle damaging exercise. Twist & Eston (2009) reported 5 min cycling time trial performance to decrease 48 h following 100 counter movement jumps and Davies *et al.* (2008) and Davies *et al.* (2009a) have shown significantly shorter times to exhaustion in maximal cycling ramp tests performed 48 h after high volume barbell squats. The muscle damaging exercise protocols used by Twist & Eston (2009) and Davies *et al.* (2008) and Davies *et al.* (2009a) were highly concentrated on the lower body musculature and the performance test modality was cycling exercise. In the present study, the ST was whole body focused and so was the performance test (2000 m on row ergometer). Interestingly, a greater rise in perceived soreness was experienced by the participants involved in the studies by Twist & Eston (2009) and Davies *et al.* (2008) and Davies *et al.* (2009a) compared to the ratings attributed by the participants in response to the ST in the

present study. This may have been due to the concentration on lower limb activity and /or because their participants had not participated in resistance training for six months prior to involvement. Marcora & Bosio (2007) have previously questioned the validity of applying results obtained from novice participants to the athletic setting. Since athletes regularly participating in resistance training (as in the present study), or any exercise featuring stressful eccentric actions would have a level of protection from such exercise due to the repeated bout effect which makes comparison with ‘novice’ trainers less meaningful (Marcora & Bosio, 2007).

The observed decreases in jump height and stroke power and the increases in markers of muscle damage indicate that at the time-points when the 2000 m test was performed, rowers exhibited muscle damage and were in a state of strain or transient over-reaching. However, this state did not seem to influence 2000 m ergometer performance. These findings are in agreement with the results of Maestu *et al.* (2005a) who assessed 2000 m ergometer performance following a three week intensive period of training. During this three week period rowers increased their training volume by 100 %, which resulted in decreases in the testosterone / cortisol ratio, an indicator of over-reaching (Vervoorn *et al.*, 1992). However, despite this 2000 m performance was not significantly altered following the intensive training period. The present findings indicate that the current practice of scheduling endurance rowing training sessions in close proximity to bouts of strength training (Chapter 4) is justified. Previous literature has shown that type II fibres may be more susceptible to damage from eccentric exercise compared to type I fibres (Jones *et al.*, 1986; Asp *et al.*, 1998). Aerobic metabolism is primarily responsible for energy provision during 2000 m rowing, thus performance is highly dependent on type I muscle fibres (Hagerman *et al.*, 1978) whereas the maximal power tests would be more dependent on recruitment of type II fibres (Potteiger, 1999). Therefore the specific muscle function required to carry out the 2000 m row, may have allowed performance to be maintained to a greater extent than that required for the power tests. This notion is supported by the consistent finding in the literature that muscle strength / power has been affected by muscle damaging exercise to a greater extent than endurance performance when both have been assessed consecutively (Paschalis *et al.*, 2005b; Chen *et al.*, 2007; Marcora & Bosio, 2007; Chen *et al.*, 2008; Davies *et al.*, 2008; Twist & Eston, 2009).

7.5 Conclusion

The findings from this study indicate that high-intensity strength training resulted in symptoms of muscle damage and decrements in rowing specific power that last 48 h but

has no impact on short-term endurance performance (~ 6 to 7 min). Since the muscle damaging exercise protocol was familiar to the participants, it is likely that the repeated bout effect protected participants from exaggerated decrements in functional performance that have been shown to result following novel exercise challenges. The findings provide important considerations for those responsible for the planning and monitoring of training in rowers, notably that it could be predicted that rowers would perform sub-optimally when engaging in primary 'anaerobic' physical tests or power training sessions up to 48 h following high-intensity strength training. However, performance in longer, more 'aerobic' sport specific tests or training sessions would not be significantly affected 24 h after high-intensity strength training. The findings indicate that the current practice of scheduling endurance rowing training sessions in close proximity to bouts of strength training is justified.

8. The effect of a five day protocol of strength training on 2000 m rowing ergometer performance and muscle function

8.1 Introduction

Previous research has shown that acute bouts of strength training can have a negative impact on subsequent endurance performance at 24 to 48 h in physically active non-athlete populations (Scott *et al.*, 2003; Davies *et al.*, 2008; Davies *et al.*, 2009a). In chapter 7, 2000 m rowing ergometer performance was unaffected at 24 h and 48 h after a single bout of high-intensity strength training in well-trained rowers, this was despite decreases in maximal rowing stroke power and maximal jump height with accompanying symptoms of muscle damage over the same. It was theorised that the specific muscle function required for maximal power production was negatively affected via damage to type II muscle fibres following acute strength training, however this loss of function did not influence performance on a 2000 m row. The selective damage of type II fibres following acute strength training and muscle damaging exercise is an established theory (Byrne *et al.*, 2004), although other researchers have indicated that decreases in strength and power might be a consequence of reduced efferent motor command as demonstrated by reductions in electromyography (EMG) response for 24-72 h following strength training (Hakkinen & Kauhanen, 1989; Hakkinen, 1993; Ahtiainen *et al.*, 2004).

Research suggests that rowers perform between two to three strength training sessions a week (Chapter 4; Ivey *et al.*, 2004) with the final session often occurring 24 h to 48 h before a high-quality rowing session or even a competition. An investigation into the effect of this frequency of strength training on rowing performance is therefore pertinent to practitioners who are responsible for the training prescription and coaching of rowers. It is also of interest to compare the known effects of a single session of strength training on rowing performance (Chapter 7) with the effects of multiple strength training sessions within a similar period (7 days) between baseline and follow-up tests. If reductions in muscle function are more marked following a period of multiple bouts then an overreaching effect can be characterised, demonstrating a carry-over effect from each bout, which is distinct from an acute fatigue effect from a single bout which has been termed a 'condition of muscular over-strain' (Kuipers & Keizer, 1988; Van Borselen *et al.*, 1992; Fry *et al.*, 1994c). Rowing specific concurrent training research, has demonstrated the effectiveness of the addition of high load [\sim 70-90 % one repetition maximum (1 RM)] strength training for eliciting greater improvements in rowing performance compared to rowing training alone or low load strength training ($<$ 70 % 1 RM) (Ebben *et al.*, 2004; Gallagher *et al.*, 2010; Izquierdo-Gabarran *et al.*, 2010). These aforementioned studies utilised two (Gallagher *et al.*, 2010; Izquierdo-Gabarran *et al.*, 2010) and three (Ebben *et al.*, 2004b) weekly strength training sessions. Furthermore, for athletes concurrently

training for strength and endurance, three weekly strength training sessions have been recommended (Garcia-Pallares & Izquierdo, 2011). In spite of this recommendation, to the authors' knowledge, no previous research has investigated the effects of an acute 'typical' weekly frequency of strength training (three times per week) on rowing performance where rowing training has been controlled between experimental groups allowing strength training alone to be the independent variable. Rowing studies have been conducted which have evaluated concomitant increases in both rowing and strength training on rowing performance, with contrasting results. Jurimae *et al.* (2002; 2004) found that 6 days of intensive training resulted in significant decreases in 2000 m rowing ergometer performance however, Maestu *et al.* (2005a) found 2000 m performance to be unaffected following a 3 week period of intensive training.

Several researchers have investigated the effects of short term protocols (4-7 days) of strength training on various aspects of muscle function although not involving rowing activity (Hakkinen *et al.*, 1988a; Warren *et al.*, 1992; Fry *et al.*, 1994a; Fry *et al.*, 1994b; Fry *et al.*, 1994c; Kraemer *et al.*, 2006). These studies observed that effects on muscle function are highly influenced by athletic status. Male participants described as 'resistance trained' experienced decreases in sprinting ability, isokinetic strength and 1 RM bench press and 1 RM squat exercises after 3-4 sessions of multi-joint strength training over 4-5 days, however endurance parameters were not evaluated (Fry *et al.*, 1994a; Fry *et al.*, 1994c; Kraemer *et al.*, 2006). In contrast, when elite weightlifters were exposed to 7 days of high volume strength training (representing a 100% increase in training volume), performance on the snatch and clean and jerk lifts were unaffected (Hakkinen *et al.*, 1988a; Warren *et al.*, 1992; Fry *et al.*, 1994b). These findings are in agreement with previous research which has found event-specific performance to be maintained following short duration periods (< 2 weeks) of intensive training (Costill *et al.*, 1988; Lehmann *et al.*, 1991).

The aim of this study was to determine the effects of a 'typical' weekly frequency of strength training (three bouts) on 2000 m rowing ergometer performance and muscle function. It was hypothesised that 2000 m rowing ergometer performance would be maintained in trained rowers despite decrements occurring in muscle function following a series of three strength training sessions performed in five days.

8.2 Methods

8.2.1 Participants

Twenty-eight highly trained male rowers were evenly assigned to two groups; an intervention group [n = 14, mean (\pm standard deviation (SD), age: 21 (3.2) years, body mass: 79.9 (7.3) kg, stature: 1.83 (0.05) m, 2000 m ergometer time: 6:34.1 (0:08.5) min:s] and a control group [n = 14, age: 22.3 (4.8) years, body mass: 84.1 (8.5) kg, stature: 1.85 (0.05) m, 2000 m ergometer time: 6:35.7 (0:11.2) min:s]. All participants had at least one year of experience at regularly performing structured strength training that featured Olympic weight-lifting style exercises. Participants were informed of the experimental procedures and any potential risks involved and gave their written informed consent to participate in the study. The study was approved by the Ethics Committee of the School of Life Sciences at Northumbria University.

8.2.2 Experimental protocol

This study adhered to a randomised control trial design, since two groups of participants performed two experimental trials. Prior to the study, all participants performed a familiarisation testing session. For the baseline trial, participants were asked to arrive at the laboratory in a hydrated state having abstained from exercise on the day of testing and strength training in the 72 h before testing. Participants completed similar training (composition, volume, intensity) throughout the study except that the intervention group participants undertook strength training between baseline and follow-up tests (see later). During the first testing session, body mass and stature were measured and participants also reported their perceived muscle soreness rating using a visual analogue scale. A capillary blood sample was taken from the finger for assessment of creatine kinase (CK) and blood lactate [Lac⁻]. Electrodes were then attached to seven anatomical sites for EMG analysis. Participants then completed a five min warm-up on a rowing ergometer, before completing a protocol of strength and power tests consisting of; assessment of maximal voluntary contraction force of the leg extensors (MVC), three individual static squat jumps (SSJ) and counter movement jumps (CMJ), and five maximal rowing power strokes (PS) on the rowing ergometer. A face mask was then placed on the participants' for analysis of expired breath-by-breath respiratory gas exchange parameters which were to be collected during the 2000 m test. The participants were instructed to warm-up for a further five min on the rowing ergometer after which they performed the 2000 m test. Heart rate [HR (beats per minute (b.min⁻¹))] was recorded every 10 s during the test. Immediately after the test was completed, participants provided a rating of perceived exertion (RPE) for how physically

demanding they found the test. Capillary blood samples were taken before and at the end of the test and at 1-, 3-, 5- and 7 min of recovery for the assessment of [Lac⁻]. The following week, the intervention group performed the strength training protocol, which involved a series of multi-joint strength training exercises which were completed three times over five days with a day break in-between the first and second and third sessions. The day after the final strength training session the intervention group performed the follow up trial, which featured the same battery of tests performed for baseline measures. At this time point the control group also performed the follow up trial.

8.2.3 Experimental test battery

Reproducibility of the following exercise tests, physiological measures and markers of muscle damage were assessed in chapter 5.

8.2.3.1 Maximal voluntary contraction (MVC)

Maximal voluntary contraction force of the right leg knee extensors was determined using a strain gauge (MIE Medical Research Ltd, Leeds, UK). Please refer to section 3.4.1 for more detail.

8.2.3.2 Static squat jump (SSJ) and counter movement jump (CMJ)

An optical measurement system (Optojump Next, Microgate, Bolzano, Italy) was used for assessment of jump performance. Three independent SSJ and CMJ trials were conducted; the highest trial was recorded for data analysis. Please refer to section 3.4.2 for more detail.

8.2.3.3 Power strokes (PS)

Maximal stroke power was assessed by an air-braked rowing ergometer (Concept 2 Model C, Concept 2 Ltd, Wilford, Notts, UK). Please refer to section 3.4.3 for more detail.

8.2.3.4 2000 m rowing ergometer test

The test was performed on an air-braked rowing ergometer (Concept 2 Model C, Concept 2 Ltd, Wilford, Notts, UK). Please refer to section 3.5 for more detail.

8.2.3.5 Rating of perceived soreness

Participants' level of perceived muscle soreness was assessed via a 10 cm long visual analogue scale. Please refer to section 3.6.1 for more detail.

8.2.3.6 Surface electromyography analysis (EMG)

A 16 channel wireless telemetric system (Myon, Myon AG, Barr, Switzerland) was used to record surface EMG from seven anatomical sites during PS and the 2000 m test; gastrocnemius (GA), biceps femoris (BF), gluteus maximus (GM), erector spinae (ES),

vastus medialis (VM), rectus abdominis (RA) and latissimus dorsi (LD), however the vastus medialis was solely recorded during the MVC measurement. Mean rectified EMG recorded during each 500 m stage of the 2000 m test and during the MVC was normalised against the mean rectified EMG recorded during the PS, and subsequently expressed as a percentage. Peak EMG recorded during the MVC was normalised against the peak EMG recorded during the PS. Please refer to section 3.5.7 for more detail.

8.2.3.7 Force analysis

Handle force was recorded during the power strokes and 2000 m test via a load cell (RLTO500kg, RDP Electronics Ltd, Wolverhampton, UK) located in series between the handle and drive chain. The handle force characteristics assessed for power strokes were maximal instantaneous force and power and mean force and power, characteristics assessed during the 2000 m test were mean handle force and power. Please refer to section 3.5.8 for more detail.

8.2.4 Strength training session

A strength training session featuring various multi-joint barbell exercises was performed by participants as described in table 8.1. Please refer to section 3.3 for more detail.

Table 8.1 Strength training session and mean (SD) of 1 RM achieved by the intervention group participants on the exercises featured

Exercise	Sets x reps	% 1 RM / weight used	1 RM achieved (kg)
Snatch grip high pull	4x5	85 %	60 (7.5)
Clean	4x5	85 %	75 (10)
Back squat	4x5	85 %	105 (12.5)
Romanian deadlift	3x8	75 % of squat 1 RM	-
Bench press	3x5	85 %	75 (12.5)
Bench pull	3x5	85 %	77.5 (10)
Weighted sit-ups	3x15	15 kg	-

Mean (SD) rounded to nearest 2.5 kg increment.

8.2.5 Blood analysis

Capillary blood samples were collected as outlined in section 3.7. This was used for the analysis of [Lac⁻] (section 3.7.1) and CK (section 3.7.2).

8.2.6 Statistical analysis

Data are presented as mean (\pm SD), unless stated otherwise. Data were tested for normality, homogeneity of variance prior to analysis. Due to the large inter-participant variability in surface EMG and serum CK (Nosaka & Clarkson, 1996; Fauth *et al.*, 2010) recorded values were log transformed using a spreadsheet produced by Hopkins (2007a) and subsequent statistical analysis were conducted on the transformed data. Absolute means for rectified EMG and CK values are presented in the results section. For all other measures, raw data values were used for statistical analysis. Independent samples *t* tests on baseline values indicated that no significant differences existed between the treatment and control groups ($p > 0.05$), this indicates that both groups possessed similar performance capabilities. To assess the effect of the strength training intervention on markers of muscle damage, strength / power test performance and the 2000 m test time and related physiological variables of mean oxygen uptake [$\dot{V}O_2$, (L.min⁻¹)] peak [Lac⁻], heart rate and RPE, two-way ANOVA (group x trial) tests were conducted. Three way (group x trial x stage) ANOVA tests were conducted to assess the impact of the strength training intervention on pacing strategy during the 2000 m test. This involved analysis of rectified EMG, stroke rate [(strokes per minute (s.min⁻¹))], mean $\dot{V}O_2$, contributions from aerobic (P_{aer}) and anaerobic metabolism (P_{anaer}) to mean power (P_{tot}) and mean handle force and power per 500 m stage of the trial. The significance level was set at $p < 0.05$ for all analyses and the LSD correction was used for the ANOVA tests. Effect size (*ES*) was calculated for any non-statistically significant result trends ($p = 0.051-0.10$) in accordance to procedures suggested by Hopkins (2003). In accordance with these procedures interpretation of observed effect sizes are as follows; trivial < 0.2 , small 0.2-0.6, moderate 0.6-1.2, large 1.2-2.0, very large > 2.0 (Hopkins, 2003).

Additionally, inferential statistics were used to quantify the magnitude of the change in measures exhibited post-strength training. This was done by calculating the smallest practical effect for each dependent variable from the product of 0.3 [which represents the smallest standardised change in mean for a group of trained participants; Hopkins *et al.* (2009)] multiplied by the between-participant standard deviation across the three re-test reliability trials of the group of participants in chapter 5. From using the smallest practical effect value, magnitude and inference of the change in each dependent variable was then analysed according to procedures developed by Hopkins (2007b). In addition practical inferences of harm or benefit caused to each dependent variable from the independent variable (intervention) were drawn using the approach identified by Batterham & Hopkins (2006). These inferences were based on percentage boundaries which indicate

the chances in percent of harm or benefit occurring to a dependent variable as a consequence of the intervention; 0 to 0.5 % indicated most unlikely; 0.5 % to 5 % indicated very unlikely; 5 % to 25 % indicated unlikely; 25 % to 75 % indicated possibly; 75 % to 95 % indicated likely; 95 % to 99.5 % indicated very likely; and > 99.5 % indicated most likely (Hopkins, 2007b).

8.3 Results

8.3.1 Markers of muscle damage

A significant trial * group interaction was present for muscle soreness ($F_{1,13} = 8.59$, $p = 0.007$), showing soreness was increased for the intervention group during the follow up trial in comparison to baseline ($p < 0.001$), while values for the control group remained unchanged ($p = 0.965$). For CK, a significant trial * group interaction ($F_{1,13} = 18.39$, $p < 0.001$) indicated an increase during the follow up trial for the intervention group ($p < 0.001$) with no change for the control group ($p = 0.883$). Practical inferences indicate that muscle soreness ratings and CK levels were ‘very’ to ‘most’ likely to increase following the ST. (see table 8.2; for performance and physiological comparisons between groups).

8.3.2 Strength and power tests

Following strength training there was a significant reduction in MVC ($F_{1,13} = 10.76$, $p = 0.003$) in the intervention group, while no change existed for the control group ($p = 0.142$). The practical inference suggested that decreases in MVC were ‘likely’ to occur following strength training. No differences existed between baseline to follow up trials for either peak or mean rectified EMG of the VM during the MVC for either group. There were significant trial * group interactions for SSJ height ($F_{1,13} = 6.41$, $p = 0.018$) and CMJ height ($F_{1,13} = 15.58$, $p = 0.001$). Pairwise comparisons demonstrated that compared to baseline values, there were significant reductions in SSJ ($p < 0.001$) and CMJ ($p < 0.001$) following the protocol of ST for the intervention group, while no changes occurred in the control group (SSJ: $p = 0.179$, CMJ: $p = 0.861$). The magnitude inference was that decreases in SSJ and CMJ height were ‘most likely’ to occur following strength training.

There was a significant trial * group interaction for PS ($F_{1,13} = 14.41$, $p = 0.001$). For the intervention group, PS was significantly reduced following the ST protocol compared to baseline ($p < 0.001$), while no changes occurred in the control group ($p = 0.740$). The practical inference suggested that decreases in stroke power were ‘very likely’ to occur following strength training. There were significant reductions in peak ($F_{1,13} =$

7.43, $p = 0.012$) and mean ($F_{1,13} = 8.95$, $p = 0.007$) handle force and peak ($F_{1,13} = 5.45$, $p = 0.029$) and mean handle power ($F_{1,13} = 12.74$, $p = 0.002$) recorded during the PS for the intervention group from baseline to follow up, while no changes occurred in the control group ($p > 0.05$). Practical inferences indicated that decreases in peak and mean handle force and mean power were ‘likely’ to occur following strength training, whereas decreases in peak power were inferred as ‘possible’.

Table 8.2 Comparison of 2000 m performance, physiological measures, strength and power tests and markers of muscle damage across baseline and follow up trials for both groups. * Significantly differently from baseline trial ($p < 0.05$). T = Trend for mean difference compared to baseline trial ($p = 0.051-0.10$).

Measure	Intervention		Control	
	Baseline	Follow up	Baseline	Follow up
2000 m time (min:s)	6:46.3 (0:07.9)	6:46.3 (0:08.8)	6:45.3 (0:12.2)	6:43.7 (0:11.4)
$\dot{V}O_2$ (L.min ⁻¹)	4.99 (0.55)	5.14 (0.38)	5.04 (0.35)	4.92 (0.39)
HR (b.min ⁻¹)	186 (11)	180* (11)	179 (8)	179 (9)
Peak lactate (mmol.L ⁻¹)	16.8 (2.6)	15.7 ^T (2.9)	17.3 (3.5)	17.8 (4.1)
RPE	18 (1)	18 (1)	17 (1)	17 (1)
MVC (N)	569 (68)	533* (61)	596 (82)	580 (81)
MVC peak EMG of VMO	0.92 (0.12)	0.88 (0.13)	0.90 (0.15)	0.98 (0.23)
MVC mean EMG of VMO	0.46 (0.20)	0.45 (0.12)	0.41 (0.08)	0.46 (0.11)
SSJ (cm)	32.6 (4.0)	29.8* (3.9)	31.9 (5.7)	31.2 (5.6)
CMJ (cm)	35.6 (4.3)	32.7* (4.0)	33.8 (5.9)	33.9 (6.5)
PS (W)	523 (51)	491* (49)	511 (47)	509 (45)
PS handle force max (N)	1098 (102)	1050* (75)	1116 (120)	1084 (103)
PS handle force mean (N)	258 (54)	228* (13)	239 (13)	228 (15)
PS handle power max (W)	2585 (292)	2486* (268)	2649 (363)	2569 (301)
PS handle power mean (W)	533 (48)	510* (43)	530 (53)	525 (45)
Muscle soreness	2.2 (2.3)	4.2* (1.3)	1.0 (1.0)	1.1 (1.4)
CK (U/L)	188 (125)	523* (348)	195 (127)	190 (105)

8.3.3 2000 m ergometer test performance and physiological measures

There were no changes in 2000 m ergometer performance time from baseline to follow up for either group ($F_{1,13} = 0.91, p = 0.350$), neither were there differences in mean $\dot{V}O_2$ ($F_{1,13} = 3.76, p = 0.065$; Intervention: $p = 0.168$, Control: $p = 0.201$) and RPE ($F_{1,13} = 0.064, p = 0.802$) across trials for both groups. There was a significant trial * group interaction effect for mean HR during the 2000 m ($F_{1,13} = 6.92, p = 0.014$), with a reduction for the intervention group during the follow up trial ($p < 0.001$), while no changes occurred in the control group ($p = 0.959$). There was a trend toward a trial * group interaction effect for peak [Lac⁻] ($F_{1,13} = 3.67, p = 0.066$) with pairwise comparisons revealing a trend toward a reduction in peak [Lac⁻] in the follow up trial for the intervention group ($p = 0.063, ES = 0.40$), whereas no changes occurred for the control group ($p = 0.449$).

8.3.4 Pacing of the 2000 m ergometer test

There were no differences in mean power output from baseline to follow up for each 500 m segment of trials; within or between experimental groups ($F_{(GG)3,13} = 0.75, p = 0.446$). Within each 2000 m trial, a fall in mean power output was observed after the initial 500 m ($p < 0.01$) compared with other stages (Figure 8.1). For both groups, handle power and force, averaged over each 500 m stage, mirrored the pattern for mean power output with the initial 500 m stage demonstrating a greater mean value than for the other 500 m stages ($p < 0.01$). There was a trend for a stage * group interaction for P_{anaer} ($F_{(GG)3,13} = 2.84, p = 0.085$), which indicated decreases in the follow-up trial for the intervention group ($F_{1,10} = 3.23, p = 0.086$), compared to the baseline trial, due to decreases in P_{anaer} during stages two ($p = 0.089, ES = 0.42$) and three ($p = 0.099, ES = 0.56$) of the follow-up trial. No changes occurred in P_{anaer} for the control group ($F_{1,13} = 0.86, p = 0.363$). There were no changes in P_{aer} ($F_{(GG)3,13} = 0.48, p = 0.553$) or mean $\dot{V}O_2$ ($F_{(GG)3,13} = 0.41, p = 0.632$), per 500 m stage, from baseline to follow up either within or between groups. Within trials, P_{aer} and $\dot{V}O_2$ were lower in the initial 500 m compared to the other 500 m stages ($p < 0.01$) demonstrating the onset of $\dot{V}O_2$ kinetics. There were no differences in stroke rate from baseline to follow up either within or between groups ($F_{(GG)3,13} = 0.412, p = 0.589$), all trials were characterised by higher stroke rates during stages one and four in comparison to stage two and three ($p < 0.01$).

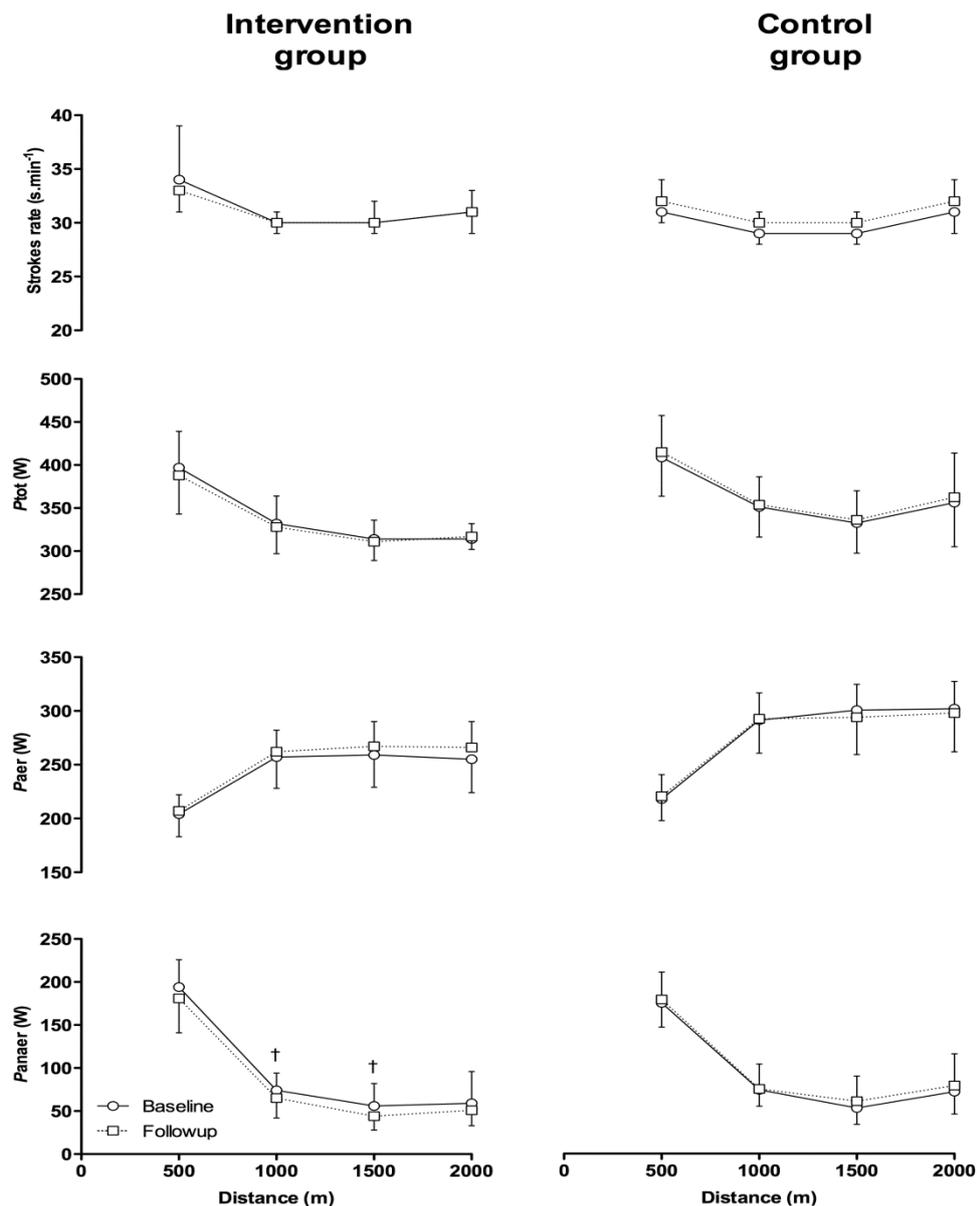


Figure 8.1 Anaerobic and aerobic contributions to total power (watts) and stroke rate (strokes per minute) for baseline and follow trials during successive 500 m stages of the 2000 m test for the intervention ($n = 11$; errors occurred during breath-by-breath measurement for 3 participants) and control groups ($n = 14$). * Significant difference between baseline and follow-up trials $p < 0.05$. † Trend for a significant difference between intervention baseline and follow-up trials $p < 0.10$.

Rectified EMG was unchanged for all seven sites between baseline and follow-up trials for the control group ($p > 0.05$). For the intervention group rectified EMG for the GM, VM and BF were unchanged between baseline and follow up trials, however changes were detected in the other four muscles (Figure 8.2). Rectified EMG for the RA ($F_{1,6} = 7.71$, $p = 0.013$) significantly decreased during the follow-up trial in comparison to baseline,

however significant increases were shown in the follow up trial for GA ($F_{1,9} = 5.09, p = 0.038$), LD ($F_{1,10} = 14.15, p = 0.001$) and ES ($F_{1,9} = 4.25, p = 0.053$) demonstrating greater overall muscle activation in the intervention groups' post-ST 2000 m trial.

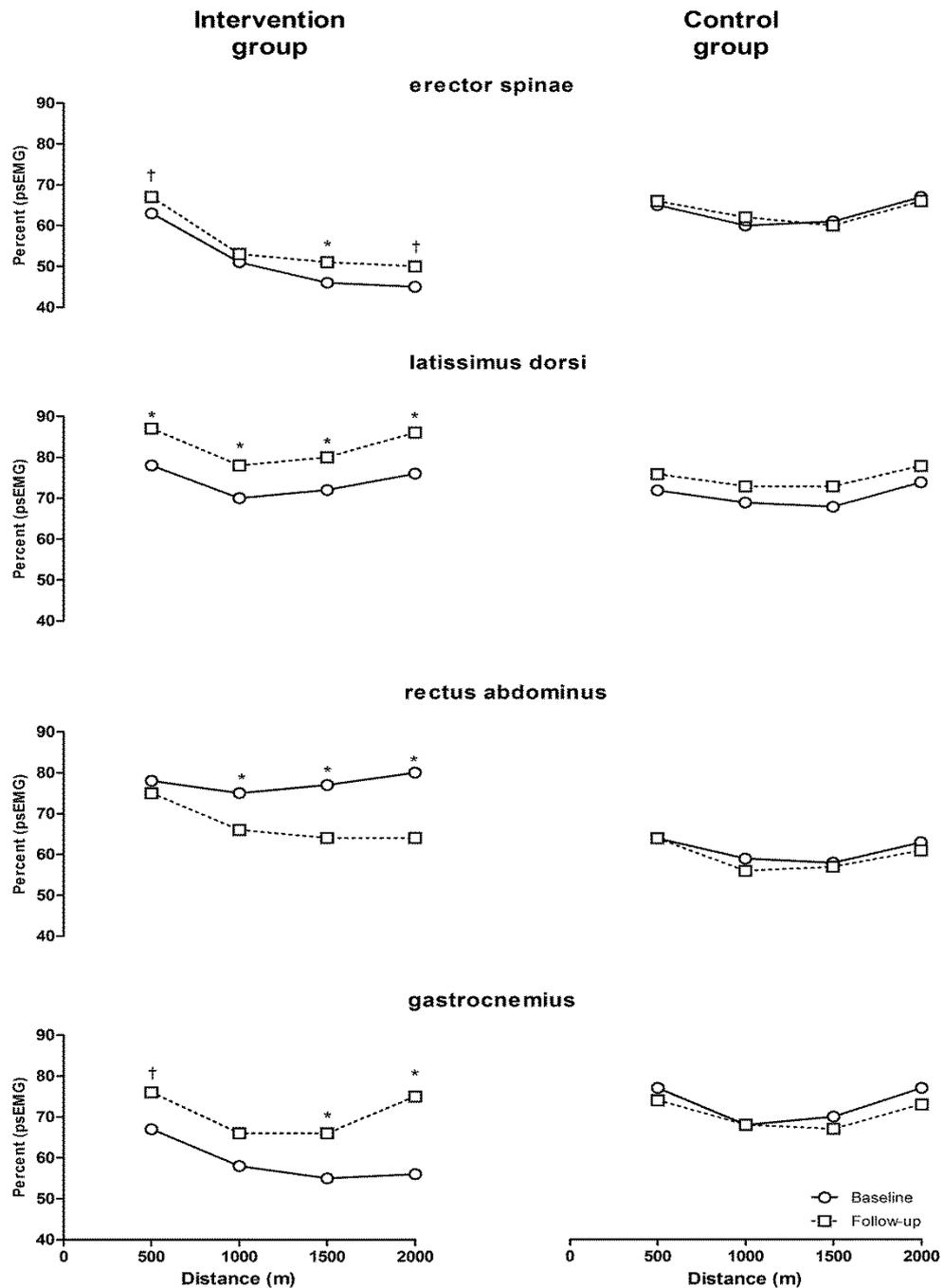


Figure 8.2 Serial pattern of EMG during the 2000 m test for the four muscle sites showing significant changes between baseline to follow-up trials. EMG for each 500 m stage is expressed as a percentage of the mean rectified EMG value recorded across the five power strokes. * Significant difference between baseline and follow-up trials $p < 0.05$. † Trend for difference between baseline and follow up trials $p < 0.10$. Error bars have been removed for reader clarity.

8.4 Discussion

The aim of the study was to investigate if three bouts of strength training over a five day period, previously established as typical training for highly-trained, competitive rowers, would affect 2000 m rowing performance and muscle function. The main finding was that trained rowers can maintain 2000 m rowing performance even following an intensive protocol of strength training involving three, strength training sessions over a five day period, despite suffering significant reductions in muscle function. After completing the strength training protocol, trained rowers exhibited significant performance decreases across a range of strength and power assessments, and there was evidence this coincided with muscle damage. These data concur with results from the previous study (Chapter 7), where 2000 m performance was maintained despite reductions in muscle function following a single bout of strength training. Reductions in peak $[\text{Lac}^-]$ and mean heart rate were observed during the 2000 m test post-strength training. In accordance with the present findings, values for these measures have frequently been shown to decrease following short term periods (< 2 weeks) of increased training load despite overall endurance performance being unaffected (Costill *et al.*, 1988; Lehmann *et al.*, 1991; Jeukendrup *et al.*, 1992; Hedelin *et al.*, 2000). Decrements in SSJ, CMJ and PS following strength training were 9-, 8- and 6 % respectively, which are similar to decrements observed 24 h after a single bout of strength training (7-, 6- and 5 %; Chapter 7). The increases in CK and perceived muscle soreness ratings at 24 h were also similar between these studies. The similarity in the decrements detected in both studies suggests that three strength training sessions as, in the present study, did not convey anymore residual fatigue than a single bout of strength training had in the previous study. Although caution is required with this last statement, as the studies utilised different participants, albeit with a similar training history and competitive ability. These data indicate that three intensive strength training sessions can be tolerated by highly-trained rowers over the course of a week, and supports current coaching practice with competitive rowers (Chapter 4).

Previous studies have shown that athletes can maintain event specific performance despite decreases in muscle function following short duration periods of strength training. Warren *et al.* (1992) and Fry *et al.* (1994b) have reported maintenance of performance in elite weightlifters in the snatch lift despite attenuated vertical jump performance following a week of high volume weightlifting training (2-4 sessions a day; 100 % increase in normal training volume). In relation to rowing, findings from studies which have featured an increase in mixed-training volume have produced contradictory results possibly due to the difficulty of controlling overall training stimulus. Jurimae *et al.* (2002; 2004) reported that

six days of intensive training (rowing and strength training) resulted in decreases in 2000 m rowing ergometer performance by ~ 4 and 9 s respectively. The increase in the volume of training prescribed equated to ~ 20 h and constituted a ~ 100 % increase in average weekly training volume. The six day heavy training period largely consisted of ‘low intensity endurance training (rowing or running)’, which equated to 85 % of total training time, with only 10 % of the prescribed training being described as ‘resistance training’, and the remaining 5 % of training time was spent performing ‘high-intensity anaerobic training (rowing)’. In contrast, a study by Maestu *et al.* (2005a) found 2000 m performance to be unaffected following a 3 week period of increased training volume. They utilised a similar participant population (junior national standard male rowers) and prescribed a similar increase in training volume during the intensive training period (~ 20 h; ~ 100 % increase in average weekly training volume). Perhaps the causal factor in these disparate results was the content of the training prescription in these studies. Maestu *et al.* (2005a) had participants perform 45 % strength training, 45 % endurance training (running, swimming and or ergometer rowing) and 10 % ball games (basketball and/or soccer) which represents a large reduction in endurance and rowing based training and a large increase in the volume of strength training in comparison to the studies of Jurimae *et al.* (2002; 2004). In the present study, three intensive strength training sessions constituted ~ 20 % of the weekly training time. Taken as a whole, these findings might suggest that overreaching in terms of endurance training might be more detrimental to 2000 m rowing performance than overreaching in terms of additional strength training.

When assessing the hormonal responses to various bouts of training in elite rowers, Kokalas *et al.* (2004) found prolonged endurance rowing (60 min) caused a greater disruption to hormonal homeostasis, including a significant rise in cortisol, compared to the response following a bout of multi-joint high load strength training (85-90 % 1 RM). Aside from hormonal disturbance, an additional reason why high-intensity strength training did not impact on 2000 m rowing performance might be related to the complement of muscle fibres activated. The strength training prescribed in the present study, reflects elite coaching practice, and is aimed at developing rapid boat speed at the start of the race, hence force and impulse loadings are high. Beltman *et al.* (2004) has shown that type I and type IIA muscle fibres show a significant reduction in phosphocreatine (PCr) (hence indicating their recruitment) at 39-, 72- and 87 % of MVC during an isometric contraction, however type IIAX fibres only demonstrated a reduction in PCr at 87 % MVC. The strength and power tests in the present study required maximal instantaneous effort, hence likely recruiting the highest threshold type II fibres (IIAX, IIaX, IIX) as well as type I and

type IIA fibres (Haff & Potteiger, 2001; Sargeant, 2007). The power outputs generated during each 500 m segment of the 2000 m test were 76-, 63-, 60-, 60 % of the mean power generated during the power strokes. Therefore the power output produced during the 2000 m test would have emanated from type I and IIA fibres, rather than the highest threshold type II fibres. This argument is supported by Fry *et al.* (1994c) who found there to be no changes in repetitions achieved on a squat machine at 70 % 1 RM despite significant decreases in 1 RM on the same device and decreases in maximal leg extension isokinetic and isometric strength following two weeks of strength training overreaching. The authors theorised that the 70 % effort was unaffected since the ‘highest threshold motor units would not be activated throughout the activity’.

In the present study, the loss of absolute muscle strength and power prior to the 2000 m row demonstrates a loss of function in higher threshold muscle fibres. The ST protocol resulted in peripheral fatigue, as despite a significant decrease in MVC in the intervention group from baseline to follow-up, there were no changes in peak and mean rectified EMG values for the VM. Peripheral changes in the leg extensor muscles were the cause of the observed decreases in MVC rather than changes in central motor drive to the motor units. An increase in EMG for the same power output indicates a decrease in the force : EMG activity ratio and has been termed a reduction in neuromuscular efficiency (Byrne *et al.*, 2004). Therefore a decrease in force despite a similar EMG, as observed in this study during the 2000 m row, would indicate the same. The increase in muscle soreness and elevated CK concentration post-ST in the intervention group likely demonstrates moderate muscle damage in type II fibres, which subsequently affected absolute power and force production. However, this effect was not detrimental to 2000 m rowing performance due to; the different combination of muscle fibre recruitment required for the activity and the fact that a loss of efficiency in some damaged/affected fibres which were recruited during the 2000 m row could be compensated for by muscle rotation and additional muscle fibre activation as a result of increased efferent motor command (Proske *et al.*, 2004). Similarly, Scott *et al.* (2003) theorised that recruitment of undamaged muscle fibres from the available pool of fibres, compensated for any damaged fibres 24-30 h following free weight strength training, which enabled endurance performance to be maintained. During the 2000 m row, a greater muscle activation at three muscle sites was detected in the post-ST intervention group follow-up trial, which taken cumulatively, suggests that an increased central motor drive was required to maintain performance during this trial. The increased central motor drive may have had a compensatory effect on power output, during the follow-up trial, which negated the effect of pre-existing damage to some

of the type II fibres. In addition, a trend toward lower P_{anaer} energy contribution and peak [Lac⁻] might indicate less type II fibres were activated / functioning effectively in the follow-up trial and that force production was spread across type I fibres perhaps due to the process termed muscle wisdom (Enoka & Stuart, 1992). During this process the CNS provides an economical activation of musculature by recruiting undamaged muscle fibres from the available pool therefore compensating for any damaged fibres (Enoka & Stuart, 1992).

If there were to be some recruitment of the highest threshold muscle fibres during the 2000 m row it would likely be at the initial period of the test (< 30 s). During the start of a 6 min rowing time trial mean power over the initial 10 strokes was found to be ~ 30 % higher than mean power over the whole trial (Hartmann *et al.*, 1993). Similarly peak power during the power stroke test in the present study was found to be 35 % higher than mean power during the 2000 m test. This indicates rowers voluntarily produce close to maximal power during the initial strokes of prolonged ergometer tests. Therefore it is possible that damage to high threshold type II fibres could affect initial power production (first 2—30 s) in a 2000 m ergometer test such as in the intervention groups' follow-up trial. However, given that rowers were still able to maintain 2000 m performance the occurrence of this effect would seemingly did not impact ergometer performance. The performance characteristics of on-water rowing differs to that of ergometer trials since the start of the on-water race necessitates higher force and power to be produced in order to get the boat up to race speed and gain a tactically advantageous position in the competitive field (Steinacker, 1993; Garland, 2005). Therefore discrepancies in initial stroke power would impact performance of a rowing race to a greater extent than a 2000 m ergometer trial. Unfortunately, in the present study, data was recorded during the 2000 m test in relatively long intervals (500 m; ~1:40 min:s), hence analysis of this initial period (< 30 s) was beyond the scope of the study.

8.5 Conclusion

This study showed that highly- trained rowers can maintain 2000 m rowing performance following an intensive five day protocol of strength training. The strength training protocol did cause disruption to functional homeostasis as evidenced by the significant performance decreases in a range of strength and power assessments and increases in markers of muscle damage. Significant increases in EMG at three anatomical sites during the follow up 2000 m trial indicated an increase in central motor drive to compensate for peripheral damage/fatigue in type II fibres. The damage induced by the strength training was likely

more specific to the high threshold type II fibres, however their apparent state of dysfunction did not adversely affect 2000 m row performance suggesting sufficient power output could be produced by adjustments in muscle recruitment patterns.

9. General discussion

9.1 Summary of aims and key findings

This thesis aimed to draw conclusions regarding the strength and conditioning practices occurring within British rowing and investigate the impact of bouts of strength training on sports specific power producing ability and 2000 m ergometer performance in well-trained rowers. Five sequential studies were undertaken to achieve these aims. This section will summarise the main findings of the thesis, provide recommendations for training practice and suggest avenues for future investigation.

9.1.1 *Strength and conditioning practices occurring within British Rowing*

The aim of chapter 4a was to survey a variety of training practices of coaches responsible for the strength and conditioning of rowers, this was accompanied by chapter 4b which provided perspectives from two practitioners involved with the physical preparation of Olympic rowers. In relation to the planning of the subsequent intervention studies the most pertinent information acquired from this chapter related to; strength training prescription, recovery from strength training and fitness testing. The consensus from both sources was that two to three strength training sessions were performed each week, with frequency being higher during the off-season. This practice is in line with the recommended strength training frequency to elicit optimal adaptations for sports involving concurrent strength and endurance training, which is three sessions a week (Garcia-Pallares & Izquierdo, 2011). Garcia-Pallares & Izquierdo (2011) reason that this is the maximal sustainable frequency that can be tolerated without interference effects occurring that would negate both strength and endurance specific training adaptations.

Strength training exercise prescription as reported in the chapter 4, favoured multi-joint free weight strength and power movements such as the clean, squat, deadlift, bench press and bench pull. These exercises have previously been recommended for rowers, share kinematic similarities to the rowing stroke and have proved successful in prolonged interventions (Ebben *et al.*, 2004b; Ivey *et al.*, 2004; McNeely *et al.*, 2005; Gallagher *et al.*, 2010; Izquierdo-Gabarren *et al.*, 2010). From analysis of the interview data, high load-with low repetition strength training was favoured with the emphasis on building strength with 3-5 sets of 3-6 repetitions per exercise. For justification of this preference for high loading, the interviewed practitioners emphasised the substantial strength requirement required to accelerate the boat during the initial strokes of a rowing race. However, the strength and conditioning coach did mention that 10 repetition sets were used in the general preparation phase. The questionnaire responses indicated a favouring of high load strength training during the competitive season (< 8 repetitions) and higher repetitions

performed in the off-season. High load strength training protocols have been more effective in eliciting improvements in rowing ergometer performance than high repetition protocols (Ebben *et al.*, 2004b; Gallagher *et al.*, 2010). Garcia-Pallares & Izquierdo (2011) cautioned against training with 8-10 RM loads when concurrently training for strength and endurance. Training with such loads will induce peripheral adaptations which culminate in declines in capillary and mitochondrial density, as well as causing considerable metabolic and hormonal stress (Docherty & Sporer, 2000). These effects will adversely affect aerobic endurance capability and interfere with adaptations from endurance training. Docherty and Sporer (2000) predict less interference effects when training with higher loads (85 % \geq 1 RM) since this training stimulus would promote neural adaptations without placing high metabolic demands on the muscle. Based on the discussed information it is reasonable to propose that training with high loads should be performed throughout all phases of the training macrocycle with the emphasis on developing qualities of maximal strength and power. A prescription of loading between 75 and 100 % 1 RM would still allow for periodisation of loading through the various training phases, however repetitions prescribed should be maintained at lower than 8 to minimise interference effects.

In relation to recovery periods afforded following strength training the majority of questionnaire responses indicated allowing 24 h between either an Olympic weightlifting style strength training session or general strength training session. The majority of responses allowed over 48 h recovery between strength training and a competitive rowing race, although \sim 40 % of responders indicated allowing 48 h or less recovery time. Considering that 2000 m ergometer performance was unaffected, in the thesis studies, at 24 and 48 h it would seem justifiable for strength training to be scheduled 48 h before rowing races. However, the decrements in maximal stroke power at 48 h could potentially hinder on-water race performance considering the high force and power demand required in the initial strokes and the tactical advantages of achieving a fast start (Steinacker, 1993; Garland, 2005). Therefore it would be advisable for rowers to allow over 48 h recovery between strength training and rowing competition. Responses from the interviews indicated that at least a week was allowed between strength training and rowing competition. Cardiovascular endurance was shown to be the most commonly assessed fitness variable from both the questionnaire responses and interviews, this finding was expected considering the aerobic energy demands of rowers and the correlations between parameters of $\dot{V}O_{2\text{max}}$ and 2000 m performance (Ingham *et al.*, 2002; Nevill *et al.*, 2011). The popularity of assessments of strength and power were also highlighted, the practitioners highlighting the regular assessment of specific rowing power through 250 m

and power stroke ergometer tests as well as 1 RM testing on power clean, bench press and bench pull.

9.1.2 Effect of acute and weekly strength training on markers of muscle damage

The markers of muscle damage featured in this thesis are CK (studies 2, 3, 4, 5), LDH (study 3), perceived soreness (studies 2, 3, 4, 5) and limb girths (studies 2, 3, 4). The acute bout of strength training resulted in significant increases in muscle soreness and CK for studies 3 and 4 for a duration of ~ 48 h. The extent and duration of these increases were similar to what has been previously experienced by strength and power athletes after bouts of free weight strength training featuring a range of multi-joint exercises (Raastad & Hallen, 2000; Hoffman *et al.*, 2010) and also resistance-trained participants following protocols of high volume barbell squats (Byrne & Eston, 2002a; 2002b; Rawson *et al.*, 2007; French *et al.*, 2008). Perceived soreness and CK have been increased to a greater extent in response to plyometric exercise protocols, indicating heightened muscle damage in comparison to the acute ST (Twist & Eston, 2005; Skurvydas *et al.*, 2006; Skurvydas *et al.*, 2008; Tofas *et al.*, 2008). This increased damage observed from jump based protocols may be due to the greater overall eccentric loading featured in these protocols compared to the ST (Jamurtas, 2000).

Limb girth measurements were found to be unaffected following the ST in studies 3 and 4. This indicates induced muscle damage was not severe enough to cause oedema and swelling which is associated with the inflammatory response that occurs as a result of muscle damage (Clarkson *et al.*, 1992). Davies *et al.* (2009b) also found no changes in limb girths despite elevations in CK and soreness following a bout of muscle damaging exercise in participants who had been regularly exposed to damaging exercise bouts. The protocol of three strength training sessions in five days had comparable effects on CK and soreness as did the acute bouts in the prior studies. This indicates either that CK or soreness could return to near baseline levels before performance of each subsequent strength session or that participants adapted to the demands of the strength training with each successive session. Research has shown that subsequent eccentric strength training bouts performed at 48 h does not exaggerate symptoms of muscle damage caused by the initial bout (Smith *et al.*, 1994; Paddon-Jones *et al.*, 2000; Nosaka & Newton, 2002).

9.1.3 Effect of acute and weekly strength training on maximal strength and power in trained rowers

The effects of an acute bout of strength training featuring free weight multi-joint exercises on sports specific functional performance have been studied infrequently. Moreover, the effects of acute strength training featuring Olympic weightlifting exercises upon sports specific functional performance has not yet been investigated to the author's knowledge. Previous research has shown that bouts of strength training have led to decrements in maximal vertical jump height and power produced and volume achieved when performing sub-maximal barbell squatting (Raastad & Hallen, 2000; Hoffman *et al.*, 2010). In studies 3 and 4, a bout of high-intensity strength training was shown to lead to decrements in SSJ and CMJ height. The decrements in SSJ and CMJ were 5-10 %, with values reducing over time from 2- to 48 h. Previous research has shown larger decrements in jump performance following exercise challenges of high volume jumps and barbell squats [9-17 %; (Marginson *et al.*, 2005; Skurvydas *et al.*, 2006; French *et al.*, 2008)]. While the Olympic weightlifting exercises included in the ST featured eccentric actions which are similar in nature to those encountered when jumping (Canavan *et al.*, 1996), the volume of repetitions during these exercises was lower (40) compared to the number of jumps commonly featured in the plyometric protocols (80-100). However, the current findings are more useful to coaches and athletes since the strength training bout was modelled on athletic training practices rather than being designed to elicit EIMD.

Of greater relevance to rowing is that, acute strength training was found to significantly reduce both 250 m sprint performance and peak power achieved during five power strokes by ~ 1 % and ~ 5 % respectively. These decrements, though small were consistent among the groups of participants and inferential statistics indicated that there were 'possible' and 'likely' chances that the changes in 250 m rowing and power stroke performance were practically harmful to performance (Hopkins, 2007b). When considering the higher power outputs required to break the rowing boat from inertia, compared to that experienced when using rowing ergometers (Steinacker, 1993), it could be hypothesised that high-intensity sprints or power strokes performed on the water would be affected to a greater extent by fatigue from acute strength training. These findings are supported by content from the interviews, since the strength and conditioning practitioner reported that there were instances when performance has been sub-optimal during high-intensity rowing sessions, giving the example of power strokes on the water, when rowers have not been fully recovered from prior strength training. Therefore the small but predictable decreases in short duration rowing performance should be considered when scheduling high-intensity

time trials or training sessions. Additionally, the 250 m row and five power stroke test provides the coach with an easy to administer assessment of whether the rower is still being affected by prior strength training and could be incorporated into the warm-up part of a training session.

9.1.4 Effect of acute and weekly strength training on 2000 m ergometer performance and pacing

Having observed the significant decreases in rowing sprint performance and power producing ability as a result of a bout of strength training, it was hypothesised that performance decrements would occur in 2000 m rowing ergometer performance after such training. However, 2000 m rowing performance was unaffected following the bout of strength training despite similar significant decreases in rowing specific maximal power being observed in agreement with the previous study. This finding was contrary to those of previous authors who found decreases in endurance performance following ‘modelled’, although unspecific, strength and power training bouts (Marcora & Bosio, 2007; Davies *et al.*, 2008; Davies *et al.*, 2009a; Twist & Eston, 2009). Although, these studies featured an unrealistic level of eccentric loading for an accurate simulation of common athlete training practices. Upon considering the strength training history of the participants it is likely that the repeated bout effect would have protected the participants from exaggerated muscle damage which could have transferred to decreases in 2000 m performance. The presence of repeated bout effect distinguishes the featured participants from those used in the aforementioned studies. Participants in those investigations had not performed resistance training for at least six months prior to their involvement in the studies, which contrasts with the participants in this thesis who were chronically accustomed to resistance training.

It is reasonable to suggest that selective damage to type II fibres following strength training might have accounted for the decreases in maximal power, and that the performance on the 2000 m test was unaffected due to the lower power requirements during this activity. In study 5, performance of the 2000 m ergometer test was also seen to be unaffected following three strength training sessions in a five day period. A larger number of measures were assessed during this study which gave further insight into the likely mechanisms for why 2000 m performance is unaffected following strength training. From EMG recording it was shown that greater muscle activation was detected at three sites in the post-ST intervention group trial. It was reasoned that this increased central motor drive had a compensatory effect on power output during the follow-up trial, which served to negate the effect of muscle damage to the type II fibres. The observed trends for

lower P_{anaer} energy contribution and peak $[\text{Lac}^-]$ during the follow up trial indicate less type II fibres were activated or functioning effectively and that force production was spread across type I fibres perhaps due to the process termed muscle wisdom (Enoka & Stuart, 1992). During this process the CNS provides an economical activation of musculature by recruiting undamaged muscle fibres from the available pool therefore compensating for any damaged fibres (Enoka & Stuart, 1992).

9.2 Recommendations for training practice based on findings

9.2.1 Recommendations for the volume and intensity of individual strength training sessions

Research has proved the effectiveness of high load strength training in comparison to high repetition strength training for well-trained rowers (Ebben *et al.*, 2004b; Gallagher *et al.*, 2010; Izquierdo-Gabarren *et al.*, 2010). The findings from study 1 provide evidence that this method is also favoured by practitioners when implementing strength training for elite rowers. Based on the findings of the studies in this thesis, it appears that rowers are able to maintain 2000 m performance despite the prior performance of three intensive strength training sessions in five days. Therefore, it can be suggested that the imposed intensity and volume of the featured session could act as a template for tolerable strength training prescription amongst rowers. The repetitions prescribed on exercises during this session (most commonly 5 at 85 % 1 RM) were generally at the limit of what the participants could perform at the prescribed loading.

Izquierdo-Gabarren *et al.* (2010) found that performing strength training with a loading of 75-92 % and a sub-maximal number of repetitions per set (2-5) was more effective at improving rowing ergometer performance, after eight weeks of training, than training to volitional failure (4-10 repetitions) with the same loading. Interestingly, in the group following the repetitions to failure approach, the power achieved in the bench pull demonstrated small decreases when assessed after two and three weeks (~ -2 and -3 % respectively) of training. While the sub-maximal repetition group recorded significant increases in power of 5 and 7 % (Figure 9.1).

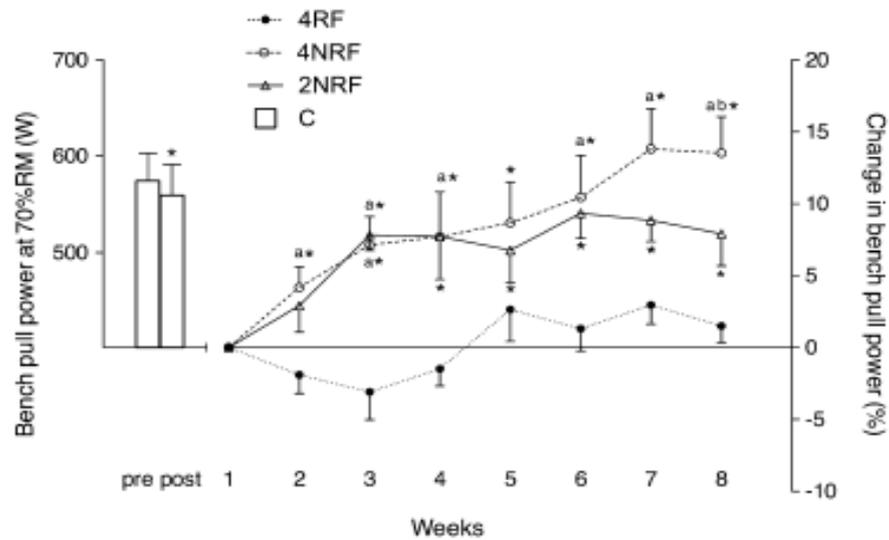


Figure 9.1 Mean \pm SD muscle power output with an absolute load corresponding to 70 % of 1 RM for the bench pull during experimental period. Figure describes the following treatment groups; 4 repetitions to failure (4RF), 4 repetitions not to failure (4NRF), 2 repetitions not to failure (2NRF) and control (C). * $p < 0.05$ from week 1. ^a $p < 0.05$ from corresponding value of 4RF. ^b $p < 0.05$ from corresponding value of 2NRF. As published by Izquierdo-Gabarrén *et al.* (2010).

The authors theorised that the performance of the repetition to failure programme may have surpassed a threshold of training volume whereby sub-optimal adaptations in strength and endurance would result. The reason for these potential sub-optimal adaptations was attributed to the development of residual fatigue in the neuromuscular system (Hickson *et al.*, 1980; Izquierdo-Gabarrén *et al.*, 2010). The imposed strength training session in this thesis featured a higher volume (seven exercises, 3-4 sets of 5-8 repetitions (except sit-ups) at 75-85 % 1 RM) than performed by the sub-maximal repetition group featured in Izquierdo-Gabarrén *et al.* (2010) (four exercises, 3-4 sets of 2-5 repetitions at 75-92 % 1 RM). Furthermore, the significant decreases in maximal strength and power and likely muscle damage observed in this thesis, could be interpreted as a similar loss of adaptive potential as to that proposed by Izquierdo-Gabarrén *et al.* (2010). These findings taken together suggest that, to elicit optimal training adaptations from strength training it is recommended that rowers should perform a sub-maximal number of repetitions at prescribed loadings. With this approach and considering the findings of Izquierdo-Gabarrén *et al.* (2010) the session imposed in this thesis would take the appearance as presented in table 9.1. It could also be argued that the ideal number of exercises would be

reduced since the volume of the session is still high compared to the sub-maximal repetition programme prescribed by Izquierdo-Gabarren *et al.* (2010).

Table 9.1 Less demanding version of the strength training session featured in study 4 to accumulate less fatigue when performed as part of a concurrent training programme

Exercise	Sets x repetitions	% 1 RM / weight used
Snatch	4x3	85 %
Clean	4x3	85 %
Back squat	4x3	85 %
Romanian deadlift	3x5	75 % of squat 1 RM
Bench press	3x3	85 %
Bench pull	3x3	85 %
Weighted sit-ups	3x15	15 kg

9.2.2 Modelling the training micro-cycle based on current findings and review of literature

In consideration of the findings from this thesis and from reviewing relevant literature two individual sample training weeks (micro-cycles) will now be presented. These models aim to optimise the scheduling of strength training sessions within the training week, the order of training sessions is devised with the aim of achieving optimal adaptations from scheduled sessions. For the purpose of the training week the information from the interviews (section 4b.8) will be used to determine the total number of sessions, which equate to 17. The daily described training frequencies from 4b.8 are adhered to for model A (Table 9.2), however these are not maintained for model B (Table 9.3). Therefore model B serves as an alternative guide for frequency distribution.

For both models the content of the 17 sessions will consist of; 11 low intensity rowing sessions (LIR), three high-intensity rowing sessions (HIR) and three strength training sessions (ST). The contributions of total training time of each training modality would equate to ~ 70 %, 20 % and 10 % for LIR, ST and HIR respectively, these volumes are based on information presented in chapters 2.4 and 4b.8 [HIR sessions are typically

shorter duration than LIR and ST; Guellich *et al.* (2009); chapter 4b.6.2]. Based on the design of study 5, the three strength training sessions will be performed on Monday, Wednesday and Friday. Model A takes into consideration the practice of scheduling strength training as the first daily training session (section 4b.6.2). Model B does not take this practice into consideration and schedules the strength training sessions to allow for optimal performance in subsequent training sessions based on findings from studies 3, 4, 5 and the literature review. It was decided that the single described LIR ‘recovery’ session would be compulsory for both models, scheduled on Sunday for model A matching the prescription described in 4b.8.2, apart from this all other rowing training bouts are scheduled as to adhere to the subsequently described training prescription principles (section 9.2.3.1) formed on the basis of the thesis findings.

Table 9.2 Model week A, training based on described daily training frequency and scheduling times of strength training

Day	Training slot 1	Training slot 2	Training slot 3
Monday	ST	LIR	LIR
Tuesday	LIR	LIR	HIR
Wednesday	ST	off	LIR
Thursday	LIR	LIR	HIR
Friday	ST	LIR	LIR
Saturday	LIR	off	HIR
Sunday	LIR	off	off

Table 9.3 Model week B, training scheduled to allow for optimal performance in rowing training sessions

Day	Training slot 1	Training slot 2	Training slot 3
Monday	HIR	off	ST
Tuesday	LIR	LIR	LIR
Wednesday	HIR	off	ST
Thursday	LIR	LIR	LIR
Friday	ST	LIR	LIR
Saturday	LIR	off	off
Sunday	HIR	LIR	LIR

9.2.2.1 General training prescription principles in devising model

9.2.2.1.1 The scheduling of low intensity rowing following strength training

The primary principle adhered to in these models is the preferable scheduling of LIR sessions following strength training as opposed to HIR. The thesis findings suggest that strength training causes muscle damage which reduces maximal rowing power output, but does not affect the functional requirements for the 2000 m test. Furthermore, from the interviews undertaken the strength and conditioning coach indicated that when a high-intensity session, giving the example of power strokes on the water, had been scheduled after strength training, reduced performance in this style of session has sometimes occurred due to insufficient recovery from the preceding strength training bout. The likely reason for the observed decreases in short term rowing performance is preferential damage to type II muscle fibres occurring as a result of strength training. Since LIR sessions will place an even lower demand on type II muscle fibres than the 2000 m test (Guellich *et al.*, 2009), given adequate glycogen replenishment, performance during these sessions should be unaffected by prior strength training. Furthermore, scheduling LIR following ST minimises interference effects occurring between strength and endurance training, since ST conditions the peripheral musculature whereas conditioning effects to the central cardiorespiratory system would occur primarily from LIR (Docherty & Sporer, 2000).

Model B allows for ~ 48 h recovery between ST and HIR, study 4 showed that maximal stroke power was still decreased at 48 h, indicating that decrements in muscle function following ST may affect HIR sessions at this time. The decrements in stroke power at 48 h were not as severe as those at 2- and 24 h. Therefore considering the total number of training sessions scheduled in the weekly micro-cycle; allowing a ~ 48 h period between these two training modalities would seem practical for elite training practice. Furthermore, the interviewed rowing coach indicated that 24-36 h was afforded between intense strength training and high quality rowing training. He indicated that this period although not ideal for recovery, was sufficient and commented; “if we prioritised everything we would never get anywhere”. For model A, due to the imposed morning ST sessions the HIR has to be prescribed on the day following ST, however by allocating training slot 3, over 24 h recovery is granted. It is important to allow adequate recovery between ST and HIR since type II fibre damage resulting from ST would likely affect the quality of certain HIR sessions, specifically those performed at above 2000 m race pace. In addition since ST and HIR both feature a high glycolytic demand (Roy & Tarnopolsky, 1998; Fiskerstrand & Seiler, 2004) and glycogen depletion resulting from strength training might affect performance in HIR (Casey *et al.*, 1996).

9.2.2.1.2 *When possible allow 8 hours between rowing training and strength training*

Garcia-Pallares & Izquierdo (2011) cautioned that residual fatigue caused by a previous endurance session may impair the achievable volume and quality of strength training. Therefore, it has been recommended to schedule endurance training undertaken at an intensity below the anaerobic threshold before strength training, since this training would primarily focus on conditioning the central cardiorespiratory mechanisms rather than cause fatigue in the peripheral musculature which occurs with higher intensity endurance training at maximal aerobic power (Sporer & Wenger, 2003; Garcia-Pallares & Izquierdo, 2011). Due to the need to avoid prescribing HIR in the period 24 h after ST this is difficult to achieve. This recommendation is perhaps more suitable for endurance events which feature loaded eccentric actions, which can cause muscle damage, such as running. For rowing, the eccentric portion of the stroke, termed the 'recovery' phase, is unloaded hence possessing a lower potential to cause EIMD (Lay *et al.*, 2002). Research in highly trained kayakers has shown that allocating 6-8 h between endurance training and strength training allows for replenishment of glycogen stores and enables strength training to be performed with sufficient quality to elicit adaptations (Garcia-Pallares *et al.*, 2009). In addition experienced strength trainers showed undiminished strength output when assessed 8 h after endurance cycling (Leveritt *et al.*, 2000). Therefore, if optimal adaptations from strength training are to be realised, then whenever possible the practice of allowing 8 h recovery should be adhered to when structuring the training of rowers. Applying this principle would only be a factor in model B, since in model A, ST is the first daily session. For model B, as only two sessions occur on Monday and Wednesday, the second training slot can be left free to allow rest to be implemented between HIR and ST, whereas for Friday ST occurs as the first session.

9.3 **Directions for future research**

This thesis was applied in nature and provides useful findings which can be related to the athletic training setting. However, through the course of the investigations an avenue for further study has arisen.

9.3.1 *The effect of acute strength training on the initial 2-30 s of a 2000 m rowing ergometer test*

During the start of a 6 min rowing time trial mean power over the initial 10 strokes was found to be ~ 30 % higher than mean power over the whole trial (Hartmann *et al.*, 1993). Similarly, peak power during the power stroke test in study 5 was found to be 35 % higher

than mean power during the 2000 m test. This indicates rowers voluntarily produce close to maximal power during the initial strokes of prolonged ergometer tests. Therefore if there were to be some recruitment of the highest threshold muscle fibres during the 2000 m row it would likely be at the initial period of the test (< 30 s). In studies 3, 4 and 5 strength training was shown to decrease anaerobic rowing performance. Therefore it is possible that damage to high threshold type II fibres could affect initial power production (first 2—30 s) in a 2000 m ergometer test. However, given that rowers were still able to maintain 2000 m performance in studies 4 and 5 the occurrence of this effect would seemingly did not impact ergometer performance. The performance characteristics of on-water rowing differs to that of ergometer trials since the start of the on-water race necessitates higher force and power to be produced in order to get the boat up to race speed and gain a tactically advantageous position in the competitive field (Steinacker, 1993; Garland, 2005). Therefore discrepancies in initial stroke power would impact performance of a rowing race to a greater extent than a 2000 m ergometer trial. An intervention investigating the effect of acute strength training on 2000 m ergometer performance with stroke-by-stroke force and power analysis would demonstrate whether the start or any stage of the trial would be specifically impacted.

9.4 Conclusion

A descriptive analysis of strength and conditioning practices within British rowing led to the establishment of several key themes which informed the design of subsequent experimental investigations. The experimental performance tests, physiological measures and markers of muscle damage were generally found to possess good reproducibility across repeated trials, therefore justifying their use in the subsequent intervention studies. A single bout of strength training, designed according to information gathered from study 1, led to transient (24 to 48 h) performance decrements in vertical jump height and 250 m rowing ergometer performance, which generated speculation that 2000 m performance may also be affected following strength training. However, in the subsequent study, 2000 m performance was maintained following a similar bout of strength training in spite of significant decrements in maximal power producing ability and increases in markers of muscle damage. This led to speculation that the imposed strength training bout was inflicting selective damage upon type II muscle fibres and that the repeated bout effect protected participants from exaggerated decrements in functional performance. In the final study, 2000 m performance was also found to be unaffected following three strength training sessions performed in five days. Findings suggested a decreased utilisation of the

anaerobic energy pathways coupled with increased central motor drive suggesting a change in muscular recruitment patterns during the follow up 2000 m rowing test. Physiological measures indicated a reduction in type II fibre recruitment during the 2000 m row following strength training, which was compensated for by an increased neural drive to the available pool of undamaged muscle fibres. It would appear that following extensive strength training, physiological processes were adapted during subsequent rowing exercise, to compensate for the loss in higher threshold muscle fibre function, in order to affect the same level of rowing performance achieved in the rested state. In consideration of the findings from this thesis, suggestions were subsequently made regarding the optimal scheduling of rowing training sessions in relation to strength training bouts.

References

- Abbiss, C. R. & Laursen, P. B. (2008) 'Describing and understanding pacing strategies during athletic competition', *Sports Medicine*, 38 (3), pp. 239-252.
- Ahtiainen, J. P., Pakarinen, A., Kraemer, W. J. & Hakkinen, K. (2004) 'Acute hormonal responses to heavy resistance exercise in strength athletes versus nonathletes', *Canadian Journal of Applied Physiology*, 29 (5), pp. 527-543.
- Apostolidis, N., Nassis, G. P., Bolatoglou, T. & Geladas, N. D. (2004) 'Physiological and technical characteristics of elite young basketball players', *Journal of Sports Medicine and Physical Fitness*, 44 (2), pp. 157-163.
- Asp, S., Daugaard, J. R., Kristiansen, S., Kiens, B. & Richter, E. A. (1998) 'Exercise metabolism in human skeletal muscle exposed to prior eccentric exercise', *Journal of Physiology*, 509 (Pt 1), pp. 305-313.
- Atkinson, G. & Nevill, A. M. (2001) 'Selected issues in the design and analysis of sport performance research', *Journal of Sports Sciences*, 19 (10), pp. 811-827.
- Avery, N. G., Kaiser, J. L., Sharman, M. J., Scheett, T. P., Barnes, D. M., Gomez, A. L., Kraemer, W. J. & Volek, J. S. (2003) 'Effects of vitamin E supplementation on recovery from repeated bouts of resistance exercise', *Journal of Strength and Conditioning Research*, 17 (4), pp. 801-809.
- Baden, D. A., McLean, T. L., Tucker, R., Noakes, T. D. & St Clair Gibson, A. (2005) 'Effect of anticipation during unknown or unexpected exercise duration on rating of perceived exertion, affect, and physiological function', *British Journal of Sports Medicine*, 39 (10), pp. 742-746; discussion 742-746.
- Baechle, T. R. & Earle, R. W. (2008) *Essentials of strength training and conditioning*. Champaign, Illinois: Human Kinetics.
- Batterham, A. & Hopkins, W. (2006) 'Making meaningful inferences about magnitudes', *International journal of sports physiology and performance*, 1 (1), pp. 50-57.
- Battista, R. A., Pivarnik, J. M., Dummer, G. M., Sauer, N. & Malina, R. M. (2007) 'Comparisons of physical characteristics and performances among female collegiate rowers', *Journal of Sports Sciences*, 25 (6), pp. 651-657.
- Bell, G. J., Petersen, S. R., Quinney, H. A. & Wenger, H. A. (1989) 'The effect of velocity-specific strength training on peak torque and anaerobic rowing power', *Journal of Sports Sciences*, 7 (3), pp. 205-214.
- Beltman, J. G., Sargeant, A. J., van Mechelen, W. & de Haan, A. (2004) 'Voluntary activation level and muscle fiber recruitment of human quadriceps during lengthening contractions', *Journal of Applied Physiology*, 97 (2), pp. 619-626.
- Bijur, P. E., Silver, W. & Gallagher, E. J. (2001) 'Reliability of the visual analog scale for measurement of acute pain', *Academic Emergency Medicine*, 8 (12), pp. 1153-1157.
- Bolgla, L. A. & Uhl, T. L. (2007) 'Reliability of electromyographic normalization methods for evaluating the hip musculature', *Journal of Electromyography and Kinesiology*, 17 (1), pp. 102-111.

- Borg, G. (1970) 'Perceived exertion as an indicator of somatic stress', *Scandinavian Journal of Rehabilitation Medicine*, 2 (2), pp. 92-98.
- Bourgois, J., Claessens, A. L., Vrijens, J., Philippaerts, R., Van Renterghem, B., Thomis, M., Janssens, M., Loos, R. & Lefevre, J. (2000) 'Anthropometric characteristics of elite male junior rowers', *British Journal of Sports Medicine*, 34 (3), pp. 213-216; discussion 216-217.
- Brancaccio, P., Maffulli, N. & Limongelli, F. M. (2007) 'Creatine kinase monitoring in sport medicine', *British Medical Bulletin*, 81-82, pp. 209-230.
- Brandon, R. & Cleather, D. (2007) 'Training the Hamstrings for High Speed Running - Part II', *Professional Strength and Conditioning*, 7.
- Braun, W. A. & Dutto, D. J. (2003) 'The effects of a single bout of downhill running and ensuing delayed onset of muscle soreness on running economy performed 48 h later', *European Journal of Applied Physiology*, 90 (1-2), pp. 29-34.
- Bret, C., Rahmani, A., Dufour, A. B., Messonnier, L. & Lacour, J. R. (2002) 'Leg strength and stiffness as ability factors in 100 m sprint running', *Journal of Sports Medicine and Physical Fitness*, 42 (3), pp. 274-281.
- Brockett, C. L., Morgan, D. L. & Proske, U. (2001) 'Human hamstring muscles adapt to eccentric exercise by changing optimum length', *Medicine and Science in Sports and Exercise*, 33 (5), pp. 783-790.
- Brown, M. R., Delau, S. & Desgorces, F. D. (2010) 'Effort regulation in rowing races depends on performance level and exercise mode', *Journal of Science and Medicine in Sport*, 13 (6), pp. 613-617.
- Burr, J. F., Jamnik, V. K., Dogra, S. & Gledhill, N. (2007) 'Evaluation of jump protocols to assess leg power and predict hockey playing potential', *Journal of Strength and Conditioning Research*, 21 (4), pp. 1139-1145.
- Byrne, C. & Eston, R. (2002a) 'The effect of exercise-induced muscle damage on isometric and dynamic knee extensor strength and vertical jump performance', *Journal of Sports Sciences*, 20 (5), pp. 417-425.
- Byrne, C. & Eston, R. (2002b) 'Maximal-intensity isometric and dynamic exercise performance after eccentric muscle actions', *Journal of Sports Sciences*, 20 (12), pp. 951-959.
- Byrne, C., Twist, C. & Eston, R. (2004) 'Neuromuscular function after exercise-induced muscle damage: theoretical and applied implications', *Sports Medicine*, 34, pp. 49-69
- Calbet, J., Chavarren, J. & Dorado, C. (2001) 'Running economy and delayed onset muscle soreness', *Journal of Sports Medicine and Physical Fitness*, 41, pp. 18-26
- Campos, G. E., Luecke, T. J., Wendeln, H. K., Toma, K., Hagerman, F. C., Murray, T. F., Ragg, K. E., Ratamess, N. A., Kraemer, W. J. & Staron, R. S. (2002) 'Muscular adaptations in response to three different resistance-training regimens: specificity

of repetition maximum training zones', *European Journal of Applied Physiology*, 88 (1-2), pp. 50-60.

- Canavan, P., Garret, G. & Armstrong, L. (1996) 'Kinematic and kinetic relationships between an Olympic-style lift and the vertical jump', *Journal of Strength and Conditioning Research*, 10 (2), pp. 127-130.
- Casartelli, N., Müller, R. & Maffiuletti, N. A. (2010) 'Validity and reliability of the Myotest accelerometric system for the assessment of vertical jump height', *Journal of Strength and Conditioning Research*, 24 (11), pp. 3186-3193.
- Casey, A., Short, A. H., Curtis, S. & Greenhaff, P. L. (1996) 'The effect of glycogen availability on power output and the metabolic response to repeated bouts of maximal, isokinetic exercise in man', *Eur J Appl Physiol Occup Physiol*, 72 (3), pp. 249-255.
- Castagna, C., Abt, G., Manzi, V., Annino, G., Padua, E. & D'Ottavio, S. (2008) 'Effect of recovery mode on repeated sprint ability in young basketball players', *Journal of Strength and Conditioning Research*, 22 (3), pp. 923-929.
- Celik, O., Kosar, S. N., Korkusuz, F. & Bozkurt, M. (2005) 'Reliability and validity of the modified Conconi test on concept II rowing ergometers', *Journal of Strength and Conditioning Research*, 19 (4), pp. 871-877.
- Chance, B., Dait, M. T., Zhang, C., Hamaoka, T. & Hagerman, F. (1992) 'Recovery from exercise-induced desaturation in the quadriceps muscles of elite competitive rowers', *American Journal of Physiology*, 262 (3 Pt 1), pp. C766-775.
- Channell, B. T. & Barfield, J. P. (2008) 'Effect of Olympic and traditional resistance training on vertical jump improvement in high school boys', *Journal of Strength and Conditioning Research*, 22 (5), pp. 1522-1527.
- Chen, T., Nosaka, K. & Tu, J. (2007) 'Changes in running economy following downhill running', *Journal of Sports Sciences*, 25, pp. 55-63.
- Chen, T. C., Nosaka, K. & Wu, C. C. (2008) 'Effects of a 30-min running performed daily after downhill running on recovery of muscle function and running economy', *Journal of Science and Medicine in Sport*, 11 (3), pp. 271-279.
- Chiu, L. & Schilling, B. (2005) 'A Primer on Weightlifting: From Sport to Sports Training', *Strength and Conditioning Journal*, 27 (1), pp. 42-48.
- Choi, S. J., Lim, J. Y., Nibaldi, E. G., Phillips, E. M., Frontera, W. R., Fielding, R. A. & Widrick, J. J. (2011) 'Eccentric contraction-induced injury to type I, IIa, and IIa/IIx muscle fibers of elderly adults', *Age*.
- Clarkson, P. M., Graves, J., Melchionda, A. M. & Johnson, J. (1984) 'Isokinetic strength and endurance and muscle fiber type of elite oarswomen', *Canadian Journal of Applied Sport Sciences*, 9 (3), pp. 127-132.
- Clarkson, P. M., Nosaka, K. & Braun, B. (1992) 'Muscle function after exercise-induced muscle damage and rapid adaptation', *Medicine and Science in Sports and Exercise*, 24 (5), pp. 512-520.

- Cook, J. L., Kiss, Z. S., Khan, K. M., Purdam, C. R. & Webster, K. E. (2004) 'Anthropometry, physical performance, and ultrasound patellar tendon abnormality in elite junior basketball players: a cross-sectional study', *British Journal of Sports Medicine*, 38 (2), pp. 206-209.
- Corbett, J. (2009) 'An analysis of the pacing strategies adopted by elite athletes during track cycling', *Int J Sports Physiol Perform*, 4 (2), pp. 195-205.
- Corbett, J., Barwood, M. J. & Parkhouse, K. (2009) 'Effect of task familiarisation on distribution of energy during a 2000 m cycling time trial', *British Journal of Sports Medicine*, 43 (10), pp. 770-774.
- Costill, D. L., Flynn, M. G., Kirwan, J. P., Houmard, J. A., Mitchell, J. B., Thomas, R. & Park, S. H. (1988) 'Effects of repeated days of intensified training on muscle glycogen and swimming performance', *Medicine and Science in Sports and Exercise*, 20 (3), pp. 249-254.
- Cronin, J. B., Jones, J. V. & Hagstrom, J. T. (2007) 'Kinematics and kinetics of the seated row and implications for conditioning', *Journal of Strength and Conditioning Research*, 21 (4), pp. 1265-1270.
- Cross, K. M. & Worrell, T. W. (1999) 'Effects of a static stretching program on the incidence of lower extremity musculotendinous strains', *Journal of Athletic Training*, 34 (1), pp. 11-14.
- Crowther, R. G., Spinks, W. L., Leicht, A. S. & Spinks, C. D. (2007) 'Kinematic responses to plyometric exercises conducted on compliant and noncompliant surfaces', *J Strength Cond Res*, 21 (2), pp. 460-465.
- Davies, R. C., Eston, R. G., Poole, D. C., Rowlands, A. V., DiMenna, F., Wilkerson, D. P., Twist, C. & Jones, A. M. (2008) 'Effect of eccentric exercise-induced muscle damage on the dynamics of muscle oxygenation and pulmonary oxygen uptake', *Journal of Applied Physiology*, 105 (5), pp. 1413-1421.
- Davies, R. C., Rowlands, A. V. & Eston, R. G. (2009a) 'Effect of exercise-induced muscle damage on ventilatory and perceived exertion responses to moderate and severe intensity cycle exercise', *European Journal of Applied Physiology*, 107 (1), pp. 11-19.
- Davies, V., Thompson, K. G. & Cooper, S. M. (2009b) 'The effects of compression garments on recovery', *Journal of Strength and Conditioning Research*, 23 (6), pp. 1786-1794.
- de Campos Mello, F., de Moraes Bertuzzi, R., Grangeiro, P. & Franchini, E. (2009) 'Energy systems contributions in 2,000 m race simulation: a comparison among rowing ergometers and water', *European Journal of Applied Physiology*, 107 (5), pp. 615-619.
- de Koning, J. J., Bobbert, M. F. & Foster, C. (1999) 'Determination of optimal pacing strategy in track cycling with an energy flow model', *Journal of Science and Medicine in Sport*, 2 (3), pp. 266-277.

- de Koning, J. J., Foster, C., Bakkum, A., Kloppenburg, S., Thiel, C., Joseph, T., Cohen, J. & Porcari, J. P. (2011) 'Regulation of pacing strategy during athletic competition', *PLoS ONE*, 6 (1), p. e15863.
- Di Cagno, A. B., C. Battaglia, C. Brasili, P. Merni, F. Piazza, M. Toselli, S. Ventrella. A.R. Guidetti, L. (2008) 'Leaping ability and body composition in rhythmic gymnasts for talent identification', *Journal of Sports Medicine and Physical Fitness*, 48 (3), pp. 341-346.
- Dick, R. W. (1993) 'Injuries in collegiate ice hockey', in Castaldi, C. R. B., P.J. and Hoerner, E.F. eds (ed.) *Safety in ice hockey: second volume*. Philadelphia: American Society for Testing and Materials, pp. 21-30.
- Docherty, D. & Sporer, B. (2000) 'A proposed model for examining the interference phenomenon between concurrent aerobic and strength training', *Sports Medicine*, 30 (6), pp. 385-394.
- Drechsler, A. J. (ed.) (1998) *The Weightlifting Encyclopedia: A Guide to World Class Performance*. New York: A is A Communications.
- Duehring, M. D. & Ebben, W. P. (2010) 'Profile of high school strength and conditioning coaches', *Journal of Strength and Conditioning Research*, 24 (2), pp. 538-547.
- Duehring, M. D., Feldmann, C. R. & Ebben, W. P. (2009) 'Strength and conditioning practices of United States high school strength and conditioning coaches', *Journal of Strength and Conditioning Research*, 23 (8), pp. 2188-2203.
- Duffield, R., Cannon, J. & King, M. (2010) 'The effects of compression garments on recovery of muscle performance following high-intensity sprint and plyometric exercise', *Journal of Science and Medicine in Sport*, 13 (1), pp. 136-140.
- duManoir, G. R., Haykowsky, M. J., Syrotuik, D. G., Taylor, D. A. & Bell, G. J. (2007) 'The effect of high-intensity rowing and combined strength and endurance training on left ventricular systolic function and morphology', *International Journal of Sports Medicine*, 28 (6), pp. 488-494.
- Durell, D. L., Pujol, T. J. & Barnes, J. T. (2003) 'A survey of the scientific data and training methods utilized by collegiate strength and conditioning coaches', *Journal of Strength and Conditioning Research*, 17 (2), pp. 368-373.
- Ebbeling, C. B. & Clarkson, P. M. (1990) 'Muscle adaptation prior to recovery following eccentric exercise', *Eur J Appl Physiol Occup Physiol*, 60 (1), pp. 26-31.
- Ebben, W. P. & Blackard, D. O. (2001) 'Strength and conditioning practices of National Football League strength and conditioning coaches', *Journal of Strength and Conditioning Research*, 15 (1), pp. 48-58.
- Ebben, W. P., Carroll, R. M. & Simenz, C. J. (2004a) 'Strength and conditioning practices of National Hockey League strength and conditioning coaches', *Journal of Strength and Conditioning Research*, 18 (4), pp. 889-897.

- Ebben, W. P., Hintz, M. J. & Simenz, C. J. (2005) 'Strength and conditioning practices of Major League Baseball strength and conditioning coaches', *Journal of Strength and Conditioning Research*, 19 (3), pp. 538-546.
- Ebben, W. P., Kindler, A. G., Chirdon, K. A., Jenkins, N. C., Polichnowski, A. J. & Ng, A. V. (2004b) 'The effect of high-load vs. high-repetition training on endurance performance', *Journal of Strength and Conditioning Research*, 18 (3), pp. 513-517.
- Enoka, R. M. (1996) 'Eccentric contractions require unique activation strategies by the nervous system', *Journal of Applied Physiology*, 81 (6), pp. 2339-2346.
- Enoka, R. M. & Stuart, D. G. (1992) 'Neurobiology of muscle fatigue', *Journal of Applied Physiology*, 72 (5), pp. 1631-1648.
- Epstein, Y. (1995) 'Clinical significance of serum creatine phosphokinase activity levels following exercise', *Israel Journal of Medical Sciences*, 31 (11), pp. 698-699.
- Escamilla, R. F. (2001) 'Knee biomechanics of the dynamic squat exercise', *Medicine and Science in Sports and Exercise*, 33 (1), pp. 127-141.
- Escamilla, R. F., Francisco, A. C., Fleisig, G. S., Barrentine, S. W., Welch, C. M., Kayes, A. V., Speer, K. P. & Andrews, J. R. (2000a) 'A three-dimensional biomechanical analysis of sumo and conventional style deadlifts', *Medicine and Science in Sports and Exercise*, 32 (7), pp. 1265-1275.
- Escamilla, R. F., Francisco, A. C., Fleisig, G. S., Barrentine, S. W., Welch, C. M., Kayes, A. V., Speer, K. P. & Andrews, J. R. (2000b) 'A three-dimensional biomechanical analysis of sumo and conventional style deadlifts', *Medicine and Science in Sports and Exercise*, 32 (7), pp. 1265-1275.
- Eston, R. G., Finney, S., Baker, S. & Baltzopoulos, V. (1996) 'Muscle tenderness and peak torque changes after downhill running following a prior bout of isokinetic eccentric exercise', *Journal of Sports Sciences*, 14 (4), pp. 291-299.
- Fauth, M. L., Petushek, E. J., Feldmann, C. R., Hsu, B. E., Garceau, L. R., Lutsch, B. N. & Ebben, W. P. (2010) 'Reliability of surface electromyography during maximal voluntary isometric contractions, jump landings, and cutting', *Journal of Strength and Conditioning Research*, 24 (4), pp. 1131-1137.
- Fenwick, C. M., Brown, S. H. & McGill, S. M. (2009) 'Comparison of different rowing exercises: trunk muscle activation and lumbar spine motion, load, and stiffness', *Journal of Strength and Conditioning Research*, 23 (2), pp. 350-358.
- Finamore, L. V. (1992) 'Survey of high school football team strength and conditioning programs', *Journal of Athletic Training*, 27 (2), pp. 125-130.
- Fiskerstrand, A. & Seiler, K. S. (2004) 'Training and performance characteristics among Norwegian international rowers 1970-2001', *Scandinavian Journal of Medicine and Science in Sports*, 14 (5), pp. 303-310.
- French, D., Thompson, K., Garland, S., Barnes, C., Portas, M., Hood, P. & Wilkes, G. (2008) 'The effects of contrast bathing and compression therapy on muscular performance', *Medicine and Science in Sports and Exercise*, 40, pp. 1297-1306.

- Friden, J. & Lieber, R. L. (2001) 'Eccentric exercise-induced injuries to contractile and cytoskeletal muscle fibre components', *Acta Physiologica Scandinavica*, 171 (3), pp. 321-326.
- Friden, J., Sjoström, M. & Ekblom, B. (1983) 'Myofibrillar damage following intense eccentric exercise in man', *International Journal of Sports Medicine*, 4 (3), pp. 170-176.
- Fry, A. C., Kraemer, W. J., Lynch, J. M., Triplett, N. T. & Koziris, L. P. (1994a) 'Does short-term near-maximal intensity machine resistance training induce overtraining?', *Journal of Strength and Conditioning Research*, 8 (3), pp. 188-191.
- Fry, A. C., Kraemer, W. J., Stone, M. H., Warren, B. J., Fleck, S. J., Kearney, J. T. & Gordon, S. E. (1994b) 'Endocrine responses to overreaching before and after 1 year of weightlifting', *Canadian Journal of Applied Physiology*, 19 (4), pp. 400-410.
- Fry, A. C., Kraemer, W. J., van Borselen, F., Lynch, J. M., Marsit, J. L., Roy, E. P., Triplett, N. T. & Knuttgen, H. G. (1994c) 'Performance decrements with high-intensity resistance exercise overtraining', *Medicine and Science in Sports and Exercise*, 26 (9), pp. 1165-1173.
- Gallagher, D., DiPietro, L., Visek, A. J., Bancheri, J. M. & Miller, T. A. (2010) 'The effects of concurrent endurance and resistance training on 2,000-m rowing ergometer times in collegiate male rowers', *Journal of Strength and Conditioning Research*, 24 (5), pp. 1208-1214.
- Garcia-Pallares, J. & Izquierdo, M. (2011) 'Strategies to optimize concurrent training of strength and aerobic fitness for rowing and canoeing', *Sports Medicine*, 41 (4), pp. 329-343.
- Garcia-Pallares, J., Sanchez-Medina, L., Carrasco, L., Diaz, A. & Izquierdo, M. (2009) 'Endurance and neuromuscular changes in world-class level kayakers during a periodized training cycle', *European Journal of Applied Physiology*, 106 (4), pp. 629-638.
- Garland, S. W. (2005) 'An analysis of the pacing strategy adopted by elite competitors in 2000 m rowing', *British Journal of Sports Medicine*, 39 (1), pp. 39-42.
- Glaister, M. (2005) 'Multiple sprint work : physiological responses, mechanisms of fatigue and the influence of aerobic fitness', *Sports Medicine*, 35 (9), pp. 757-777.
- Gleeson, M., Blannin, A. K., Walsh, N. P., Field, C. N. & Pritchard, J. C. (1998) 'Effect of exercise-induced muscle damage on the blood lactate response to incremental exercise in humans', *Eur J Appl Physiol Occup Physiol*, 77 (3), pp. 292-295.
- Gleeson, M., Blannin, A. K., Zhu, B., Brooks, S. & Cave, R. (1995) 'Cardiorespiratory, hormonal and haematological responses to submaximal cycling performed 2 days after eccentric or concentric exercise bouts', *Journal of Sports Sciences*, 13 (6), pp. 471-479.
- Goodall, S. & Howatson, G. (2008) 'The effects of multiple cold water immersions on indices of muscle damage', *Journal of Sports Science and Medicine*, 7, pp. 235-241.

- Gourgoulis, V., Aggelousis, N., Mavromatis, G. & Garas, A. (2000) 'Three-dimensional kinematic analysis of the snatch of elite Greek weightlifters', *Journal of Sports Sciences*, 18 (8), pp. 643-652.
- Gourgoulis, V., Aggeloussis, N., Kalivas, V., Antoniou, P. & Mavromatis, G. (2004) 'Snatch lift kinematics and bar energetics in male adolescent and adult weightlifters', *Journal of Sports Medicine and Physical Fitness*, 44 (2), pp. 126-131.
- Grindstaff, T. L., Beazell, J. R., Saliba, E. N. & Ingersoll, C. D. (2010) 'Treatment of a female collegiate rower with costochondritis: a case report', *J Man Manip Ther*, 18 (2), pp. 64-68.
- Guellich, A., Seiler, S. & Emrich, E. (2009) 'Training methods and intensity distribution of young world-class rowers', *Int J Sports Physiol Perform*, 4 (4), pp. 448-460.
- Hackney, K. J., Engels, H. J. & Gretebeck, R. J. (2008) 'Resting energy expenditure and delayed-onset muscle soreness after full-body resistance training with an eccentric concentration', *Journal of Strength and Conditioning Research*, 22 (5), pp. 1602-1609.
- Haff, G. G. & Potteiger, J. A. L., R.H. Haub, M.D. Dolezal, B.A. Alumzaini, K.S. Schroeder, J.M. Zebas, C.J. (2001) 'A brief review: explosive exercises and sports performance', *Strength and Conditioning Journal*, 23 (3), pp. 13-20.
- Hagerman, F. C. (1994) 'Physiology and nutrition of rowing', in Lamb, D. R., Knuttgen, H. G. & Murray, R. (eds.) *Perspectives in Exercise Science and Sports Medicine*. Indianapolis: Cooper Publishers, pp. 221-302.
- Hagerman, F. C., Connors, M. C., Gault, J. A., Hagerman, G. R. & Polinski, W. J. (1978) 'Energy expenditure during simulated rowing', *Journal of Applied Physiology*, 45 (1), pp. 87-93.
- Hagerman, F. C., Fielding, R. A., Fiatarone, M. A., Gault, J. A., Kirkendall, D. T., Ragg, K. E. & Evans, W. J. (1996) 'A 20-yr longitudinal study of Olympic oarsmen', *Medicine and Science in Sports and Exercise*, 28 (9), pp. 1150-1156.
- Hakkinen, K. (1993) 'Neuromuscular fatigue and recovery in male and female athletes during heavy resistance exercise', *International Journal of Sports Medicine*, 14 (2), pp. 53-59.
- Hakkinen, K. & Kauhanen, H. (1989) 'Daily changes in neural activation, force-time and relaxation-time characteristics in athletes during very intense training for one week', *Electromyography and Clinical Neurophysiology*, 29 (4), pp. 243-249.
- Hakkinen, K., Pakarinen, A., Alen, M., Kauhanen, H. & Komi, P. V. (1988a) 'Daily hormonal and neuromuscular responses to intensive strength training in 1 week', *International Journal of Sports Medicine*, 9 (6), pp. 422-428.
- Hakkinen, K., Pakarinen, A., Alen, M., Kauhanen, H. & Komi, P. V. (1988b) 'Neuromuscular and hormonal adaptations in athletes to strength training in two years', *Journal of Applied Physiology*, 65 (6), pp. 2406-2412.

- Hart, J. M., Swanik, C. B. & Tierney, R. T. (2005) 'Effects of sport massage on limb girth and discomfort associated with eccentric exercise', *Journal of Athletic Training*, 40 (3), pp. 181-185.
- Hartmann, U., Mader, A., Wasser, K. & Klauer, I. (1993) 'Peak force, velocity, and power during five and ten maximal rowing ergometer strokes by world class female and male rowers', *International Journal of Sports Medicine*, 14 Suppl 1, pp. S42-45.
- Hartmann, U. & Mester, J. (2000) 'Training and overtraining markers in selected sport events', *Medicine and Science in Sports and Exercise*, 32 (1), pp. 209-215.
- Hedelin, R., Kentta, G., Wiklund, U., Bjerle, P. & Henriksson-Larsen, K. (2000) 'Short-term overtraining: effects on performance, circulatory responses, and heart rate variability', *Medicine and Science in Sports and Exercise*, 32 (8), pp. 1480-1484.
- Hermens, H. J., Freriks, B., Disselhorst-Klug, C. & Rau, G. (2000) 'Development of recommendations for SEMG sensors and sensor placement procedures', *Journal of Electromyography and Kinesiology*, 10 (5), pp. 361-374.
- Hickson, R. C., Rosenkoetter, M. A. & Brown, M. M. (1980) 'Strength training effects on aerobic power and short-term endurance', *Medicine and Science in Sports and Exercise*, 12 (5), pp. 336-339.
- Highton, J. M., Twist, C. & Eston, R. G. (2009) 'The effects of exercise-induced muscle damage on agility and sprint running performance', *Journal of Exercise Science & Fitness*, 7 (1), pp. 24-30.
- Hoffman, J. R., Ratamess, N. A., Tranchina, C. P., Rashti, S. L., Kang, J. & Faigenbaum, A. D. (2010) 'Effect of a proprietary protein supplement on recovery indices following resistance exercise in strength/power athletes', *Amino Acids*, 38 (3), pp. 771-778.
- Hopkins, W. G. (2000) 'Measures of reliability in sports medicine and science', *Sports Medicine*, 30 (1), pp. 1-15.
- Hopkins, W. G. (2003) *A spreadsheet for analysis of straightforward controlled trials*. [Online]. Available at: sportsci.org/jour/03/wghtrials.htm
- Hopkins, W. G. (2007a) *Analysis of reliability with a spreadsheet*. [Online]. Available at: <http://sportsci.org/resource/stats/xrely.xls>.
- Hopkins, W. G. (2007b) 'A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a p value', *Sportscience*, 11, pp. 16-20.
- Hopkins, W. G., Hawley, J. A. & Burke, L. M. (1999) 'Design and analysis of research on sport performance enhancement', *Medicine and Science in Sports and Exercise*, 31 (3), pp. 472-485.
- Hopkins, W. G., Marshall, S. W., Batterham, A. M. & Hanin, J. (2009) 'Progressive statistics for studies in sports medicine and exercise science', *Medicine and Science in Sports and Exercise*, 41 (1), pp. 3-13.

- Hopkins, W. G., Schabert, E. J. & Hawley, J. A. (2001) 'Reliability of power in physical performance tests', *Sports Medicine*, 31 (3), pp. 211-234.
- Hori, N., Newton, R. U., Andrews, W. A., Kawamori, N., McGuigan, M. R. & Nosaka, K. (2008) 'Does performance of hang power clean differentiate performance of jumping, sprinting, and changing of direction?', *Journal of Strength and Conditioning Research*, 22 (2), pp. 412-418.
- Horsley, I. G., Herrington, L. C. & Rolf, C. (2010) 'Does a SLAP lesion affect shoulder muscle recruitment as measured by EMG activity during a rugby tackle?', *J Orthop Surg Res*, 5, p. 12.
- Hortobagyi, T., Hill, J. P., Houmard, J. A., Fraser, D. D., Lambert, N. J. & Israel, R. G. (1996) 'Adaptive responses to muscle lengthening and shortening in humans', *Journal of Applied Physiology*, 80 (3), pp. 765-772.
- Howatson, G., Gaze, D. & van Someren, K. A. (2005) 'The efficacy of ice massage in the treatment of exercise-induced muscle damage', *Scandinavian Journal of Medicine and Science in Sports*, 15 (6), pp. 416-422.
- Ingalls, C. P., Warren, G. L., Williams, J. H., Ward, C. W. & Armstrong, R. B. (1998) 'E-C coupling failure in mouse EDL muscle after in vivo eccentric contractions', *Journal of Applied Physiology*, 85 (1), pp. 58-67.
- Ingham, S. A., Carter, H., Whyte, G. P. & Doust, J. H. (2007) 'Comparison of the oxygen uptake kinetics of club and olympic champion rowers', *Medicine and Science in Sports and Exercise*, 39 (5), pp. 865-871.
- Ingham, S. A., Carter, H., Whyte, G. P. & Doust, J. H. (2008) 'Physiological and performance effects of low- versus mixed-intensity rowing training', *Medicine and Science in Sports and Exercise*, 40 (3), pp. 579-584.
- Ingham, S. A., Whyte, G. P., Jones, K. & Nevill, A. M. (2002) 'Determinants of 2,000 m rowing ergometer performance in elite rowers', *European Journal of Applied Physiology*, 88 (3), pp. 243-246.
- Ivey, P., Oakley, J. & Hagerman, P. (2004) 'Strength training for the preparatory phase in collegiate women's rowing', *Strength and Conditioning Journal*, 26 (6), pp. 10-15.
- Izquierdo-Gabarren, M., Exposito, R. G., de Villarreal, E. S. & Izquierdo, M. (2011) 'Physiological factors to predict on traditional rowing performance', *European Journal of Applied Physiology*, 108 (1), pp. 83-92.
- Izquierdo-Gabarren, M., Gonzalez De Txabarri Exposito, R., Garcia-pallares, J., Sanchez-medina, L., De Villarreal, E. S. & Izquierdo, M. (2010) 'Concurrent endurance and strength training not to failure optimizes performance gains', *Medicine and Science in Sports and Exercise*, 42 (6), pp. 1191-1199.
- Izquierdo, M., Ibanez, J., Gonzalez-Badillo, J. J., Hakkinen, K., Ratamess, N. A., Kraemer, W. J., French, D. N., Eslava, J., Altadill, A., Asiain, X. & Gorostiaga, E. M. (2006) 'Differential effects of strength training leading to failure versus not to failure on hormonal responses, strength, and muscle power gains', *Journal of Applied Physiology*, 100 (5), pp. 1647-1656.

- Jamurtas, A. Z. F., I.G. Buckenmeyer, P.K. Efstratios, T.K. Kambas, A. and Kyriazis, G. (2000) 'Effects of Plyometric Exercise on Muscle Soreness and Plasma Creatine Kinase Levels and its comparison With Eccentric and Concentric Exercise', *Journal of Strength and Conditioning Research*, 14 (1), pp. 68-74.
- Jensen, K. (1994) 'Test procedures for rowing', *FISA Coach*, 5, pp. 1-6.
- Jensen, K. & Nielsen, T. (1993) 'High altitude training does not increase maximum oxygen uptake or work capacity at sea level in rowers', *Scandinavian Journal of Medicine and Science in Sports*, 3, pp. 56-62.
- Jeukendrup, A. E., Hesselink, M. K., Snyder, A. C., Kuipers, H. & Keizer, H. A. (1992) 'Physiological changes in male competitive cyclists after two weeks of intensified training', *International Journal of Sports Medicine*, 13 (7), pp. 534-541.
- Jones, D. A., Newham, D. J., Round, J. M. & Tolfree, S. E. (1986) 'Experimental human muscle damage: morphological changes in relation to other indices of damage', *Journal of Physiology*, 375, pp. 435-448.
- Joyner, M. J. & Coyle, E. F. (2008) 'Endurance exercise performance: the physiology of champions', *Journal of Physiology*, 586 (1), pp. 35-44.
- Jurimae, J., Maestu, J., Purge, P. & Jurimae, T. (2004) 'Changes in stress and recovery after heavy training in rowers', *Journal of Science and Medicine in Sport*, 7 (3), pp. 335-339.
- Jurimae, J., Maestu, J., Purge, P., Jurimae, T. & Soot, T. (2002) 'Relations among heavy training stress, mood state, and performance for male junior rowers', *Perceptual and Motor Skills*, 95 (2), pp. 520-526.
- Kendall, B. & Eston, R. (2002) 'Exercise-induced muscle damage and the potential protective role of estrogen', *Sports Medicine*, 32 (2), pp. 103-123.
- Kennedy, M. D. & Bell, G. J. (2003) 'Development of race profiles for the performance of a simulated 2000-m rowing race', *Canadian Journal of Applied Physiology*, 28 (4), pp. 536-546.
- Kerr, D. A., Ross, W. D., Norton, K., Hume, P., Kagawa, M. & Ackland, T. R. (2007) 'Olympic lightweight and open-class rowers possess distinctive physical and proportionality characteristics', *Journal of Sports Sciences*, 25 (1), pp. 43-53.
- Kipp, K., Harris, C. & Sabick, M. B. (2011) 'Lower extremity biomechanics during weightlifting exercise vary across joint and load', *Journal of Strength and Conditioning Research*, 25 (5), pp. 1229-1234.
- Kleshnev, V. & Kleshnev, I. (1998) 'Dependence of rowing performance and efficiency on motor coordination of the main body segments', *Journal of Sports Sciences*, 16 (5), pp. 418-419.
- Knutson, L. M., Soderberg, G. L., Ballantyne, B. T. & Clarke, W. R. (1994) 'A study of various normalization procedures for within day electromyographic data', *Journal of Electromyography and Kinesiology*, 4 (1), pp. 47-59.

- Kokallas, N., Tsalis, G., Tsigilis, N. & Mougios, V. (2004) 'Hormonal responses to three training protocols in rowing', *European Journal of Applied Physiology*, 92 (1-2), pp. 128-132.
- Komi, P. V. & Buskirk, E. R. (1972) 'Effect of eccentric and concentric muscle conditioning on tension and electrical activity of human muscle', *Ergonomics*, 15 (4), pp. 417-434.
- Kraemer, W. J. (1997) 'A series of studies - The physiological basis for strength training in American Football: Fact over philosophy', *Journal of Strength and Conditioning Research*, 11 (3), pp. 131-142.
- Kraemer, W. J., Fry, A. C., Warren, B. J., Stone, M. H., Fleck, S. J., Kearney, J. T., Conroy, B. P., Maresh, C. M., Weseman, C. A., Triplett, N. T. & et al. (1992) 'Acute hormonal responses in elite junior weightlifters', *International Journal of Sports Medicine*, 13 (2), pp. 103-109.
- Kraemer, W. J. & Ratamess, N. A. (2005) 'Hormonal responses and adaptations to resistance exercise and training.', *Sports Medicine*, 35, pp. 339-361.
- Kraemer, W. J., Ratamess, N. A., Volek, J. S., Hakkinen, K., Rubin, M. R., French, D. N., Gomez, A. L., McGuigan, M. R., Scheett, T. P., Newton, R. U., Spiering, B. A., Izquierdo, M. & Dioguardi, F. S. (2006) 'The effects of amino acid supplementation on hormonal responses to resistance training overreaching', *Metabolism: Clinical and Experimental*, 55 (3), pp. 282-291.
- Kramer, J. F., Morrow, A. & Leger, A. (1993) 'Changes in rowing ergometer, weight lifting, vertical jump and isokinetic performance in response to standard and standard plus plyometric training programs', *International Journal of Sports Medicine*, 14 (8), pp. 449-454.
- Kuipers, H. & Keizer, H. A. (1988) 'Overtraining in elite athletes. Review and directions for the future', *Sports Medicine*, 6 (2), pp. 79-92.
- Labs, K. H., Tschoepl, M., Gamba, G., Aschwanden, M. & Jaeger, K. A. (2000) 'The reliability of leg circumference assessment: a comparison of spring tape measurements and optoelectronic volumetry', *Vascular Medicine*, 5 (2), pp. 69-74.
- Lakomy, H. K. & Lakomy, J. (1993) 'Estimation of maximum oxygen uptake from submaximal exercise on a Concept II rowing ergometer', *Journal of Sports Sciences*, 11 (3), pp. 227-232.
- Larsson, L. & Forsberg, A. (1980) 'Morphological muscle characteristics in rowers', *Canadian Journal of Applied Sport Sciences*, 5 (4), pp. 239-244.
- Lavender, A. P. & Nosaka, K. (2008) 'A light load eccentric exercise confers protection against a subsequent bout of more demanding eccentric exercise', *Journal of Science and Medicine in Sport*, 11 (3), pp. 291-298.
- Lawton, T. W., Cronin, J. B. & McGuigan, M. R. (2011) 'Strength testing and training of rowers: a review', *Sports Medicine*, 41 (5), pp. 413-432.

- Lay, B. S., Sparrow, W. A., Hughes, K. M. & O'Dwyer, N. J. (2002) 'Practice effects on coordination and control, metabolic energy expenditure, and muscle activation', *Hum Mov Sci*, 21 (5-6), pp. 807-830.
- Lehmann, M., Dickhuth, H. H., Gendrisch, G., Lazar, W., Thum, M., Kaminski, R., Aramendi, J. F., Peterke, E., Wieland, W. & Keul, J. (1991) 'Training-overtraining. A prospective, experimental study with experienced middle- and long-distance runners', *International Journal of Sports Medicine*, 12 (5), pp. 444-452.
- Leveritt, M., MacLaughlin, H. & Abernethy, P. J. (2000) 'Changes in leg strength 8 and 32 h after endurance exercise', *Journal of Sports Sciences*, 18 (11), pp. 865-871.
- Linnamo, V., Pakarinen, A., Komi, P. V., Kraemer, W. J. & Hakkinen, K. (2005) 'Acute hormonal responses to submaximal and maximal heavy resistance and explosive exercises in men and women', *Journal of Strength and Conditioning Research*, 19 (3), pp. 566-571.
- Lohman, T. G. R., A.F. Martorell, R. (ed.) (1988) *Anthropometric Standardization Reference Manual*. Champaign, Illinois: Human Kinetics.
- Machado, M., Koch, A. J., Willardson, J. M., Pereira, L. S., Cardoso, M. I., Motta, M. K., Pereira, R. & Monteiro, A. N. (2011) 'Effect of varying rest intervals between sets of assistance exercises on creatine kinase and lactate dehydrogenase responses', *Journal of Strength and Conditioning Research*, 25 (5), pp. 1339-1345.
- MacIntyre, D. L., Reid, W. D., Lyster, D. M., Szasz, I. J. & McKenzie, D. C. (1996) 'Presence of WBC, decreased strength, and delayed soreness in muscle after eccentric exercise', *Journal of Applied Physiology*, 80 (3), pp. 1006-1013.
- Maestu, J., Cicchella, A., Purge, P., Ruosi, S., Jurimae, J. & Jurimae, T. (2006) 'Electromyographic and neuromuscular fatigue thresholds as concepts of fatigue', *Journal of Strength and Conditioning Research*, 20 (4), pp. 824-828.
- Maestu, J., Jurimae, J. & Jurimae, T. (2005a) 'Hormonal response to maximal rowing before and after heavy increase in training volume in highly trained male rowers', *Journal of Sports Medicine and Physical Fitness*, 45 (1), pp. 121-126.
- Maestu, J., Jurimae, J. & Jurimae, T. (2005b) 'Monitoring of performance and training in rowing', *Sports Medicine*, 35 (7), pp. 597-617.
- Magnusen, M. J. (2010) 'Differences in strength and conditioning coach self-perception of leadership style behaviors at the National Basketball Association, Division I-A, and Division II levels', *Journal of Strength and Conditioning Research*, 24 (6), pp. 1440-1450.
- Marcora, S. M. & Bosio, A. (2007) 'Effect of exercise-induced muscle damage on endurance running performance in humans', *Scandinavian Journal of Medicine and Science in Sports*, 17, pp. 662-671.
- Marginson, V., Rowlands, A. V., Gleeson, N. P. & Eston, R. G. (2005) 'Comparison of the symptoms of exercise-induced muscle damage after an initial and repeated bout of plyometric exercise in men and boys', *Journal of Applied Physiology*, 99 (3), pp. 1174-1181.

- Markovic, G., Dizdar, D., Jukic, I. & Cardinale, M. (2004) 'Reliability and factorial validity of squat and countermovement jump tests', *Journal of Strength and Conditioning Research*, 18 (3), pp. 551-555.
- Marlow, L. (2002) 'Basketball conditioning: Power. ', *Courtside: Official Magazine of Basketball Coaches Association*, 14.
- Massey, C. D., Maneval, M. W., Phillips, J., Vincent, J., White, G. & Zoeller, B. (2002) 'An analysis of teaching and coaching behaviors of elite strength and conditioning coaches', *Journal of Strength and Conditioning Research*, 16 (3), pp. 456-460.
- McBride, J. M., Triplett-McBride, T., Davie, A. & Newton, R. U. (1999) 'A Comparison of Strength and Power Characteristics Between Power Lifters, Olympic Lifters, and Sprinters', *Journal of Strength and Conditioning Research*, 13 (1), pp. 58-66.
- McBride, J. M. R., R. Mangino, L. McCormick, M. McCormick, T. Volek, J. Bush, J.A. Augilera, B. Newton, R.U. and Kraemer, W.J. (1995) 'Responses of Serum Creatine Kinase Activity to Heavy Resistance Exercise in Endurance and Recreationally Trained Women', *Journal of Strength and Conditioning Research*, 9 (3), pp. 139-142.
- McGregor, A., Anderton, L. & Gedroyc, W. (2002) 'The assessment of intersegmental motion and pelvic tilt in elite oarsmen', *Medicine and Science in Sports and Exercise*, 34 (7), pp. 1143-1149.
- McGregor, A. H., Bull, A. M. & Byng-Maddick, R. (2004) 'A comparison of rowing technique at different stroke rates: a description of sequencing, force production and kinematics', *International Journal of Sports Medicine*, 25 (6), pp. 465-470.
- McHugh, M. P. (2003) 'Recent advances in the understanding of the repeated bout effect: the protective effect against muscle damage from a single bout of eccentric exercise', *Scandinavian Journal of Medicine and Science in Sports*, 13 (2), pp. 88-97.
- McHugh, M. P., Connolly, D. A., Eston, R. G., Gattman, E. J. & Gleim, G. W. (2001) 'Electromyographic analysis of repeated bouts of eccentric exercise', *Journal of Sports Sciences*, 19 (3), pp. 163-170.
- McNeely, E. (2001) 'How strong is strong enough', *Rowing Canada Magazine*, 24, pp. 24-26.
- McNeely, E., Sandler, D. & Bamel, S. (2005) 'Strength and power goals for competitive rowers', *Strength and Conditioning Journal*, 27 (3), pp. 10-15.
- Messonnier, L., Aranda-Berthouze, S. E., Bourdin, M., Bredel, Y. & Lacour, J. R. (2005) 'Rowing performance and estimated training load', *International Journal of Sports Medicine*, 26 (5), pp. 376-382.
- Messonnier, L., Freund, H., Bourdin, M., Belli, A. & Lacour, J. R. (1997) 'Lactate exchange and removal abilities in rowing performance', *Medicine and Science in Sports and Exercise*, 29 (3), pp. 396-401.

- Meyer, T., Davison, R. C. & Kindermann, W. (2005) 'Ambulatory gas exchange measurements--current status and future options', *International Journal of Sports Medicine*, 26 Suppl 1, pp. S19-27.
- Mikulic, P. (2008) 'Anthropometric and physiological profiles of rowers of varying ages and ranks', *Kinesiology*, 40 (1), pp. 80-88.
- Mikulic, P. (2009) 'Anthropometric and metabolic determinants of 6,000-m rowing ergometer performance in internationally competitive rowers', *Journal of Strength and Conditioning Research*, 23 (6), pp. 1851-1857.
- Mikulic, P., Smoljanovic, T., Bojanic, I., Hannafin, J. & Pedisic, Z. (2009a) 'Does 2000-m rowing ergometer performance time correlate with final rankings at the World Junior Rowing Championship? A case study of 398 elite junior rowers', *Journal of Sports Sciences*, 27 (4), pp. 361-366.
- Mikulic, P., Smoljanovic, T., Bojanic, I., Hannafin, J. A. & Matkovic, B. R. (2009b) 'Relationship between 2000-m rowing ergometer performance times and World Rowing Championships rankings in elite-standard rowers', *Journal of Sports Sciences*, 27 (9), pp. 907-913.
- Miles, M. P. & Clarkson, P. M. (1994) 'Exercise-induced muscle pain, soreness, and cramps', *Journal of Sports Medicine and Physical Fitness*, 34 (3), pp. 203-216.
- Miletello, W. M., Beam, J. R. & Cooper, Z. C. (2009) 'A biomechanical analysis of the squat between competitive collegiate, competitive high school, and novice powerlifters', *Journal of Strength and Conditioning Research*, 23 (5), pp. 1611-1617.
- Miyama, M. & Nosaka, K. (2007) 'Protection against muscle damage following fifty drop jumps conferred by ten drop jumps', *Journal of Strength and Conditioning Research*, 21 (4), pp. 1087-1092.
- Morgan, D. L. & Allen, D. G. (1999) 'Early events in stretch-induced muscle damage', *Journal of Applied Physiology*, 87 (6), pp. 2007-2015.
- Morgan, D. L. & Proske, U. (2004) 'Popping sarcomere hypothesis explains stretch-induced muscle damage', *Clinical and Experimental Pharmacology and Physiology*, 31, pp. 541-545.
- Nevill, A. M., Allen, S. V. & Ingham, S. A. (2011) 'Modelling the determinants of 2000 m rowing ergometer performance: a proportional, curvilinear allometric approach', *Scandinavian Journal of Medicine and Science in Sports*, 21 (1), pp. 73-78.
- Newham, D. J., Jones, D. A. & Clarkson, P. M. (1987) 'Repeated high-force eccentric exercise: effects on muscle pain and damage', *Journal of Applied Physiology*, 63 (4), pp. 1381-1386.
- Newton, R. U., Hakkinen, K., Hakkinen, A., McCormick, M., Volek, J. & Kraemer, W. J. (2002) 'Mixed-methods resistance training increases power and strength of young and older men', *Medicine and Science in Sports and Exercise*, 34 (8), pp. 1367-1375.

- Ng, J. K., Kippers, V. & Richardson, C. A. (1998) 'Muscle fibre orientation of abdominal muscles and suggested surface EMG electrode positions', *Electromyography and Clinical Neurophysiology*, 38 (1), pp. 51-58.
- Nicholson, G. A., Morgan, G., Meerkin, M., Strauss, E. & McLeod, J. G. (1985) 'The creatine kinase reference interval. An assessment of intra- and inter-individual variation', *Journal of the Neurological Sciences*, 71 (2-3), pp. 225-231.
- Noakes, T. D., St Clair Gibson, A. & Lambert, E. V. (2004) 'From catastrophe to complexity: a novel model of integrative central neural regulation of effort and fatigue during exercise in humans', *British Journal of Sports Medicine*, 38 (4), pp. 511-514.
- Norrbrand, L., Pozzo, M. & Tesch, P. A. (2010) 'Flywheel resistance training calls for greater eccentric muscle activation than weight training', *European Journal of Applied Physiology*, 110 (5), pp. 997-1005.
- Nosaka, K. & Clarkson, P. M. (1995) 'Muscle damage following repeated bouts of high force eccentric exercise', *Medicine and Science in Sports and Exercise*, 27 (9), pp. 1263-1269.
- Nosaka, K. & Clarkson, P. M. (1996) 'Variability in serum creatine kinase response after eccentric exercise of the elbow flexors', *International Journal of Sports Medicine*, 17 (2), pp. 120-127.
- Nosaka, K. & Newton, M. (2002) 'Repeated eccentric exercise bouts do not exacerbate muscle damage and repair', *Journal of Strength and Conditioning Research*, 16 (1), pp. 117-122.
- Nosaka, K., Sakamoto, K., Newton, M. & Sacco, P. (2001) 'How long does the protective effect on eccentric exercise-induced muscle damage last?', *Medicine and Science in Sports and Exercise*, 33 (9), pp. 1490-1495.
- Paddon-Jones, D., Muthalib, M. & Jenkins, D. (2000) 'The effects of a repeated bout of eccentric exercise on indices of muscle damage and delayed onset muscle soreness', *Journal of Science and Medicine in Sport*, 3 (1), pp. 35-43.
- Palmer, C. L., Burwitz, L., Dyer, A. N. & Spray, C. M. (2005) 'Endurance training adherence in elite junior netball athletes: a test of the theory of planned behaviour and a revised theory of planned behaviour', *Journal of Sports Sciences*, 23 (3), pp. 277-288.
- Parkin, S., Nowicky, A. V., Rutherford, O. M. & McGregor, A. H. (2001) 'Do oarsmen have asymmetries in the strength of their back and leg muscles?', *Journal of Sports Sciences*, 19 (7), pp. 521-526.
- Paschalis, V., Koutedakis, Y., Baltzopoulos, V., Mougios, V., Jamurtas, A. Z. & Theoharis, V. (2005b) 'The effects of muscle damage on running economy in healthy males', *International Journal of Sports Medicine*, 26 (10), pp. 827-831.
- Paschalis, V., Koutedakis, Y., Jamurtas, A. Z., Mougios, V. & Baltzopoulos, V. (2005a) 'Equal volumes of high and low intensity of eccentric exercise in relation to muscle

- damage and performance', *Journal of Strength and Conditioning Research*, 19 (1), pp. 184-188.
- Patton, M. Q. (ed.) (1990) *Qualitative evaluation and research methods (2nd ed)*. . Newbury Park, CA: Sage Publications.
- Peterson, M. D., Alvar, B. A. & Rhea, M. R. (2006) 'The contribution of maximal force production to explosive movement among young collegiate athletes', *Journal of Strength and Conditioning Research*, 20 (4), pp. 867-873.
- Pollitt, D. J. (2003) 'Sled dragging for hockey training', *Strength and Conditioning Journal*, 25 (3), pp. 7-16.
- Potteiger, J. A. L., R.H. Haub, M.D. Dolezal, B.A. Alumzaini, K.S. Schroeder, J.M. Zebas, C.J. (1999) 'Muscle power and fiber characteristic following 8 weeks of plyometric training', *Journal of Strength and Conditioning Research*, 13 (3), pp. 275-279.
- Pripstein, L. P., Rhodes, E. C., McKenzie, D. C. & Coutts, K. D. (1999) 'Aerobic and anaerobic energy during a 2-km race simulation in female rowers', *Eur J Appl Physiol Occup Physiol*, 79 (6), pp. 491-494.
- Proske, U. & Allen, T. J. (2005) 'Damage to skeletal muscle from eccentric exercise', *Exercise and Sport Sciences Reviews*, 33 (2), pp. 98-104.
- Proske, U., Gregory, J. E., Morgan, D. L., Percival, P., Weerakkody, N. S. & Canny, B. J. (2004) 'Force matching errors following eccentric exercise', *Hum Mov Sci*, 23 (3-4), pp. 365-378.
- Proske, U. & Morgan, D. L. (2001) 'Muscle damage from eccentric exercise: mechanism, mechanical signs, adaptation and clinical applications', *Journal of Physiology*, 537 (Pt 2), pp. 333-345.
- Raastad, T., Glomsheller, T., Bjoro, T. & Hallen, J. (2001) 'Changes in human skeletal muscle contractility and hormone status during 2 weeks of heavy strength training', *European Journal of Applied Physiology*, 84 (1-2), pp. 54-63.
- Raastad, T., Glomsheller, T., Bjoro, T. & Hallen, J. (2003) 'Recovery of skeletal muscle contractility and hormonal responses to strength exercise after two weeks of high-volume strength training', *Scandinavian Journal of Medicine and Science in Sports*, 13 (3), pp. 159-168.
- Raastad, T. & Hallen, J. (2000) 'Recovery of skeletal muscle contractility after high- and moderate-intensity strength exercise', *European Journal of Applied Physiology*, 82 (3), pp. 206-214.
- Rawson, E. S., Conti, M. P. & Miles, M. P. (2007) 'Creatine supplementation does not reduce muscle damage or enhance recovery from resistance exercise', *Journal of Strength and Conditioning Research*, 21 (4), pp. 1208-1213.
- Requena, B., Gonzalez-Badillo, J. J., de Villareal, E. S., Ereline, J., Garcia, I., Gapeyeva, H. & Paasuke, M. (2009) 'Functional performance, maximal strength, and power characteristics in isometric and dynamic actions of lower extremities in soccer players', *Journal of Strength and Conditioning Research*, 23 (5), pp. 1391-1401.

- Reverter-Masia, J., Legaz-Arrese, A., Munguia-Izquierdo, D., Barbany, J. R. & Serrano-Ostariz, E. (2009) 'A profile of the resistance training practices of elite Spanish club teams', *Journal of Strength and Conditioning Research*, 23 (5), pp. 1537-1547.
- Riechman, S. E., Zoeller, R. F., Balasekaran, G., Goss, F. L. & Robertson, R. J. (2002) 'Prediction of 2000 m indoor rowing performance using a 30 s sprint and maximal oxygen uptake', *Journal of Sports Sciences*, 20 (9), pp. 681-687.
- Rodriguez, R. J., Rogriguez, R. P., Cook, S. D. & Sandborn, P. M. (1990) 'Electromyographic analysis of rowing stroke biomechanics', *Journal of Sports Medicine and Physical Fitness*, 30 (1), pp. 103-108.
- Roig, M., O'Brien, K., Kirk, G., Murray, R., McKinnon, P., Shadgan, B. & Reid, W. D. (2009) 'The effects of eccentric versus concentric resistance training on muscle strength and mass in healthy adults: a systematic review with meta-analysis', *British Journal of Sports Medicine*, 43 (8), pp. 556-568.
- Rosier, E. M., Iadarola, M. J. & Coghill, R. C. (2002) 'Reproducibility of pain measurement and pain perception', *Pain*, 98 (1-2), pp. 205-216.
- Rowlands, A. V., Eston, R. G. & Tilzey, C. (2001) 'Effect of stride length manipulation on symptoms of exercise-induced muscle damage and the repeated bout effect', *Journal of Sports Sciences*, 19 (5), pp. 333-340.
- Roy, B. D. & Tarnopolsky, M. A. (1998) 'Influence of differing macronutrient intakes on muscle glycogen resynthesis after resistance exercise', *Journal of Applied Physiology*, 84 (3), pp. 890-896.
- Russell, A. P., Le Rossignol, P. F. & Sparrow, W. A. (1998) 'Prediction of elite schoolboy 2000m rowing ergometer performance from metabolic, anthropometric and strength variables', *Journal of Sports Sciences*, 16 (8), pp. 749-754.
- Rutherford, O. M., Jones, D. A. & Newham, D. J. (1986) 'Clinical and experimental application of the percutaneous twitch superimposition technique for the study of human muscle activation', *Journal of Neurology, Neurosurgery and Psychiatry*, 49 (11), pp. 1288-1291.
- Sargeant, A. J. (2007) 'Structural and functional determinants of human muscle power', *Experimental Physiology*, 92 (2), pp. 323-331.
- Saxton, J. M. & Donnelly, A. E. (1996) 'Length-specific impairment of skeletal muscle contractile function after eccentric muscle actions in man', *Clinical Science*, 90 (2), pp. 119-125.
- Schabort, E. J., Hawley, J. A., Hopkins, W. G. & Blum, H. (1999) 'High reliability of performance of well-trained rowers on a rowing ergometer', *Journal of Sports Sciences*, 17 (8), pp. 627-632.
- Schabort, E. J., Hawley, J. A., Hopkins, W. G., Mujika, I. & Noakes, T. D. (1998) 'A new reliable laboratory test of endurance performance for road cyclists', *Medicine and Science in Sports and Exercise*, 30 (12), pp. 1744-1750.

- Scott, K. E., Rozenek, R., Russo, A. C., Crussemeyer, J. A. & Lacourse, M. G. (2003) 'Effects of delayed onset muscle soreness on selected physiological responses to submaximal running', *Journal of Strength and Conditioning Research*, 17 (4), pp. 652-658.
- Secher, N. (1993a) 'The physiology of rowing', *Sports Medicine*, 15, pp. 23-53.
- Secher, N. H. (1975) 'Isometric rowing strength of experienced and inexperienced oarsmen', *Medicine and Science in Sports*, 7 (4), pp. 280-283.
- Secher, N. H. (1993b) 'Physiological and biomechanical aspects of rowing. Implications for training', *Sports Medicine*, 15 (1), pp. 24-42.
- Secher, N. H. V., O. and Jackson, R. (1982) 'Rowing performance and maximal aerobic power of oarsmen', *Scandinavian Journal of Sports Sciences*, 4 (1), pp. 9-11.
- Semark, A., Noakes, T., St. Clair Gibson, A. & Lambert, M. (1999) 'The effect of a prophylactic dose of flurbiprofen on muscle soreness and sprinting performance in trained subjects', *Journal of Sports Sciences*, 17 (3), pp. 197-203.
- Shephard, R. J. (1998) 'Science and medicine of rowing: A review', *Journal of Sports Sciences*, 16, pp. 603-620.
- Simenz, C. J., Dugan, C. A. & Ebben, W. P. (2005) 'Strength and conditioning practices of National Basketball Association strength and conditioning coaches', *Journal of Strength and Conditioning Research*, 19 (3), pp. 495-504.
- Skurvydas, A., Kamandulis, S., Stanislovaitis, A., Streckis, V., Mamkus, G. & Drazdauskas, A. (2008) 'Leg immersion in warm water, stretch-shortening exercise, and exercise-induced muscle damage', *Journal of Athletic Training*, 43 (6), pp. 592-599
- Skurvydas, A., Streckis, V., Mickeviciene, D., Kamandulis, S., Stanislovaitis, A. & Mamkus, G. (2006) 'Effect of age on metabolic fatigue and on indirect symptoms of skeletal muscle damage after stretch-shortening exercise', *Journal of Sports Medicine and Physical Fitness*, 46 (3), pp. 431-441.
- Slater, G. J., Rice, A. J., Mujika, I., Hahn, A. G., Sharpe, K. & Jenkins, D. G. (2005) 'Physique traits of lightweight rowers and their relationship to competitive success', *British Journal of Sports Medicine*, 39 (10), pp. 736-741.
- Smith, J. C. & Hill, D. W. (1991) 'Contribution of energy systems during a Wingate power test', *British Journal of Sports Medicine*, 25 (4), pp. 196-199.
- Smith, L. L., Fulmer, M. G., Holbert, D., McCammon, M. R., Houmard, J. A., Frazer, D. D., Nsien, E. & Israel, R. G. (1994) 'The impact of a repeated bout of eccentric exercise on muscular strength, muscle soreness and creatine kinase', *British Journal of Sports Medicine*, 28 (4), pp. 267-271.
- Soper, C. & Hume, P. A. (2004) 'Reliability of power output during rowing changes with ergometer type and race distance', *Sports Biomechanics*, 3 (2), pp. 237-248.

- Souza, A. L., Shimada, S. D. & Koontz, A. (2002) 'Ground reaction forces during the power clean', *Journal of Strength and Conditioning Research*, 16 (3), pp. 423-427.
- Spiering, B. A., Kraemer, W. J., Vingren, J. L., Hatfield, D. L., Fragala, M. S., Ho, J. Y., Maresh, C. M., Anderson, J. M. & Volek, J. S. (2007) 'Responses of criterion variables to different supplemental doses of L-carnitine L-tartrate', *Journal of Strength and Conditioning Research*, 21 (1), pp. 259-264.
- Sporer, B. C. & Wenger, H. A. (2003) 'Effects of aerobic exercise on strength performance following various periods of recovery', *Journal of Strength and Conditioning Research*, 17 (4), pp. 638-644.
- St Clair Gibson, A., Lambert, E. V., Rauch, L. H., Tucker, R., Baden, D. A., Foster, C. & Noakes, T. D. (2006) 'The role of information processing between the brain and peripheral physiological systems in pacing and perception of effort', *Sports Medicine*, 36 (8), pp. 705-722.
- St Clair Gibson, A. & Noakes, T. D. (2004) 'Evidence for complex system integration and dynamic neural regulation of skeletal muscle recruitment during exercise in humans', *British Journal of Sports Medicine*, 38 (6), pp. 797-806.
- Steinacker, J., Lormes, W., Lehmann, M. & Altenburg, D. (1998) 'Training of rowers before world championships', *Medicine and Science in Sports and Exercise*, 30 (7), pp. 1158-1163.
- Steinacker, J. M. (1993) 'Physiological aspects of training in rowing', *International Journal of Sports Medicine*, 14 Suppl 1, pp. S3-10.
- Steinacker, J. M., Laske, R., Hetzel, W. D., Lormes, W., Liu, Y. & Stauch, M. (1993) 'Metabolic and hormonal reactions during training in junior oarsmen', *International Journal of Sports Medicine*, 14 Suppl 1, pp. S24-28.
- Steinacker, J. M., Lormes, W., Kellmann, M., Liu, Y., Reissnecker, S., Opitz-Gress, A., Baller, B., Gunther, K., Petersen, K. G., Kallus, K. W., Lehmann, M. & Altenburg, D. (2000) 'Training of junior rowers before world championships. Effects on performance, mood state and selected hormonal and metabolic responses', *Journal of Sports Medicine and Physical Fitness*, 40 (4), pp. 327-335.
- Steinacker, J. M., Marx, T. R., Marx, U. & Lormes, W. (1986) 'Oxygen consumption and metabolic strain in rowing ergometer exercise', *Eur J Appl Physiol Occup Physiol*, 55 (3), pp. 240-247.
- Stodden, D. F., Fleisig, G. S., McLean, S. P. & Andrews, J. R. (2005) 'Relationship of biomechanical factors to baseball pitching velocity: within pitcher variation', *Journal of Applied Biomechanics*, 21 (1), pp. 44-56.
- Stone, M. R., Thomas, K., Wilkinson, M., St Clair Gibson, A. & Thompson, K. G. (2011) 'Consistency of perceptual and metabolic responses to a laboratory-based simulated 4,000-m cycling time trial', *European Journal of Applied Physiology*, 111 (8), pp. 1807-1813.

- Stutchfield, B. M. & Coleman, S. (2006) 'The relationships between hamstring flexibility, lumbar flexion, and low back pain in rowers', *European Journal of Sport Science*, 6 (4), pp. 255-260.
- Sutherland, T. M. & Wiley, J. P. (1997) 'Survey of strength and conditioning services for professional athletes in four sports', *Journal of Strength and Conditioning Research*, 11 (4), pp. 266-268.
- Swart, J. & Jennings, C. L. (2004) 'Use of blood lactate concentration as a marker of training status : review article', *South African Journal of Sports Medicine*, 16 (3), pp. 1-5.
- Swinton, P. A., Lloyd, R., Agouris, I. & Stewart, A. (2009) 'Contemporary training practices in elite British powerlifters: survey results from an international competition', *Journal of Strength and Conditioning Research*, 23 (2), pp. 380-384.
- Syrotuik, D. G., Game, A. B., Gillies, E. M. & Bell, G. J. (2001) 'Effects of creatine monohydrate supplementation during combined strength and high intensity rowing training on performance', *Canadian Journal of Applied Physiology*, 26 (6), pp. 527-542.
- Szymanski, D. J., Szymanski, J. M., Molloy, J. M. & Pascoe, D. D. (2004) 'Effect of 12 weeks of wrist and forearm training on high school baseball players', *Journal of Strength and Conditioning Research*, 18 (3), pp. 432-440.
- Tachibana, K., Yashiro, K., Miyazaki, J., Ikegami, Y. & Higuchi, M. (2007) 'Muscle cross-sectional areas and performance power of limbs and trunk in the rowing motion', *Sports Biomechanics*, 6 (1), pp. 44-58.
- Takekura, H., Fujinami, N., Nishizawa, T., Ogasawara, H. & Kasuga, N. (2001) 'Eccentric exercise-induced morphological changes in the membrane systems involved in excitation-contraction coupling in rat skeletal muscle', *Journal of Physiology*, 533 (Pt 2), pp. 571-583.
- Tamborra, S. (ed.) (2008) *Complete Conditioning for Baseball*. Champaign, Illinois: Human Kinetics.
- Thomas, K., Stone, M. R., Thompson, K. G., St Clair Gibson, A. & Ansley, L. (2012) 'Reproducibility of pacing strategy during simulated 20-km cycling time trials in well-trained cyclists', *European Journal of Applied Physiology*, 112 (1), pp. 223-229.
- Tofas, T., Jamurtas, A. Z., Fatouros, I., Nikolaidis, M. G., Koutedakis, Y., Sinouris, E. A., Papageorgakopoulou, N. & Theocharis, D. A. (2008) 'Plyometric exercise increases serum indices of muscle damage and collagen breakdown', *Journal of Strength and Conditioning Research*, 22 (2), pp. 490-496.
- Totsuka, M., Nakaji, S., Suzuki, K., Sugawara, K. & Sato, K. (2002) 'Break point of serum creatine kinase release after endurance exercise', *Journal of Applied Physiology*, 93 (4), pp. 1280-1286.

- Tricoli, V., Lamas, L., Carnevale, R. & Ugrinowitsch, C. (2005) 'Short-term effects on lower-body functional power development: weightlifting vs. vertical jump training programs', *Journal of Strength and Conditioning Research*, 19 (2), pp. 433-437.
- Tse, M. A., McManus, A. M. & Masters, R. S. (2005) 'Development and validation of a core endurance intervention program: implications for performance in college-age rowers', *Journal of Strength and Conditioning Research*, 19 (3), pp. 547-552.
- Twist, C. & Eston, R. (2005) 'The effects of exercise-induced muscle damage on maximal intensity intermittent exercise performance ', *European Journal of Applied Physiology*, 94 (5-6), pp. 652-658.
- Twist, C. & Eston, R. G. (2007) 'The effect of muscle-damaging exercise on maximal intensity cycling and drop jump performance', *Journal of Exercise Science & Fitness*, 5 (2), pp. 79-87.
- Twist, C. & Eston, R. G. (2009) 'The effect of exercise-induced muscle damage on perceived exertion and cycling endurance performance', *European Journal of Applied Physiology*, 105 (4), pp. 559-567.
- Twist, C., Gleeson, N. & Eston, R. (2008) 'The effects of plyometric exercise on unilateral balance performance', *Journal of Sports Sciences*, 26 (10), pp. 1073-1080.
- Urhausen, A., Kullmer, T. & Kindermann, W. (1987) 'A 7-week follow-up study of the behaviour of testosterone and cortisol during the competition period in rowers', *Eur J Appl Physiol Occup Physiol*, 56 (5), pp. 528-533.
- Van Borselen, F., Vos, N. H., Fry, A. C. & Kraemer, W. J. (1992) 'The role of anaerobic exercise in overtraining', *National Strength and Conditioning Association Journal*, 14 (3), pp. 74-79.
- Vervoorn, C., Vermulst, L. J., Boelens-Quist, A. M., Koppeschaar, H. P., Erich, W. B., Thijssen, J. H. & de Vries, W. R. (1992) 'Seasonal changes in performance and free testosterone: cortisol ratio of elite female rowers', *Eur J Appl Physiol Occup Physiol*, 64 (1), pp. 14-21.
- Viale, F., Nana-Ibrahim, S. & Martin, R. J. (2007) 'Effect of active recovery on acute strength deficits induced by passive stretching', *Journal of Strength and Conditioning Research*, 21 (4), pp. 1233-1237.
- Volianitis, S. & Secher, N. H. (2009) 'Rowing, the ultimate challenge to the human body - implications for physiological variables', *Clinical Physiology and Functional Imaging*, 29 (4), pp. 241-244.
- Warren, B. J., Stone, M. H., Kearney, J. T., Fleck, S. J., Johnson, R. L., Wilson, G. D. & Kraemer, W. J. (1992) 'Performance measures, blood lactate and plasma ammonia as indicators of overwork in elite junior weightlifters', *International Journal of Sports Medicine*, 13 (5), pp. 372-376.
- Warren, G. L., Ingalls, C. P., Lowe, D. A. & Armstrong, R. B. (2001) 'Excitation-contraction uncoupling: major role in contraction-induced muscle injury', *Exercise and Sport Sciences Reviews*, 29 (2), pp. 82-87.

- Warren, G. L., Lowe, D. A., Hayes, D. A., Karwoski, C. J., Prior, B. M. & Armstrong, R. B. (1993) 'Excitation failure in eccentric contraction-induced injury of mouse soleus muscle', *Journal of Physiology*, 468, pp. 487-499.
- Webster, T. G., Gervais, P. L., Syrotuik, D. G. & Bell, G. J. (2006) 'The combined effects of 8-weeks aerobic and resistance training on simulated 2000-meter rowing performance and the related biomechanical and physiological determinants in men and women', *Advances in Exercise and Sports Physiology*, 12 (4), pp. 135-143.
- Wilberg, R. B. & Pratt, J. (1988) 'A survey of the race profiles of cyclists in the pursuit and kilo track events', *Canadian Journal of Sport Sciences*, 13 (4), pp. 208-213.
- Williford, H. N., Kirkpatrick, J., Scharff-Olson, M., Blessing, D. L. & Wang, N. Z. (1994) 'Physical and performance characteristics of successful high school football players', *American Journal of Sports Medicine*, 22 (6), pp. 859-862.
- Wilson, J. M. J. R., D.G.E. and Stothart, J.P. (1988) 'Analysis of lower limb muscle function in ergometer rowing', *International Journal of Sports Biomechanics* 4(4), pp. 315-325.
- Xue, Q. & Yeung, E. S. (1994) 'Variability of intracellular lactate dehydrogenase isoenzymes in single human erythrocytes', *Analytical Chemistry*, 66 (7), pp. 1175-1178.
- Yoshiga, C. C. & Higuchi, M. (2003a) 'Bilateral leg extension power and fat-free mass in young oarsmen', *Journal of Sports Sciences*, 21 (11), pp. 905-909.
- Yoshiga, C. C. & Higuchi, M. (2003b) 'Rowing performance of female and male rowers', *Scandinavian Journal of Medicine and Science in Sports*, 13 (5), pp. 317-321.
- Zech, A., Witte, K. & Pfeifer, K. (2008) 'Reliability and performance-dependent variations of muscle function variables during isometric knee extension', *Journal of Electromyography and Kinesiology*, 18 (2), pp. 262-269.

Appendices

Appendix A. Informed consent



INFORMED CONSENT FORM

Project Title: **The effect of a week of strength training on 2000m rowing performance and maximal power**

Principal Investigator: Thomas Gee

Participant Number: _____

*please tick
where applicable*

I have read and understood the Participant Information Sheet.

I have had an opportunity to ask questions and discuss this study and I have received satisfactory answers.

I understand I am free to withdraw from the study at any time, without having to give a reason for withdrawing, and without prejudice.

I agree to take part in this study.

I would like to receive feedback on the overall results of the study at the email address given below. I understand that I will not receive individual feedback on my own performance.

Email address.....

Signature of participant..... Date.....

(NAME IN BLOCK LETTERS).....

Signature of Parent / Guardian in the case of a minor

.....

Signature of researcher..... Date.....

(NAME IN BLOCK LETTERS).....

FOR USE WHEN TISSUE IS BEING REMOVED BUT NOT STORED

Project Title: **The effect of a week of strength training on 2000m rowing performance and maximal power**

Principal Investigator: Thomas Gee

Participant Number: _____

I agree that the following tissue or other bodily material may be taken and used for the study:

Tissue/Bodily material	Purpose	Removal Method
Blood	Creatine Kinase, Lactate and Glucose analysis	Capillary sample via the finger tip

I understand that if the material is required for use in any other way than that explained to me, then my consent to this will be specifically sought. I understand that I will not receive specific feedback from any assessment conducted on my samples, but should any kind of abnormality be discovered then the investigator will contact me.

Signature of participant..... Date.....

Signature of Parent / Guardian in the case of a minor
..... Date.....

Signature of researcher..... Date.....

Appendix B: Strength and conditioning questionnaire pertaining to chapter 4a

STRENGTH AND CONDITIONING QUESTIONNAIRE

PERSONAL DETAILS

Age: _____ (years)

Gender: **M** / **F** (please circle)

Please state job/coaching title: _____

Coaching experience: _____ months/years

Athletes you work with:

Olympic

National

Regional

Club

University

Do you have any fellow coaching staff? If so what are their responsibilities

Membership of professional bodies (e.g. UKSCA, ARA)

Vocational Qualifications

BAWLA

UKSCA accredited

ACSM Health / Fitness Instructor

Other (Please specify) _____

Academic Qualifications

Bachelors Degree

Was the Bachelors degree in a exercise science or related field? Yes No

Masters Degree

Was the Masters degree in a exercise science or related field? Yes No

Other (please specify)

STRENGTH AND CONDITIONING

Section 1. Physical Testing

(i). Do you conduct physical testing on your rowers?

Yes No (If No, please go to Section 2)

(ii). When do you perform testing?

Pre-season In-season Post-season

Other (please state) _____

(iii). Which fitness variables are measured and what specific tests are used?
(Please tick variables tested and indicate test(s) used)

Yes	No	Fitness Variable	Specific test(s) used to assess variable
<input type="checkbox"/>	<input type="checkbox"/>	Acceleration	_____
<input type="checkbox"/>	<input type="checkbox"/>	Agility	_____
<input type="checkbox"/>	<input type="checkbox"/>	Anaerobic capacity	_____
<input type="checkbox"/>	<input type="checkbox"/>	Body composition	_____
<input type="checkbox"/>	<input type="checkbox"/>	Cardiovascular Endurance	_____
<input type="checkbox"/>	<input type="checkbox"/>	Flexibility	_____
<input type="checkbox"/>	<input type="checkbox"/>	Muscular endurance	_____
<input type="checkbox"/>	<input type="checkbox"/>	Muscular power	_____
<input type="checkbox"/>	<input type="checkbox"/>	Muscular strength	_____
<input type="checkbox"/>	<input type="checkbox"/>	Speed	_____
<input type="checkbox"/>	<input type="checkbox"/>	Other	_____

Section 2. Strength / Power Development

2a. Strength / Weight Training

(i). In your opinion does strength training benefit rowing performance?

(ii). Do your rowers perform strength training?

Yes No (If No, please go to section 3, page 4)

In-season training

(i). How many days per week do the rowers participate in strength/power training during the in-season?

1 2 3 4 5 6 7

(ii). What days of the week are used for strength / power training? (*please tick where appropriate*)

Mon Tues Wed Thurs Frid Sat Sun

(iii). What is the average length (**minutes**) of the strength training sessions performed by your rowers during the in-season?

0-15 15-30 30-45 45-60 60-75 75+min

(iv). Please indicate the number of sets and reps typically used for strength training exercises In-season?

Off-season

(i). How many days per week do the rowers participate in strength/power training during the off-season?

1 2 3 4 5 6 7

(ii). Please indicate the average length (**minutes**) of the strength training sessions performed by your rowers during the off-season?

0-15 15-30 30-45 45-60 60-75 75+min

(iii). Please indicate the number of sets and reps typically used for strength training exercises in the off-season?

Program Design

(i). Do you include Olympic style weightlifting exercises in your training program (e.g. clean, snatch, jerk, hang clean)?

Yes No

(ii). What recovery time period do you prescribe between a Olympic weightlifting style strength training session (eg clean, snatch, hang clean) and a **high quality rowing session**?

Same day 24hrs 36hrs 48hrs > 48hrs

(iii). What recovery time period do you prescribe between a general strength training session (eg squat, bench press, bent over row, shoulder press) and a **high quality rowing session**?

Same day 24hrs 36hrs 48hrs > 48hrs

(iv). What recovery time period do you prescribe between a Olympic weightlifting style strength training session (eg clean, snatch, hang clean) and a **competitive rowing race**?

Same day 24hrs 36hrs 48hrs > 48hrs

(v). What recovery time period do you prescribe between a general strength training session (eg squat, bench press, bent over row, shoulder press) and a **competitive rowing race**?

Same day 24hrs 36hrs 48hrs > 48hrs

(vi). Do you believe that muscle strength and power influence 2000m rowing performance?

Strongly agree Agree Unsure Disagree Strongly disagree

(vii). List 5 **weightlifting** exercises that are most important in your program (1 = most important)?

- 1 _____
- 2 _____
- 3 _____
- 4 _____
- 5 _____

(viii). Do you use **periodisation** to structure training programs?

Yes (If yes, please indicate why below) No

(viii). How do you determine the load (weight) rowers use in typical strength training exercises?

2 b. Speed Development

(i). What training methods do you use for speed development?

2 c. Plyometrics

(i). Do you prescribe plyometrics for your rowers?

Yes No (If No, please proceed to Section 3)

(ii). Why do you prescribe plyometrics?

(iii). At what phase(s) of the year are plyometrics used?

Pre-season Post-season In-season Pre-training
Training camp Year round Other (please state below)

(iv). How do you integrate plyometrics into your training program?

(v). Please identify the plyometric exercises regularly used in your program?

YES	NO	Fitness Variable	Times per week
<input type="checkbox"/>	<input type="checkbox"/>	Bounding	
<input type="checkbox"/>	<input type="checkbox"/>	Box drills	
<input type="checkbox"/>	<input type="checkbox"/>	Depth jumps	
<input type="checkbox"/>	<input type="checkbox"/>	Jumps in place	
<input type="checkbox"/>	<input type="checkbox"/>	Multiple hops	
<input type="checkbox"/>	<input type="checkbox"/>	Standing jumps	
<input type="checkbox"/>	<input type="checkbox"/>	Upper body plyometrics	
<input type="checkbox"/>	<input type="checkbox"/>	Other (please state)	

Section 3. Flexibility Development

(i). Do your rowers perform stretching / flexibility exercises?

Yes No (If No, please proceed to Section 4)

(ii). What type of flexibility/stretching exercises are used?

Static PNF dynamic Other _____

(iii). When do the rowers perform flexibility exercises? (e.g. before rowing practice or after strength training workout- please tick below)

Before practice During practice After Practice

On their own Before workout During workout After workout

Other times (please state) _____

(iv). What is the length of a typical flexibility session?

0-5 mins 5-10 mins 10-15 mins 15-20 mins 20+mins

(v). On average, what is the length of time you encourage your rowers to hold a static stretch?

0-5 secs 5-10 secs 10-15 secs 15-20 secs 20+secs

Section 4. Unique aspects of your program

(i). What are unique aspects of your prescribed physical conditioning program?

(ii). What would you like to do differently with your physical conditioning programs?

Section 5. Any further relevant comments on your prescribed training program

Appendix C: Strength and conditioning coach interview questions pertaining to chapter 4b

Strength and conditioning coach interview questions

Background Information

- *What is your job title?*
- *What athletes do you currently work with?*
- *How long have you been involved in strength and conditioning delivery for elite rowing?*

Strength Training

- *For elite GB rowers how many strength training sessions are performed per week?*
- *With regards to a standard strength training session, what exercises, sets and reps do the rowers typically perform?*
- *In your opinion what effect, if any, does strength training have on rowing performance?*
- *Do you think Olympic lifting is an important training method for rowers, and if so why?*
- *In terms of a 2000m rowing race, at what stages of the race, if any, do you think strength and power benefit rowing performance?*

- Is the strength training programme manipulated to suit the needs of experienced rowers with a long history of strength training and younger rowers with less exposure? If so how?

- At the high performance level, are the top elite rowers also the ones who are able to lift the most weight on commonly performed strength training exercises?

- What do you believe are the common perceptions of rowing coaches towards strength training?

- Is there anything you would change in the delivery of strength and conditioning in British rowing?

Fitness Testing

- What physical tests are conducted to monitor rowers' progress?

- Is the programme manipulated on the basis of fitness tests results?

Recovery

- Typically for elite rowers what is the recovery period afforded between an intense strength training session and a rowing race?

- Do you think this period is sufficient recovery for peak race performance?

- Typically for elite rowers what is the recovery period afforded between an intense strength training session and a high quality rowing training session?

- *Do you think this period is sufficient recovery for peak performance during the rowing training session?*

- *In your opinion is the required recovery time different following a general strength training session and an Olympic lifting based strength training session?*

- *In your opinion do rowing coaches understand the recovery demands elicited by an intense strength training session?*

- *Are there any strategies GB rowing uses to aid recovery and especially for recovery following strength training sessions?*

- *Are there any specific strategies employed to monitor recovery?*

Appendix D: Rowing coach interview questions pertaining to chapter 4b

Rowing coach interview questions

Background Information

- *What is your job title?*
- *What rowers do you currently work with?*
- *How long have you been involved in the coaching of elite rowers?*

Strength Training Prescription

- *What input do you have as a rowing coach on the performance of strength training by the rowers?*
- *Is there anything you would change in the delivery of strength and conditioning in British rowing?*
- *How many strength training sessions do the rowers you work with perform per week?*
- *With regards to a standard strength training session what exercises, sets and reps do the rowers typically perform?*
- *How does strength training fit into the overall training programme / a typical training week?*

- Are you completely satisfied with the current strength training prescription in terms of exercises, sets, reps and frequency of training, or would you like to see changes / modifications in any of these areas?

- Rowing has been defined as a strength-endurance type of sport, in terms of strength training prescription do you think it is more appropriate for rowers to perform high reps and low-moderate weight or lower reps and heavier weight, please justify?

- Is the strength training programme manipulated to suit the needs of different types/age groups of rowers ie men vs women, seniors vs juniors? If so how?

- What are your thoughts on modifying strength training amongst different types of rowers?

The Importance of Strength Training to Rowing

- What is your overall perception towards strength training as an aspect of training for rowing?

- In terms of the overall training plan, how important is the inclusion of strength training?

- In your opinion what effect, if any, does strength training have on rowing performance?

- In terms of a 2000m rowing race, at what stages of the race, if any, do you think strength and power benefit rowing performance?

- *Do you think Olympic lifting is an important training method for rowers, and if so why?*
- *What elements of fitness/performance qualities for rowing does Olympic lifting benefit?*
- *At the high performance level, are the top elite rowers also the ones who are able to lift the most weight on commonly performed strength training exercises?*

Fitness Testing

- *At what stages of the training programme is fitness testing performed?*
- *Which fitness variables are measured when fitness testing is conducted and with what tests?*
- *In your opinion, of the assessed fitness variables which are the most important to assess?*
- *Are there any fitness variables not assessed in the testing battery that you think should be included?*
- *Is the programme manipulated on the basis of fitness tests results?*

Ergometer performance

- *In your opinion and experience how indicative is 2000m rowing ergo performance of 2000m rowing (water) race performance?*

- In your opinion how reflective is 250m rowing ergo performance of 2000m ergo performance and rowing race performance?

Recovery

- Typically for elite rowers what is the recovery period afforded between an intense strength training session and a rowing race?

- Do you think this period is sufficient recovery for peak race performance?

- Typically for elite rowers what is the recovery period afforded between an intense strength training session and a high quality rowing training session?

- Do you think this period is sufficient recovery for peak performance during the rowing training session?

- In your opinion is the required recovery time different following a general strength training session and an Olympic lifting based strength training session?

- In your experience, how are the rowers affected in terms of aspects of their performance in the hours / days after an intensive strength training session?

- Are there any strategies GB rowing uses to aid recovery and especially for recovery following strength training sessions / rowing training sessions?

- Are there any specific strategies employed to monitor recovery?

Overall training programme

- *What is the structure / periodisation of the training programme after a major competition and leading up to another major competition, ie a macrocycle of training?*
- *Describe the structure of a typical week of training in the pre-season (out of competition) phase?*
- *Are rest periods/days scheduled regularly into the programme? If so how frequently?*

Appendix E. Visual analogue scale used for assessment of muscle soreness

Muscle Pain/Soreness Data Sheet

Name: _____ Date: _____ Time: _____

Trial (please circle): Baseline
Follow up 1
Follow up 2
Follow up 3

Instructions: Draw a vertical line corresponding to the pain/soreness that you have as a result of the strength training session

