THE PHYSIOLOGICAL DETERMINANTS OF ELITE ROWING PERFORMANCE: IMPLICATIONS FOR DEVELOPING ROWERS

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ABSTRACT

Olympic Rowing is a 'power endurance' sport with a range of anthropometric, physiological and technical requirements. Literature examining the physiological determinants of elite rowing performance has rarely included the analysis of different groups or their longitudinal development. Elite rowing traditionally adopts a 'squad based' approach to training which often fails to recognise the potential benefits of individualised training. To date, limited data exist examining the individualised profiling of elite rowers leading to the inclusion of bespoke training prescription in order to maximise performance.

Study 1 investigated the relationship between 2,000m ergometer performance and regularly monitored physiological variables, which contribute to selection, in male and female elite senior and development rowers. Analysed individually, there were large differences in the relationships observed across gender and competitive level, with sub-maximal aerobic capacity (power at 4 mmol·l^{-1} lactate; $W_{4mmol\cdot l}{}^{-1}$) being the only variable to significantly correlate with 2,000m performance in all squads. Results were further analysed using bivariate regression to examine the degree of shared variance between physiological status and performance. $W_{4mmol\cdot l}{}^{-1}$ was able to explain 25-59% of the variation in performance. Other variables were able to explain the variance in performance to differing degrees, depending on the squad. This suggests that coaches and practitioners should examine performance determinants of homogenous groups, as the determinants of performance may be different depending on gender and competitive level.

Study 2 investigated the importance of $W_{4mmol\cdot l}{}^{-1}$ by tracking its longitudinal development in a large group of elite male rowers completing the same training programme. Changes in $W_{4mmol\cdot l}{}^{-1}$ were analysed in order to investigate progression rates and differences between Olympians (OLY) and non-Olympians (NON). OLY improved significantly following each of the first 3 years of elite level training. The results of a case series analysis of individual athletes, including a double Olympic gold medallist with >12 years of international experience, suggested a clear upward trend in $W_{4mmol\cdot l}{}^{-1}$ throughout a career, despite fluctuations within individual seasons and Olympiads. Improvements were attributed to the physiological adaptations associated with a consistent and well executed high volume/low intensity training model. Differences in the development of $W_{4mmol\cdot l}{}^{-1}$ between OLY and NON were not significant until the 3rd year of elite level training. The stagnation in $W_{4mmol\cdot l}{}^{-1}$ observed in NON athletes at this time was ascribed to a ceiling of aerobic development or an inability to effectively polarise training in order to maximise adaptation. At this point alternative training methods could be introduced in order to avoid stagnation in development and subsequent performance. Physiological profiling during the early stages of an athlete's career could also identify those more likely to thrive in a high volume/low intensity training programme.

Study 3 involved the implementation of a physiological 'Spider Profile' for club rowing coaches. Using key performance determinants, development athlete's relative strengths were identified in order to inform the training process. Results were compared to senior athletes and 'Olympian Standards'. U23 international athletes possessed significantly greater maximal and sub-maximal 'rowing specific' endurance capacities than non-international rowers, and were significantly weaker than senior athletes in measures of maximal strength. It was therefore suggested that in order to improve their chances of U23 and senior team selection, development athletes should prioritise the improvement

of technical and aerobic indices of performance rather than strength and power. Also, the identification of new athletes should be weighted more towards endurance factors than maximal strength and power production.

Study 4 refined the physiological profiling system developed in the previous studies and used it to implement training interventions that improved individual weakness in a group of six elite male rowers. Athletes were assigned to either an endurance (END, N=4) or maximal power (MAX, N=2) group depending on the results of a complete physiological profile. All rowers completed a generic rowing training programme (mean volume = 131 km per week) with 2 of the 14 sessions per week comprising either high intensity aerobic interval training or additional weight lifting. Results were analysed as a case series with individual responses discussed as a lack of control group made the relative impact of training interventions difficult to assess. Three out of four END athletes improved aerobic indices, in particular $\dot{V}$O2peak, but made no improvements in markers of power production. MAX athletes improved their maximum power and aerobic performance. This was attributed to increased mechanical efficiency, muscle coordination and recruitment, strength related technical improvements and/or the reduced relative intensity of sub-maximal work leading to conservation of energy. In conclusion, the minor adaptation of a generic rowing training programme can have a marked effect on the physiological adaptation of athletes struggling to make progress in a traditional high-volume/low-intensity system.

In summary, this thesis has highlighted that the analysis of heterogeneous groups of rowers does not provide the level of detail necessary to describe elite performance. Instead, due to individual differences in determinants of performance, a case series approach is a more appropriate means of identifying strengths and weaknesses and implementing interventions to make improvements. Aerobic indices of performance are highlighted as the most important descriptors at both a development and international level. In particular sub-maximal capacity, which is superior in elite development athletes, can be used to differentiate between those that achieve senior team selection, Olympic success, and those that fail to reach the upper echelons of the sport. Spider Profiles are an effective tool which highlight individual strengths and weaknesses in development athletes. Such profiles can be used to provide bespoke interventions to individuals failing to make an impact in elite rowing teams, and the subsequent improvements made can have a global effect on performance if they can be applied to the rowing stroke effectively.

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ABBREVIATIONS

$1RM_{clean}$	One repetition maximum power clean
$1RM_{press}$	One repetition maximum bench press
$1RM_{pull}$	One repetition maximum bench pull
ANOVA	Analysis of variance
AT	Anaerobic threshold
ATP	Adenosine Triphosphate
BF	Breathing Frequency
CII	Concept 2 ergometer
cm	Centimetres
CMJ_{mean}	Average power for a unloaded counter-movement jump
DEV_{men}	Development team men
DEV_{women}	Development team women
$\dot{V}_E$	Ventilation
END	Additional endurance training group (Study 4)
FISA	Fédération Internationale des Sociétés d'Aviron
GBRT	Great Britain Rowing Team
ISAK	International Society for the Advancement of Kinanthropometry
kg	kilograms
LT	Lactate Threshold
L	Litre
m	Metre
$m \cdot s^{-1}$	metres per second
MAX	addition strength & power training group (study 4)
Min	Minute
ml	Millilitre
NON	Did not achieve Olympic (Study 2) or U23 selection (Study3)
OLY	Represented GBRT at the Olympic games (Study 2)
PART	Athletes with a partially complete profile (Study 3)
RPE	Rate of perceived exertion
SEE	Standard Error of Estimate
SNR_{men}	Senior team men
SNR_{women}	Senior team women
SPM	Strokes per minute
UKSCA	United Kingdom Strength and Conditioning Association
U23	Under twenty-three international rower
$\dot{V}CO_2$	Carbon dioxide expiration
$\dot{V}O2_{peak}$	Peak Oxygen Consumption
$\dot{V}O_2$	Oxygen Consumption
$W\dot{V}O_{2LT,LSS}$	$\dot{V}O_2$at LT calculated using least sum of squares
W	watts
W_{2000m},	Average power for a 2,000m ergometer test
W_{250m}	Average Watts for a 250m test
$W_{2mmol \cdot l^{-1}}$	The power associated with $2mmol \cdot l^{-1}$ blood lactate
$W_{4mmol \cdot l^{-1}}$	The power associated with $4mmol \cdot l^{-1}$ blood lactate
W_{4MIN}	Average power for a 4 minute ergometer test
W_{5000m}	Average power for a 5,000m ergometer test
W_{max},	Maximum rowing power
$W\dot{V}O2_{peak}$	The power associated with maximal oxygen consumption
Yrs	Years

CHAPTER 1:

INTRODUCTION

Rowing, in its various forms has been a preferred mode of aquatic transport for over 1000 years, and a recognised international sport for over 100 years. The Fédération Internationale des Sociétés d'Aviron (FISA) have organised rowing championships since 1893 with the sport gaining Olympic recognition in 1900 for men, and 1976 for women. All competitive rowing takes place over a 2000m course with a maximum of six boats per race. There are 14 Olympic boat classes (and a further 8 international classes) which include various combinations of male/female, open weight/lightweight, and sculling/sweep rowing. The worlds best times range from 5:19.35 for the Men's Eight (M8+) to 7:07.71 for the Women's single scull (W1x).

Early research investigating the physiological demands of rowing suggested a metabolic efficiency of 18-23% (Di Prampero et al., 1971). Later studies characterised the energy system contribution during rowing using specific rowing ergometers and laboratory based expired gas analysis (Hagerman et al., 1978; Secher et al., 1983; Roth et al., 1983). Whilst simplistic breakdowns of 2000m performance such as 70% aerobic and 30% anaerobic metabolism (Hagerman et al., 1978) provide an overview, the different requirements necessary to surmount hydrodynamic resistance, race tactics and pacing strategy have obvious impact on physiological requirements in a race.

The start involves athlete(s) overcoming water resistance by applying maximal power at a high stroke rate. A typical race strategy is divided into 3 phases: (1) A fast start; (2) Sustained middle section; and (3) Sprint finish. Tactically, a fast start allows the leading crew to observe their opponents movements and avoid their wake (Garland, 2005). The middle segment is a sustained, rhythmic 'race-pace' aimed at maintaining a high boat speed and tactical advantage. The final portion often includes the reapplication of high power and increased rating to achieve a sprint finish if required (Garland, 2005). Due to this pacing strategy, the various morphological and physiological demands of this 'power-endurance' sport are complex and unique (Mikulic, 2011a).

Elite rowers tend to have distinctive anatomical and physiological characteristics which have increased in recent years alongside faster times (Lawton et al., 2011). Morphologically, rowers are usually tall with long limb lengths in order to produce long rowing strokes, providing a biomechanical advantage (Cosgrove et al., 1999; Yoshiga et al., 2003a). Body mass and lean muscle mass tend to be high in order to contribute to propulsive, low cadence, force production (Secher, 1983). Rowing requires the recruitment of approximately 70% of the body's muscle mass, which, in elite athletes, is composed of a high percentage (75-85%) of slow twitch (ST) muscle fibres (Steinacker, 1993; Roth et al, 1993) and highly oxidative fast twitch (FT) type IIb fibres (Steinacker, 1993; Fiskerstrand et al., 2004).

The physiological determinants of rowing performance have been investigated over the past two decades giving rise to a number of key predictors. Maximal aerobic power ($\dot{V}O_{2max}$) is widely reported as the strongest predictor of both 2000m ergometer (Kramer, 1984; Cosgrove et al., 1999) and on-water international competition performance (Secher et al., 1983; Secher, 1983) with values reported to average 6.4-6.6 $L.min^{-1}$ and 4.1 $L.min^{-1}$ for men and women respectively (Yoshiga & Higuchi, 2003a). As has been reported in running, the power associated with $\dot{V}O_{2max}$ ($W\dot{V}O_{2max}$) has been identified as a strong correlate of performance (Ingham et al., 2002). Sub-maximal markers of aerobic capacity such as the power produced at 2 and $4mmol \cdot l^{-1}$ of lactate during incremental tests are a commonly used field measure in rowing, and are highly correlated to ergometer performance (Steinacker, 1993; Steinacker et al., 1998).

Race length and slow contraction velocity/frequencies suggest anaerobic metabolism is crucial to rowing performance (Secher, 1983). Rowers are reported to have a high intracellular buffering capacity within skeletal muscle and are therefore able to cope effectively with the high intracellular hydrogen ion production resulting in high blood lactate concentrations experienced after maximal rowing performance (Parkhouse et al., 1985). In a study using elite rowers, Smith (2000) reported that 500m ergometer performance correlated strongly with 2000m performance (r=0.96) which explained 92.2% of the variation over the racing distance. Reichmann et al. (2002) reported 75.7% of variation in performance due to differences in peak power output during 30 seconds of 'all-out' rowing. Power and strength are also important as rowers must initially overcome a high degree of water resistance in order to achieve momentum, and produce large dynamic forces throughout the race. Shimonda et al. (2009) and Yoshiga et al (2003b) found isokinetic and isometric leg strength correlated well with ergometer performance.

Reflecting the range of physical and physiological determinants described here, several authors have attempted to combine physiological factors to describe elite performance by using statistical modelling to produce multi-variable prediction models. Cosgrove et al (1999) and Ingham et al (2002) suggested aerobic factors such as $\dot{V}O_{2max}$ and $W\dot{V}O_{2max}$ dominate the explanation of variance within an elite group of rowers, with smaller contributions from anaerobic sources such as maximum power (W_{max}). In contrast, Reichmann et al. (2002) and Jurimae et al. (2000) reported anaerobic capacity as to the key determinant accounting for variation in rowing performance. Differences in derived models are likely due to the determinants considered, the experimental design (age, competitive standard, and gender; male, female or mixed group), and differences between ergometer and on-water rowing.

The Great Britain Rowing Team (GBRT) is one of the most successful Olympic teams in British sport and the world of rowing. However, the complete physiological profiling of GBRT athletes has never been achieved at a senior or development level. The benefits of such information are clear; the validation of key physiological/training markers and their relative importance to performance; the identification of athlete strengths and weaknesses; the calculation of athlete progression rates in order to track improvement/stagnation and make potential interventions.

The training required to help athletes better meet the demands of elite rowing evolved considerably during the 1960's due to a structured, volume based programme popularised by the German Democratic Republic. Strict training zone adherence is widely adopted by international programmes (Steinacker et al., 1993; Gullich et al.,2009; Fiskerstrand & Sieler, 2004) and increased training has coincided with improved times in published data (Jensen et al., 1990). High volume/low intensity training evokes maximal positive adaptation, while avoiding excess sympathetic stress and allowing technical reinforcement of locomotor movement at low stroke rates (Guellich et al., 2009).

However, rowing training programmes generally offer a 'centralised' approach to improving athlete fitness, regardless of physiological strengths and weaknesses. Areas where certain athletes may benefit from individualised training include strength gains and responses to different types of aerobic training. Research has highlighted the difficulty of combining endurance and strength training within an elite programme (Secher, 1993; Bell et al., 1993; Lawton et al., 2011) and suggestions for improving both elements include periodised training blocks focusing on one type of training rather than both simultaneously (Yamamoto et al., 2010; Garcia-Pallares & Izquierdo, 2011). Gaskill et al. (1999) showed cross-country skiers who did not respond positively to a traditional volume based training programme, did benefit from a shift to higher intensity/lower volume training. The effect of training programmes which vary the composition of endurance, strength and power based on an individual rowers 'physiological footprint' have not been published.

This thesis will attempt to identify the physiological performance determinants in homogenous rowing groups and further investigate the development of key variables. Also, a profiling tool that can be used throughout the GB Rowing Team system will be developed. The efficacy of this tool will then be tested via a training intervention aimed at improving the performance of already well established athletes. The research programme for this thesis is presented in figure 1.1

AIMS:

1. Describe the physiological determinants of elite 2000m ergometer rowing and investigate differences between genders and experience levels.
2. Describe the longitudinal changes in sub-maximal aerobic capacity in elite male rowers based on success criteria
3. Design and implement a physiological profiling protocol to analyse the physiological strengths and weaknesses of GBRT 'development' rowers
4. Based on physiological profiling, design and implement a partially individualised training programme aimed at improving the key physiological determinants of rowing performance.

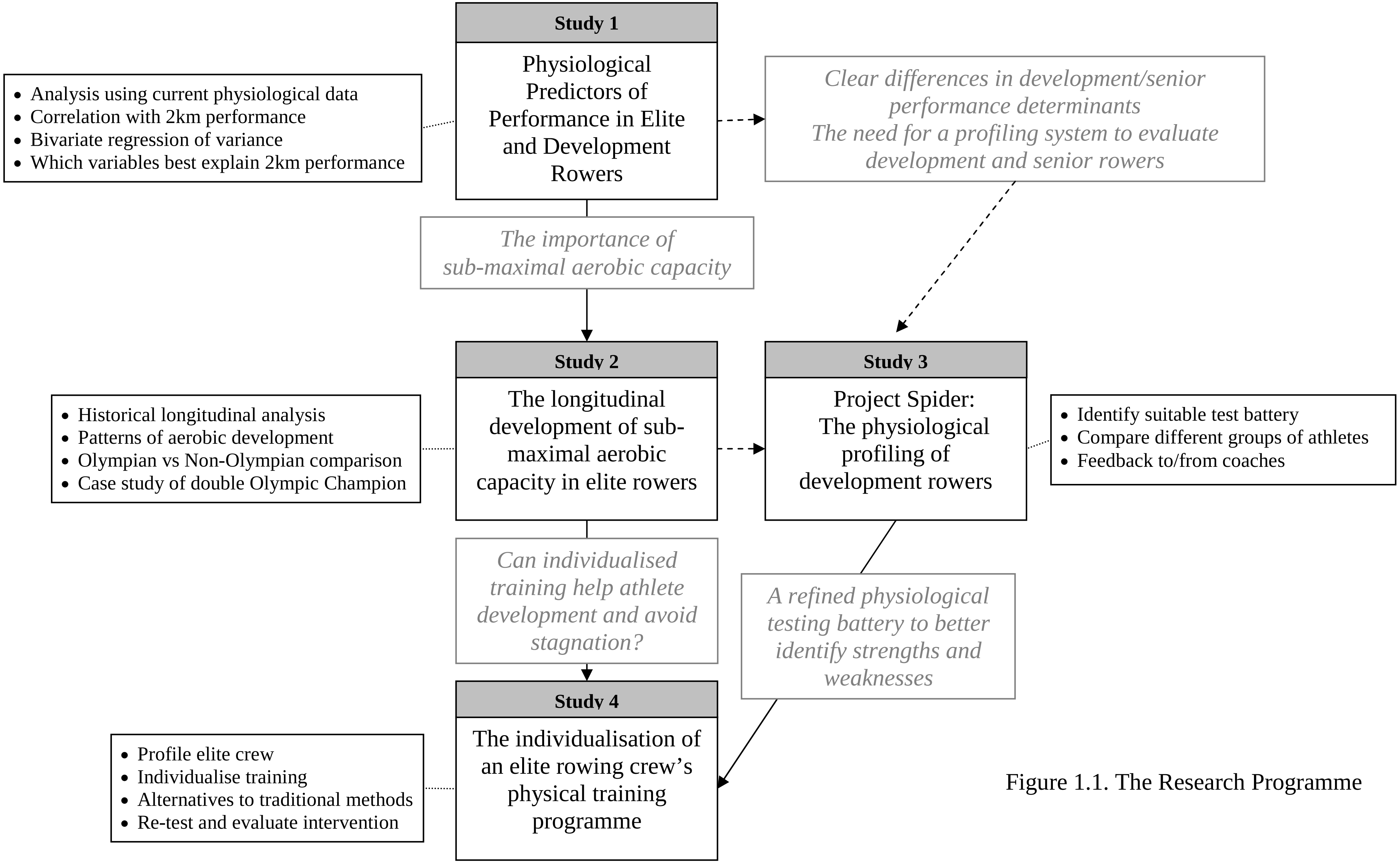


Figure 1.1. The Research Programme

CHAPTER 2:

REVIEW OF LITERATURE

2.1 Rowing

2.1.1 History

Since Egyptian times, rowing has been used as a mode of transport, a means of warfare and a competitive sport (Burnell & Page, p13). Eighteenth century races on the River Thames, including the university Boat Race, resemble the rowing first featured in the 1900 Olympic Games.

2.1.2 International Structure and competition

The Fédération Internationale des Sociétés d'Aviron (FISA) was founded in 1892 and organises European, World and Olympic regattas. All races, regardless of discipline, crew size or gender are 2000m in length. There are currently 14 Olympic events which include sculling (two oars per person) and sweep rowing (one oar per person) in various combinations of one, two, four or eight athletes. The worlds best times range from 5:19.35 for the Men's Eight (M8+) to 7:07.71 for the Women's single scull (W1x).

Elite rowing performance is underpinned by a combination of technical and physiological factors. This literature review will critically analyse the academic research which attempts to explain the physiological determinants of elite rowing, their relative influence, and the methods used to improve them in oarsmen and women from the development to elite level.

2.2 Physiological determinants of Elite Rowing Performance

2.2.1 Performance requirements & tactics

Rowing is considered a “power endurance” sport (Peltonen & Rusko, 1993) as athletes must overcome significant water resistance at a relatively low cadence during the ~5 minute 30 seconds – 7 minute 30 seconds (depending on boat class) of typical racing (Baudouin & Hawkins, 2002). During the 220-240 (32-38 strokes per minute) rowing strokes performed in a race (Lucia et al., 2002), upwards of 70% of the whole body muscle mass is used (di Prampero et al.,1971; Steinacker et al., 1998) to apply force and length to the oar in a cyclic repetition of legs (~50% of total stroke power), trunk (~30%) and arms (~20%) (Kleshnev, 1998).

In order to overcome water resistance, the power per stroke at the start of a race is approximately 800-1200w and 600-900w during the race (Secher, 1993; Steinacker, 1993). In an analysis of elite competition tactics, Garland (2005) reported that men, women, winners and losers all adopt the same race profile of 103.3% (of 2km average speed), 99.0%, 98.3% and 99.7% for the four 500m segments respectively. Tactically, a fast start is advantageous as, due to the backward nature of racing, leaders can see their opponent’s movements behind them and react accordingly.

Given the complexity and expense of on-water rowing, ergometer rowing has become an integral part of training in elite and recreational rowers. Ergometer rowing differs from on-water rowing in technical and skill related requirements, but replicates the metabolic demands of performance accurately (Ingham et al., 2002; Des Capos Mello et al., 2009). Ergometer performance times also exhibit a positive relationship with World Rowing Championship rankings (Mikulic et al., 2009a; Mikulic et al., 2009b). The majority of research examining the physiological demands of rowing is therefore land based, and this is reflected in this literature review. On-water analysis is discussed where applicable.

2.2.2 Morphological determinants

The consistency of data collected from elite rowers highlights the importance of anthropometric variables in international rowing competition success (Mikulic, 2008). Successful rowers are tall, >195cm for men and >182cm for women (Volianitis & Secher, 2009) with long arms and legs to provide a biomechanical advantage (Claessens et al., 2005). A large body mass comprised of a high muscle mass/low fat mass is also advantageous as the accompanying increase in aerobic capacity and strength outweigh the negative effect on hull drag (Hageman, 1984; Secher, 1993). Also, Yoshiga and Higuchi (2003a) suggested that the relationship between fat free mass, blood volume and stroke volume (aerobic capacity) helps explain why more muscular rowers are more successful. Several studies have investigated the relationship between on-water rowing performance and anthropometric data (Barrett & Manning, 2004; Yoshiga & Higuchi, 2003a) and explained a high degree of variance in performance based on these variables alone. However, the use of heterogeneous samples which include lightweight and openweight athletes, suggest that these results should be treated with caution especially when considering transferring research findings to the training of athletes (Maestu et al., 2005).

2.2.3 Energetic requirements

Several studies have attempted to compartmentalise rowing performance by energy system contribution (Hagerman, 1984; Secher, 1993; Messonier et al., 1997). Although a general trend is clear, ~70% aerobic and ~30% anaerobic, differences are associated with gender, performance level and testing methodologies employed. Furthermore, such a basic explanation of rowing fails to highlight the extreme physiological demands of the start, middle and finish of a race.

2.2.3.1 Aerobic requirements

The first studies to investigate the metabolic demands of modern Olympic rowing estimated oxygen consumption ($\dot{V}O_2$) from its relationship with heart rate both in a rowing tank and on water (di Prampero et al., 1971). 5.6L.min^{-1} was required for each oarsman of a coxed pair to cover 2,000m in 7 minutes 15 seconds. This work, alongside later studies analysing 'on-water' and ergometer rowing (Jackson & Secher, 1976; Hagerman et al., 1972; Hagerman et al., 1975) suggest that high performance rowing requires large amounts of energy and ATP resynthesis.

2.2.3.1.1 Aerobic Capacity

Alongside improved performance times in Olympic events, the average size and the maximal aerobic capacity ($\dot{V}O_{2max}$) of successful rowers has increased over time (Seiler, 2006). Many studies have demonstrated a relationship between $\dot{V}O_{2max}$ and ergometer performance (Kramer et al., 1994; Cosgrove et al., 1999; Ingham et al., 2002), on-water performance (Secher et al., 1982; Secher, 1983; Des Campos Mello et al., 2009), and international competition ranking (Secher et al., 1982; Secher, 1983). Average values of 6.5-7.0 l·min^{-1} (men) and 4.5-5l·min^{-1} (women) have been recorded in groups of elite rowers (Secher, 1993, Steinacker, 1993) and highly successful individuals (Godfrey et al., 2005; Mukulic, 2011a).

Several studies have suggested that $\dot{V}O_{2max}$ will plateau after extended full-time endurance training, and any subsequent changes are due to seasonal fluctuations in training status (Rusko, 1987; Legaz Arrese et al., 2005; Godfrey et al., 2005; Mikulic, 2012). This trend would suggest that subsequent improvements in rowing performance are due to alternative factors including: sub-maximal aerobic capacity; anaerobic capacity and strength/power development.

The power associated with $\dot{V}O_{2max}$ ($W\dot{V}O_{2max}$) is a function of maximal aerobic capacity and exercise economy. It is obtained by calculating the regression equation describing $\dot{V}O_2$ and power for results of a multi-stage sub-maximal incremental step-test and is a strong predictor of middle-distance running performance (Jones, 1998; Jones & Carter, 2000). In rowers, $W\dot{V}O_{2max}$ also correlates well with performance (Cosgrove et al., 1999; Ingham et al., 2002). Mikulic (2011a) in a maturation (16-22yrs old) case study of a World Champion crew reported a stabilisation in $\dot{V}O_{2max}$ when the crew reached 20yrs of age, but a continued improvement in $W\dot{V}O_{2max}$ (calculated as the actual power required to achieve $\dot{V}O_{2max}$) was observed. However, 2000m ergometer performance mirrored the plateau in $\dot{V}O_{2max}$ rather than the improvement in $W\dot{V}O_{2max}$ in this small group.

2.2.3.1.2 Sub-maximal aerobic capacity

While a large $\dot{V}O_{2max}$ is a pre-requisite for elite performance, the fractional utilisation of this capacity is also vital as sustaining a high $\dot{V}O_2$ during competition is more important than the maximum consumption possible (Maestu et al., 2005).

Traditionally, blood lactate is the preferred measurement and monitoring tool for assessing training intensity in elite rowing (Altenburg et al., 2012 p43). The power associated with 2 and 4 mmol·l^{-1} ($W_{2mmol\cdot l^{-1}}$ & $W_{4mmol\cdot l^{-1}}$) of lactate are highly correlated with elite ergometer rowing performance (Steinacker, 1993; Cosgrove et al., 1999) and improvements in this power output can reflect a reduction in the rate of lactate production, an ability to clear lactate more effectively, a lower rate of glycogen depletion or speeded up oxygen kinetics (Jones & Carter, 2000).

In endurance sport, the aerobic-anaerobic threshold and its movement is a popular means of prescribing training intensity (Maestu 2005). Rowing literature has suggested the adoption of this approach (Steinacker, 1993) as the power produced at fixed volumes of blood lactate does not consider individual kinetics, higher lactate formation or lactate tolerance (Steinacker, 1993). However, elite rowing training includes very little work at or around the aerobic-anaerobic threshold intensity (Guellich et al., 2009) (see section 2.3.2.1). Unlike long distance cycling and running events where athletes must maintain their highest sustainable speed, rowing competition is performed at a higher intensity for a short time. This suggests that the need to identify and train at this intensity is not seen as relevant.

Despite its relevance to W$\dot{V}O_{2max}$ calculations, rowing economy has received little attention in the literature. Defined as the volume of oxygen consumed by the working musculature at a given steady-state workload (Cosgrove et al., 1999), research has demonstrated that a low $\dot{V}O_{2max}$ in elite cyclists and runners can be compensated for by improved economy (Saltin et al., 1995; Lucia et al., 2002). Jurimae et al. (2000) identified differences in economy between rowers and non-rowers using an ergometer, but no difference between selected and non-selected elite lightweights. Described as ml/watt, it is possible that the measure is not sensitive enough to detect differences between individuals or across time.

2.2.3.2 Anaerobic requirements

Although aerobic metabolism largely dominates rowing performance, race length and slow contraction velocity/frequencies suggest anaerobic capacity and strength/maximal power production are vital (Secher, 1983). This is particularly evident during the tactically crucial start, and often necessary sprint finish (Maestu et al., 2005). Post-performance, blood lactate concentrations are high in oarsmen due to a large muscle mass. Subsequently, rowers have a high buffering capacity in the skeletal muscle (Parkhouse et al., 1985). Reichmann et al. (2002) reported 75.7% of variation in performance due to differences in peak power output during 30s of 'all-out' exercise in competitive female rowers. However, this study used young athletes without the endurance training history of elite rowers. Such rowers may rely more on anaerobic contributions and strength to meet the demands of a 2km performance. Other studies using elite rowers have suggested that the contribution from anaerobic sources is smaller and less influential on performance (De Campos Mello 2009).

Smith (2000) reported 500m ergometer performance correlated strongly with 2000m performance (r=0.96) which could explain 92.2% of the variance over the racing distance. 500m (<1:30.0 in elite male rowers) will be dominated by anaerobic metabolism but, similar to other tests/methods (cycle/rowing ergometer Wingate test, indirect accumulated O_2 deficit method), involve an aerobic contribution (as much as 20-30%, Beneke, Hutler & Leithauser, 2007) which may explain differences in the literature (Reichmann et al 2002). As this parameter is thought to be impactful during the initial and closing stages only, isolated measures may not be sensitive enough and the impact on overall performance may not be large enough. The training phase will also affect measures of anaerobic capacity (Maestu et al., 2005; Russell et al., 1998).

2.3.3.3 Strength & maximal power requirements

Weight lifting is seen as a crucial component of training at all competitive levels to overcome water resistance at the start and sustain high propulsive forces during the race (Lawton, 2011). Non-specific one-repetition maximum strength tests (for example, bench press) demonstrate a weak relationship to rowing performance on either the ergometer or on-water (Jurimae et al., 2010; Shimonda et al., 2009). However, isokinetic, dynamic strength and explosive power measured in rowing-related conditions (i.e. low duty cycle) are reported to relate to rowing performance (Secher, 1993; Yoshiga & Higuchi 2003b). Dynamic tests such as bi-lateral leg press, that utilise the large rowing muscles, are more effective performance markers than upper body exercises (Lawton et al., 2011). Despite often having discrepancies between legs due to bowside/strokeside sweep rowing technique, rowers are able to develop strength effectively with both legs while sedentary/other athletes only produce 80% of the sum of individual leg strength using two legs (Secher, 1993). Increasing the specificity, Ingham et al. (2002) identified maximum power (measured as part of a 5 stroke ergometer test) as one of the single strongest independent correlates of rowing performance.

As with the anaerobic contribution to rowing performance, it appears that specific rowing strength and explosive power correlate well with rowing performance, but their impact is greatest during small (but crucial) aspects of the race.

2.3.4 Multi-variable prediction models

The previous sections have highlighted the range of capacities that influence rowing performance. Several studies have analysed the relative contributions of multiple physiological components in an attempt to offer a global explanation of rowing performance. Through multiple regression calculations, such studies provide more information than basic correlations by providing indications of the relative contribution of selected variables to performance. This information allows athletes, coaches and scientists to make changes to training in order to maximise potential gains based on strength/weaknesses and current athlete condition.

Ingham et al. (2002) in a population of elite rowers reported $W\dot{V}O_{2max}$, maximum power, power at the lactate threshold and $W_{4mmol \cdot l^{-1}}$ as able to explain 95.5% of the variation in ergometer performance. Nevill et al., (2011) produced a model whereby

W$\dot{V}O_{2max}$ explained 95.3% of the variation in ergometer performance and described the relative increment in power required to improve performance at various speeds due to the non-linear relationship of the two variables. However, these results were based on a combination of male and female rowers which would have skewed the multiple regression calculation due to the heterogeneous spread of results. Analysing the data as gender specific groups may have better highlighted the intra group variations in variables and led to alternative results.

Womack et al. (1996) reported a combination of $\dot{V}O_{2max}$, peak rowing velocity, velocity at 4mmol·l^{-1} and $\dot{V}O_2$ at 4mmol·l^{-1} able to explain 81% of the variation in ergometer performance. Cosgrove et al. (1999) showed that $\dot{V}O_{2max}$ was the single biggest predictor of 2km performance in a small group of trained university boat club rowers (72%). Alternatively, Reichman et al. (2002) reported a combination of mean power output of an all-out 30s ergometer test and $\dot{V}O_{2max}$ as a strong predictor of performance, while Jurimae et al (2000) identified maximum power and power output of 40s work to be the strongest predictors of performance in less experienced rowers.

As highlighted by Nevill et al. (2011), the results of multivariate analyses suggest the functional capacity of the aerobic system and a measure of anaerobic capacity, when seen collectively, will make a valuable contribution to 2km rowing. Variations in the variables used to predict performance reported in the literature could be explained by the differences in gender, level of competition, determinants measured and methodologies used.

Several studies have had limited success in explaining the determinants of on-water performance from ergometer based measures (Jurimae et al. 2000; Mikulic et al., 2009a; Mikulic et al., 2009b). Jurimae et al. (2000) found muscle mass to be the only variable related to on-water rowing performance, leading Maestu et al. (2005) to suggest that care should be taken when attempting to predict on-water performance due to the influence of anthropometric variables. Again, the analysis of homogenous weight-discipline specific groups may have reduced the influence of such variables. Technical skills are also required to balance and maintain boat speed during movement on water alongside the physiological requirements (Mukulic et al 2009a). However, studies investigating the effects of such variables have often examined physiological responses during crew boat performances, making ergometer comparisons difficult (Mikulic et al. 2009a; Mikulic et al., 2009b; Shimonda et al., 2009).

In summary, there is a wealth of research which independently investigates the physiological requirements of elite rowing performance. Evidence suggests that maximal and sub-maximal aerobic capacity are dominant determinants, with anaerobic capacity and markers of strength and power production playing a supplementary role. Contrasting findings between studies generally stem from variations in competitive level, gender or weight class differences. When these groups are combined – the relationships between performance and physiological indices are clear, but such methods fail to explain the subtle difference between such groups. A comprehensive analysis of a rower's physiology could allow a more accurate description of rowing performance and better explain differences between homogenous groups of performers.

2.3 Rowing Training

During an Olympiad, elite rowers (training full-time) will take approximately 7600 strokes in training for every single stroke of an Olympic final (based on a personal calculation). An optimal training programme will seek to develop the physiological and biomechanical factors that dictate performance. Due to the multi-factoral demands of rowing performance, the design and implementation of such a training programme is difficult. Current methods in elite teams are the result of an evolutionary process that has identified the most effective way to produce high performing athletes (Seiler, 2010).

2.3.1 Structure

Due to a limited number of international racing events, the elite rowing season traditionally includes a long preparatory ‘winter’ training phase – November – March, and a competitive period, starting in April and culminating in the August or September with the Olympic Games or World Championships. Fiskerstrand & Seiler (2004) in their analysis of elite Norwegian rowing, break the season into two halves - October to March (preparatory period) and April to September (competition period).

Training is traditionally divided into multiple daily sessions including a range of intensities aimed at developing the various physiological capacities which determine rowing performance. Alongside gym based strength and power training, according to Guellich et al. (2009) the German national (junior) rowing team has a spectrum of six rowing training intensities. These are used to prescribe training sessions, and evidence suggests that internationally successful programmes (in all sports) have their own similar matrix (Seiler & Tonnessen, 2009).

2.3.2 Endurance training

The physiological and metabolic adaptations to endurance training and their rate of change depend on the frequency, duration and intensity of work done. Manipulating these variables alters the demand on metabolic pathways within the muscle cell (Laursen, 2010). In response to these demands, chronic benefits occur both centrally and peripherally, including adaptation to the pulmonary, cardiovascular and neuromuscular systems that increase the delivery of oxygen to the working muscles and enhance metabolic control within the muscle cells (Jones & Carter, 2000).

Full-time Norwegian rowing programmes include an average of 1128 training hours per year (Fiskerstrand & Seiler, 2004). Norwegian rowing has seen a steady increase in training volume since the 1970s (924hrs per year), but other nations such as Germany have trained at this level since the 1960s (Roth, 1979; cited in Fiskerstrand & Seiler, 2004). Mikulic (2011a) report a world champion crew completing 116 km (2009) and 124 km (2010) of on-water rowing alongside 1.4 land based and 2.4 weights sessions per week. Lacour et al., (2009) in a case study of an Olympic champion reports 119 km per week (alongside 0.9 cross training and 1.6 resistance endurance strength sessions) during the 1999 season, and 142 km per week during the 35 weeks preceding the Sydney 2000 Olympic Games.

Several studies suggest that training volume is the critical determining factor to success in elite rowing (Jensen et al., 1990; Lehmann et al., 1997; Fiskerstrand & Sieler, 2004). According to Steinacker (1998) some eastern European teams completed over 6 hrs of on-water training at low intensities per day during the 1970's. Roth et al. (1979, in Steinacker 1993) examined changes in $\dot{V}O_{2max}$ relative to training volume. $\dot{V}O_{2max}$ increased with volume, but levelled off when mileage reached 5000-6000 km annually. Martindale et al. (1984) reported that $\dot{V}O_{2max}$ reduces significantly if training is reduced to <100 km per week, such as in the off season.

2.3.2.1 Polarised intensity distribution

In order to complete the high mileage reported, the intensity distribution of elite rowing programmes has developed into a polarised model whereby the majority of rowing and aerobic cross-training is completed at low intensities (below anaerobic threshold). A small percentage of work is completed at very high intensities (above the anaerobic threshold) (Seiler, 2010; Seiler & Kjerland, 2006) with little work done at an intensity equal to anaerobic threshold. This pattern of training has been reported in elite endurance sports such as cycling (Zapico et al., 2007) and distance running (Billat et al., 2001) which suggest that across elite endurance sports, a common distribution of 80:20 (low intensity:threshold & high intensity training) exists (Seiler, 2010).

Elite rowing training data is limited to published case studies and anecdotal evidence, which follows a similar trend to other endurance sports (Steinacker et al., 1998, Fiskerstrand & Seiler 2004; Maestu et al., 2005; Guellich et al., 2009). Neykov & Zhelyazkof (2011) report the W1x Olympic champion's training volumes for the 2008 season. R. Neykova trained for 276 days, completed 566 training sessions rowing 5510km. Of this, 66.7% was completed below $3 mmol \cdot l^{-1}$. According to Aasen (2008, cited in Seiler & Tonnessen, 2009), during the 2004 season, Olaf Tufte trained for 1100 hours on his way to winning the M1x Olympic gold medal. Approximately 92 % of this time was spent endurance training, with the rest consisting of strength training. Finally, Mikulic (2011a) in his study of the 2011 M4x World Champion crew briefly describes the training completed. In 2009 the athletes completed an average of 116 km per week, and 124km per week in 2011. This was broken down further into 11.1 training sessions per week consisting of 7.2 rowing sessions, 2.4 weight training sessions, 1.5 land based cross-training sessions. Seiler & Tonnessen (2009) suggest that this training distribution model may be optimal for maximising peripheral adaptations, and the periods of high intensity work satisfy the increased cardiac function demands and enhanced buffer capacity.

At the muscle, morphological adaptations involve hypertrophy of (and conversion to) type 1 muscle fibres (Spina et al., 1996), increased capillary density, increased size and number of mitochondria, and an augmented concentration of the enzymes involved in ATP re-synthesis (Jones & Carter, 2000). Changes to the acid-base status of skeletal muscle include an increased turnover and oxidation of lactate (Hawley & Steptoe, 2001). There is also a change in the balance of fuel supply, due to an increased utilisation of fat (Hawley & Steptoe, 2001). Central adaptations include an increased cardiac output via an augmented stroke volume and arteriovenous oxygen difference (Levine, 2008).

Guellich & Seiller (2010) studied the changes in power per kilogram at $4mmol \cdot l^{-1}$ over a 15 week training block in 51 well trained junior endurance track cyclists. ‘Responders’ (66^{th} percentile) and ‘non-responders’ (33^{rd} percentile) were differentiated by their training zone distribution rather than training volume. Responders spent more time below $2mmol \cdot l^{-1}$ (3722±742km) and less time between $3\text{-}6mmol \cdot l^{-1}$ (244±103km) than non-responders (3128±310 & 442±107km) with an overall higher ratio of cycling volume at low vs. high intensity. Responders and non-responders did not however differ in competition success later in the same year. This was attributed to the homogenous nature of the group studied and the influence of factors beyond physiological variables.

Besides the numerous physiological and metabolic adaptations to low intensity-high volume rowing training, there are health and technical related benefits. Training predominantly at low intensities reduces the excessive sympathetic stress and muscle damage associated with high blood lactate production (Gulstrand, 1996; Esteve-Lanao et al., 2007). Also, the adaptations related to this type of training increases an athlete's ability to recover from higher intensity exercise (Esteve-Lanao et al., 2007).

Technically, peak forces and profiles during a rowing stroke remain relatively constant and enhanced power and subsequent speed is developed through increasing the stroke rate (McGregor, 2004). Training at low intensities utilises the same muscle groups and recruitment patterns as high rate rowing and leads to specific adaptations that can be applied at the higher intensities (Esteve-Lanao et al., 2007). Technical development is also easier to implement at lower rates and repeated practice leads to a more effective maintenance and permanent changes (Guellich et al., 2009).

The benefits and importance of including high intensity training should not be overlooked. Steinacker (1993) suggests that the differences in total fibre recruitment between low and high rate/force application can leave those completing incredibly high volumes less prepared for competition.

'Race-pace' and 'over-speed' intensity training is traditionally used during the competition phase in an attempt to improve the anaerobic capacity of athletes (Fukuda et al 2011). This is necessary in order to meet the demands of ATP re-synthesis that exceed the energy production possible via aerobic metabolism and therefore requires an additional anaerobic contribution. This is particularly evident during 2,000m rowing which is completed at power outputs corresponding to 100-110% $\dot{V}O_{2max}$ (Hagerman, 1984). Guellich et al. (2009) report that, as a percentage of total rowing, such training increases 141% during the competition phase. Training to improve the anaerobic capacity requires work above the lactate threshold with adequate recovery between repetitions and sessions (Fukuda et al 2011).

Adaptations to such training include increased muscle buffering of muscle lactate and pH. In rowing, blood lactate during performance has been reported to reach 32 $mmol \cdot l^{-1}$ (Nielson, 1999) suggesting that increased buffering capacity would be beneficial to performance. This suggestion is supported by the number of research studies investigating the benefits of sodium bicarbonate and beta alanine on rowing performance and subsequent improvements in performance (Hobson et al., 2013).

2.3.2.2 Threshold training distribution

Exercising at an individual's highest steady-state pace or their anaerobic threshold for repeated intervals is known as 'pace/tempo' 'transition' or 'threshold' training (Seiler & Kjerland, 2006). The main aims of such training include increased race-pace muscle fibre recruitment (Lucia et al., 2002), improved lactate threshold (Driller et al., 2009), buffering capacity (Weston et al 1997) and increased fat oxidation compared to carbohydrate (Yeo et al., 2008) which subsequently lead to improved endurance performance during 'intense exercise' such as Olympic rowing (Laursen, 2010).

The number, duration and intensity of such intervals have been manipulated in studies (Stepto et al., 1999; Seiler et al., 2011; Sandbakk et al., 2013) with results suggesting that two sessions per week including sustained high intensity intervals (e.g., 4x8mins or 3x15mins) elicit significant improvements in maximal and sub-maximal aerobic parameters. However, these findings are often in recreational (Seiler et al., 2011) or sub-elite athletes (Steptoe et al., 1999; Sandbackk et al., 2013).

Studies comparing the effects of different threshold-interval and continuous low-intensity training programmes on elite athletes have generally reported only small differences in subsequent performance (Eversten et al., 1997; Ingham et al., 2008). In a long-term study, Gaskill et al. (1999) assigned cross-country skiers to a one-year high-intensity, low volume regime based on their poor response to a high-volume, low-intensity programme. The author reported significant improvements in $\dot{V}O_{2max}$, lactate threshold and competitive performance, while the control groups improvements were similar to that experienced after the initial year's training. The findings of this study suggest that individual differences may be significant in optimising the training of endurance athletes.

In conclusion, although described as separate training methods, elite athletes can, and appear to, benefit from various endurance intensities due to a variation in the adaptation stimulus (Laursen, 2010). Elite rowing programmes acknowledge this by primarily (and slowly) developing an aerobic platform on which the adaptations to higher-intensity training can be based. The short-term benefits and potential risks (due to increased system stress) of high-intensity training are managed by utilising such training in competition preparation (Guellich et al., 2009; Steinacker et al., 1998) when its race-related adaptations are required.

2.3.3 Strength & Power training

As previously mentioned, rowing can be classified as a 'power endurance' sport (Peltonen & Rusko, 1993) which requires the production of high forces in order to overcome the drag caused by water and wind resistance (Sheppard, 1998). The priorities of strength and power training for rowing are threefold, and their achievement is dependent on the emphasis of the programme undertaken. First, the inducement of neuromuscular adaptations such as increased recruitment, rate and synchronicity of muscle fibre contractions (Lawton et al., 2011) are traditionally accomplished via high resistance/low repetition training. Second, hypertrophy of the muscle fibres can lead to adaptations such as an increased cross-sectional area of the contractile site, the conversion of type IIb to type IIa fibres and increased capillarisation associated with aerobic training (Campos et al., 2002). Finally, the prevention of common rowing injuries through the use of strength training has been used to correct muscular imbalances such as hamstring/quadriceps or abdominal/lower back stabilisers (Lawton et al., 2011).

2.3.3.1 Structure, type and intensity

The seasonal strength and power training habits of elite rowers are largely unknown. Gee et al. (2011) in a review of British based S&C coaching practices (including Olympic and National level coaches) reported an average of 2-3 sessions per week during the off/non-competitive season and competitive season respectively. Lawton et al. (2011) suggest that strength training should be prioritised during the non-competition phase of the training year. After this, strength training should be reduced and replaced with specific on-water training. Bell et al. (1993) found that the gains in maximal strength following 10 weeks of x3 weight lifting session were maintained following a 6 week endurance training phase which included x2 weight lifting sessions in non-elite women. However, when resistance training was halted prior to the competitive phase, Hagerman & Staron (1983) recorded a 12-16% reduction in the isokinetic leg strength of elite male rowers at the end of the season.

Gee et al. (2011) report 87% of respondents implemented Olympic style weightlifting exercises, and this was attributed to the close relationship between the whole body sequencing of a rowing stroke and exercise that involve coordination between the upper and lower body. Cleans, squats and deadlifts make up the majority of exercises in a rowing programme - alongside leg press, bench-pull and bench press (Gee et al., 2011).

Research investigating the sets, repetitions and percentage of one repetition maximum (1RM) required to maximise rowing performance gains is ubiquitous (Bell et al., 1993; Webster et al., 2006; Gallagher et al., 2010). However, all studies are short-term (~8-12 weeks) and participants are sub-elite athletes. In order to develop maximum strength, training normally consists of 5-12RM loads with the weight increased to 1-5RM loads (Ebben et al., 2004; Gallagher et al., 2010). Ebben et al. (2004) suggest that such training is more beneficial to elite rowers than strength endurance training consisting of 15-32RM loads.

2.3.3.2 Power production

The effectiveness of a rowing strength programme should be assessed using a sport specific scenario (McNeely et al., 2005). While strength can be defined as maximal force production, power is characterised by high force production combined with high movement velocities (McBride et al., 1999). High force/velocity movements are commonly developed via the Olympic style lifting discussed earlier (Gee et al., 2011).

A benefit of reducing the weight lifted is the rowing specific velocities that can be replicated (Izquierdo et al., 2010). Using isokinetic strength training, Kraemer et al. (2002) reported the largest gains when training was completed at testing speeds. However, in a rowing study, Bell et al. (1989) found no relation between velocity specific resistance training and improved rowing performance. Izquierdo-Gabarren et al. (2010) reduced the number of repetitions during concurrent endurance (460 minutes per week, 87% $<2 mmol \cdot l^{-1}$) and strength training (4 exercises to failure, 4 exercises not to failure or 2 exercises not to failure with half the maximum reps) which led to an increased focus on greater movement velocity. Maximum power and strength increased significantly more than in athletes completed a traditional ‘to fatigue’ strength training programme.

2.3.3.4 Concurrent Training

The biggest problem encountered with strength training for rowing is its effectiveness within an aerobic endurance programme. Acutely, residual fatigue when completing several training sessions in a day can lead to reduced capability of the muscle to maximally contract during a strength session (Leveritt et al., 1999) while depleted glycogen levels can cause disruption in optimal signalling responses (Creer et al., 2005). Also, a catabolic state reduces total protein synthesis rate (Nader, 2006). Chronically, the difference in muscle recruitment patterns and shift in fibre type instigated through endurance training places polar metabolic and morphologic demands on the muscle which cannot all be met, and the adaptations resulting from strength training are compromised (Leveritt et al., 1999). The effect of rowing endurance training on strength gains (Bell et al., 1997) appears less than running (Kraemer et al., 1995) and cycling (Nelson et al 1990). Trained endurance athletes appear to exhibit larger relative strength gains during concurrent training than untrained individuals (Hunter et al., 1987).

Training intervention studies have attempted to maximise strength gains within an aerobic endurance programme by scheduling training during the off-season or preparatory phase (Bell et al., 1993, Hagerman & Staron, 1983). Such studies replace aerobic sessions with strength training and demonstrate increased strength in sub-elite rowers at the end of the strength training period. However, the adapted endurance training volumes in these studies are low, reflecting the competitive standard of the rowers used. After replacing 3-4 endurance based sessions with strength training, the volume of aerobic work in an elite programme would still exceed 15hrs or 130km per week (personal observation). Without elite athlete/programme data, the effect of this regime on maximal strength is unknown.

Furthermore, in reality, this ‘front loading’ method of periodisation is unlikely to be adopted in a group of elite rowers due to the emphasis placed on aerobic capacity development within a training programme. Instead, the elite programme will combine strength and endurance work for a longer period in an attempt to maintain maximal strength closer to the competition period (Maestu et al., 2005).

2.4 The developing rower

At an international level, FISA organises regattas for junior competitors (<19yrs) and under 23yrs. This section will discuss the physiological and performance data of such athletes. Sub-elite senior athletes will be discussed where relevant.

2.4.1 Performance

The world's best times for single scull U23 athletes are 6:46.93 (men) and 7:27.23 (women) which are 96.8% 95.6% of the senior records respectively. On an ergometer the U18 world record for men is 5:47.0 (97.5% of senior record) and for women is 6:33.9 (98.6% of senior record). In a comparison of senior and junior New Zealand rowers, Lawton et al (2012) identified a 3.6% (men) and 4.2% (women) difference in 2000m ergometer scores respectively.

2.4.2 Morphology and Physiology

According to Bourgois et al. (2001), finalists from the Junior World Championships in 1997 were significantly taller than their less successful peers, with greater segment lengths. In a comparison of elite Croation seniors and junior rowers, Mikulic (2008) also reported significant differences between groups in height, mass and fat free mass. The junior athletes did have lower fat mass values than the seniors, which the author attributed to the difficulties of combining muscularity with leanness and the positive relations between mass and rowing strength.

Senior rowers have a higher $\dot{V}O_{2max}$ than juniors ($0.3\ l\cdot min^{-1}$) when measured during the preparatory period (Mikulic, 2008; Steinacker, 1993). When adjusted for body mass, junior rowers score higher than seniors due to their lower body mass and fat mass (Mikulic, 2008). However, in rowing, this calculation has little relevance due to the support offered by a sliding seat in water.

Measured directly, the power associated with $\dot{V}O_{2max}$ is significantly higher in senior rowers. However, when compared to a group of sub-elite seniors, juniors recorded a higher average $\dot{V}O_{2max}$ but lower maximum power values (Mikulic, 2008). Senior rowers demonstrate increased technical proficiency and efficiency with accumulated years of specific training allowing them to apply energy production into output and minimise power ‘leakage’. This finding is supported by senior/junior comparisons at the aerobic-anaerobic threshold. Zdanowicz et al. (1992) reported the power outputs for juniors, older juniors and seniors as 226W, 258W, and 316W for men, and 153W, 170W and 212W for women. Mikulic (2008) reported oxygen consumption at the ventilatory anaerobic threshold to be 0.35 $l \cdot min^{-1}$ higher in the seniors than the juniors. The junior means were similar to a sub-elite group (4.58 $l \cdot min^{-1}$ & 4.55 $l \cdot min^{-1}$) but when expressed as a percentage of $\dot{V}O_{2max}$, the superior efficiency of the sub-elite seniors was evident as their O_2 consumption was 88.7% of $\dot{V}O_{2max}$ compared to 85.5% for the juniors (Mikulic, 2008).

There is a paucity of research reporting measures of anaerobic capacity in development rowers. Mikulc (2011b) recorded the mean power from a modified Wingate test in 21 17 year old rowers to be 607±76W. Using the same test, Mikulic et al. (2010) report the mean power in 17 year olds 617±93 and 18 year olds 633±79W.

Development and sub-elite rowers are not as strong as their elite counterparts (Russell et al., 1998; Yoshiga & Higuchi, 2003; Shimonda et al., 2009). Lawton et al. (2012) reported an 18.8% difference in isometric whole body pull between junior and senior athletes. There was also a 17.9% difference in 5RM leg press and 31.5% in 5RM seated arm pull using a Concept II Dynamometer. Mikulic (2010) measured maximum power (mean of the highest 5 consecutive strokes during a modified Wingate test) in 12-18 year old male rowers and recorded 689±102W and 713±104W respectively. No comparison with senior rowers was made.

2.4.3 Training

The training methods, volume and intensity distribution of young elite rowers has been described (Steinacker et al., 1993; Steinacker et al., 1993; Guellich et al., 2009). During high load phases, the German Junior National Team trained for 150 $min \cdot day^{-1}$ in 1989, increasing to 190 $min \cdot day^{-1}$ in 1995. The volume of actual rowing training remained the same (59%), but intensive semi-specific cross-training increased total volume by 22%. Steinacker et al. (1998) highlights this increase in training volume by reporting that the 1995 junior team trained as much as the senior team in 1990, and this is further supported by Fiskerstrand & Seiler (2004) who report a 20% increase in training volume over a 30 year period in senior Norwegian rowers. However, Guellich et al. (2009) analysed the same team in 2001 and reported a decreased average training time of 12.8hrs per week (109.7 $min \cdot day^{-1}$) with 52% of time spent rowing.

2.4.3.1 Intensity distribution

In a study of the elite junior German national rowing team, Guellich et al. (2009) reported a similar pattern of training to that demonstrated in studies of senior athletes (Fiskerstrand & Seiler, 2004) whereby 71% of training was low-intensity exercise corresponding to a blood lactate concentration under 2$mmol \cdot l^{-1}$. The remainder of training was conducted at a blood lactate concentration of 2-4$mmol \cdot l^{-1}$ (21%) and above 4$mmol \cdot l^{-1}$ (8%). As the season progressed towards the competition period, intensity polarisation increased as moderate intensity ‘lactate threshold’ was sacrificed for more race-pace intensity training (close to $\dot{V}O_{2max}$). Steinacker et al. (1993) reports that during a pre-world championships training camp, the German junior national rowing team completing 93% of training below 3.5mmol·l^{-1} lactate, 5% between 3.5 and 6mmol·l^{-1}, and 2% above 6mmol·l^{-1}. After 16 days, the programme emphasis changed to competition preparation where volume was reduced by 24%, and the zone distribution altered to 93%, 4% and 3% respectively.

Guellich et al. (2009) also conducted retrospective analysis of the differences in training between athletes with senior international and national success, three years after the initial reporting period. There were no differences in total training frequency or volume, or total training zone intensity distribution. A statistically significant difference was recorded in the intensity distribution of specific rowing endurance training. Results suggested that the more successful rowers demonstrated a more distinct polarisation, i.e. more distance at the lowest and highest training intensities. The author speculates that this may be due to effective 'intensity management' discipline in order to avoid overstress.

Guellich & Seller (2010) examined the physiological and performance differences in elite junior track cyclists following 15 weeks of baseline polarised training (high volume-low intensity). The main difference noted between 'responders' and 'non-responders' was the significantly increased time spent training below 2mmol·l^{-1} by responders, compared to the non-responders who spent more time training and racing at 3-6mmol·l^{-1}.

2.4.3 Improvement rates

The identification and development of sporting talent traditionally focuses on children and adolescent athletes in an attempt to maximise the competitive advantages offered by early recruitment (Vaeyens et al., 2008). However, little research has focused on the transition from sub-elite to elite performer or the failure to do so. Case studies have analysed the longitudinal development of both developing and biologically mature rowers immediately prior to and subsequently within senior training programmes (Hagerman, 1984; Mikulic, 2011a).

2.4.4.1 Aerobic determinants

Hagerman (1984) monitored several physiological parameters in successful oarsmen during 2,000m ergometer performances at an identical stage of the season, over a 6- to 8- year period (1972-1980). The examples provided demonstrate that in 3 of these athletes, maximal or peak values of ventilation, oxygen consumption and heart rate improved only slightly over the time period. However, mechanical efficiency (calculated from 2,000m power output and total metabolic cost in $l \cdot min^{-1}$) demonstrated the most significant improvement over time. The author concluded that prolonged and specific training had little effect on maximal physiological values, but a significant effect on rowing specific skeletal muscle oxygen delivery and consumption.

In a longitudinal case study of a M4x World Champion (and subsequently Olympic Silver Medal winning) crew, Mikulic (2011a) reported a 26% mean difference in $\dot{V}O_{2max}$ between 2005 (average age 16.3yrs) and 2009 (20.2yrs). The linear increase seen over this 4 year period ($R^2 = 0.998$), $p<0.001$) does not apply for the following 2 years as the 4 athletes maximum oxygen consumption stabilised. The author demonstrated a similar trend increase in $W\dot{V}O_{2max}$, but power at AT and $\%\dot{V}O_{2max}$ utilised at AT failed to show continued improvement alongside the plateau in $\dot{V}O_{2max}$. The improvements in 2000m and 6000m ergometer performance also slowed, possibly for this reason (Mikulic 2011a).

2.4.4.2 Strength & power determinants

In terms of strength development, Lawton et al. (2012) investigated whether anthropometric and muscle strength/endurance accounted for differences between junior and senior elite rowing ergometer performance. Measures of upper body strength and endurance provided the best indication of junior rowers who possess the physiological characteristics to be successful at a senior level. The differences in strength and strength endurance between junior and senior athletes allowed for the calculation of average annualised (or compounding) development rates based on 5 years of continuous training. Improvements greater than 2.5% per annum for lower body endurance and 6.0% per annum for upper body strength and strength endurance were suggested as useful in identifying those with the greatest potential for success in rowing.

2.5 Summary & thesis justification

This review of literature provides an overview of the physiological requirements and training completed by elite and development rowers. The conclusions drawn are often based on heterogeneous groups including men, women, open-weights, lightweights and different experience levels resulting in equivocal findings. The analysis of homogenous groups may suggest that the true determinants are less clear and the impact of alternative variables more influential. Comparisons between development, sub-elite and elite rowers are difficult due to a lack of consistency in the tests used, while the longitudinal tracking of elite competitors is limited to case studies of successful individuals rather than large groups of high level athletes.

There is a lack of individual profiling, or tools to assess an individuals physiological 'make-up' which may aid in training prescription and performance optimisation. Attempts to manipulate training based on the reported determinants of rowing performance are limited and do not reflect elite training (Ingham et al., 2008). The 'one size fits all' approach to elite rowing training may not be the most effective means of maximising the performance of a group of potential Olympians. Rowers who reach a ceiling of improvement may benefit from a shift in training focus that allows them to maintain strengths while improving other significant contributors to performance.

CHAPTER 3:

PHYSIOLOGICAL PREDICTORS OF PERFORMANCE IN ELITE AND DEVELOPMENT ROWERS

3.1 Abstract

This study investigated the relationship between 2,000m ergometer performance and physiological variables in male and female, elite senior and development rowers. Twenty nine men and twenty four women completed a 2,000m ergometer assessment alongside monitored physiological indices of rowing performance which were conducted as part of regular scientific support, contributing to selection. A rowing ergometer incremental step-test was used to assess sub-maximal and maximal indices, including power at $2mmol \cdot l^{-1}$ ($W_{2mmol \cdot l}{}^{-1}$) and $4mmol \cdot l^{-1}$ ($W_{4mmol \cdot l}{}^{-1}$) blood lactate concentrations, peak oxygen consumption ($\dot{V}O_{2peak}$) and power at $\dot{V}O_{2peak}$ ($W\dot{V}O_{2peak}$) in all participants. Other tests included 250m ergometer speed (women) and 1 repetition maximum bench press, bench pull, and power clean (men). Significant correlations ($p<0.05$) were recorded for height, body mass, $\dot{V}O2peak$, $W\dot{V}O2peak$ $W_{2mmol \cdot l}{}^{-1}$, and $W_{4mmol \cdot l}{}^{-1}$ irrespective of gender and competitive level. Analysed individually, there were large differences in the relationships observed across gender and competitive level, with $W_{4mmol \cdot l}{}^{-1}$ being the only variable to significantly correlate with 2,000m performance in all squads. Results were further analysed using bivariate regression to examine the degree of shared variance between physiological status and performance, multiple regression being inappropriate due to small sample sizes. When squads were combined, $\dot{V}O_{2peak}$, $W\dot{V}O_{2peak}$, $W_{2mmol \cdot l}{}^{-1}$, $W_{4mmol \cdot l}{}^{-1}$ and body mass explained over 80% of the variation in 2,000m speed. Individually, $W_{4mmol \cdot l}{}^{-1}$ was able to explain 25-59% of the variation in performance and $\dot{V}_{O2peak}$ 11-69%. Other variables were able to explain the variance in performance to differing degrees, depending on the squad. The results indicate that different predictors of 2000m rowing ergometer performance exist between different groups of rowers. These contrasting results suggest that coaches and practitioners should examine performance determinants of homogenous groups, as the determinants of performance may be different depending on gender and competitive level.

3.2 Introduction

Elite rowing competition requires athletes to perform maximally whilst retaining a high degree of technical proficiency and teamwork (Volianitis & Secher 2009). Over the course of a 2,000 m race athletes complete approximately 220-240 cyclic strokes (Shimonda et al., 2009) using the combined strength of the legs (75-80%), back, and arms (20-25%) for between 5:19.35 and 7:07.71 minutes according to the world best times for the fourteen Olympic categories (Lawton et al., 2011). Individuals or crews must initially overcome hydrodynamic resistance by producing near maximal power, in synchrony, before settling into a race-pace and, if necessary and possible, re-apply maximum power during the race climax (Muehlbauer & Melges 2011; Steinacker, 1993; Secher, 1993).

In order to meet these demands, elite rowers have distinctive anatomical and physiological characteristics. Morphologically, Olympic rowers are tall (males 1.94±0.05, females (1.81±0.05, Kerr et al., 2006) with associated longer limbs than non-rowers (Kerr et al., 2006) to produce long rowing strokes; a biomechanical advantage (Yoshiga et al., 2003; Cosgrove et al., 1999). Body mass and lean muscle mass are high in order to contribute to propulsive, low cadence, force production (Lawton et al., 2012, Mikulic, 2008; Secher, 1983). Skeletal muscles are composed of a high percentage (75-85%) of slow twitch (ST) muscle fibres (Steinacker, 1993; Roth et al., 1993) and highly oxidative fast twitch (FT) type IIb fibres, developed through high volume-low intensity training (Fiskerstrand et al., 2004; Steinacker, 1993).

Previous studies have sought to establish the physiological determinants of rowing performance using semi-specific ergometers, which are largely able to replicate the physiological demands of on-water rowing in a controlled environment (Mikulic et al., 2009). Single variable investigations (Secher et al., 1983) and multi-factorial investigations to investigate performance prediction (Ingham et al., 2002; Cosgrove et al 1999) have been published which report various physiological contributions to 2000m ergometer rowing performance. Maximal aerobic capacity ($\dot{V}O2_{max}$) is historically recognised as the single strongest predictor of both 2000m ergometer performance (Cosgrove et al., 1999; Kramer, 1984) and on-water international competition performance (Secher et al., 1983; Secher, 1983) with values reported to average 6.4 - 6.6 $l \cdot min^{-1}$ for men and 4.1 $l \cdot min^{-1}$ for women (Yoshiga & Higuchi, 2003). In addition, Ingham et al. (2002) identified a combination of power at $\dot{V}O_{2\ max}$, ($W\dot{V}O_{2\ max}$), maximum power (W_{max},), oxygen consumption at lactate threshold ($\dot{V}O_{2LT}$) and power at 4mmol·l ($W_{4mmol \cdot l^{-1}}$) as explaining 98% of the variance in 2000m ergometer times in a combined cohort of elite male and female rowers. Nevill et al. (2009) reported similar findings (96.2%) using a curvilinear allometric modelling approach. Alternatively, Reichman et al. (2002) suggested that 2000m performance could be characterised predominantly by the mean power output of maximal anaerobic capacity tests alongside $\dot{V}O_{2\ max}$ and an index of fatigue (96%). Other studies have only managed to relate anthropometric variables to ergometer performance (Maestu et al., 1999). The differences in physiological parameters contributing to performance reported in the literature can be explained, in part, by differences in age, gender and experience of the participants tested.

A major limitation of previous research is the analysis of heterogeneous samples caused by grouping male and female rowers from different weight disciplines, and of varying competitive level. Elite athletes performing at the highest level, following the same training programme are likely to be relatively homogenous in the traditional rowing physiology variables such as aerobic capacity, sub-maximal aerobic capacity, strength, and power, as differences in performance are small. Practitioners working with elite athletes require studies from representative samples when considering recommendations for a change to training which targets particular physiological adaptations. A coach or sport scientist requires knowledge that predicted changes would correspond with improvements in performance.

The aim of the present study was to identify the strength of relationships between currently monitored physiological variables and 2000m ergometer rowing performance in elite homogeneous groups of male and female senior and development squad rowers. A key aspect of the research was to examine the strength and practical significance of relationships between variables. We argue that findings from the present study could provide an evidence based approach for athletes, coaches and sport scientists to identify areas for potential development, that could lead to improved performance.

3.3 Methods

Following ethical approval from the Liverpool John Moores University Research Ethics Committee, 53 members of the 2011 Great Britain International Rowing team: 18 open-weight senior men (SNR_{men}); 14 open weight senior women (SNR_{women}); 11 open-weight Development squad men (DEV_{men}); and 10 open-weight Development squad women (DEV_{women}), gave written informed consent to participate. The Development squad comprised the top ranked, club based athletes not in training as part of the senior international team, representing Great Britain at the U23 World Championships and European Rowing Championships. Being part of the GB Rowing Team requires agreement to complete a number of regular, routine assessments. The present study used data collected from routine support rather than discreet testing sessions. Accordingly, a strength of the data collection protocol employed was that it retained a degree of ecological validity and ensured meaningful attention to the competed tests, due to the selection consequences of such performances.

Squad	Age (yrs)	Height (cm)	Weight (kg)	2,000m Time (mm.ss.0)	2,000m speed ($m \cdot s^{-1}$)
SNR_{men} (n=18)	26.7±4.2	194.9±4.1	96.9±4.3	5:52.7±00:04.1	5.67±0.06
SNR_{women} (n=14)	27.9±2.8	182.3±5.7	76.1±4.0	6:46.0±00:08.7	4.92±0.11
DEV_{men} (n=11)	21.8±2.2	193.4±3.6	93.1±3.7	6:08.2±00:06.0	5.43±0.08
DEV_{women} (n=10)	21.7±2.0	181.7±6.1	79.3±6.2	7:02.3±00:07.0	4.74±0.07

Table 3.1. Demographic & Anthropometric data of participating rowers

3.3.1 Performance Tests

2000m ergometer time-trials were performed using Concept II model D machines (Nottingham, UK). The drag factor was set according to squad specific guidelines (Men = 138, Women = 130) and the computer set to record 500m split times. Average speed ($m \cdot s^{-1}$) was used as the performance measure.

3.3.2 Physiological Profiling

3.3.2.1 Anthropometry

Height (cm) and body mass (kg) were recorded using a stadiometer (Holtain, Crymych, Pembrokshire) and electronic scales (Marsden, Rotherham, England).

3.3.2.2 Aerobic step-test

Tests were conducted in an air conditioned laboratory (18°C, 35% relative humidity). The generic squad training programmes did not include intensive exercise 24 hours prior to laboratory assessment Sessions were limited to steady-state (≤2 $mmol \cdot l^{-1}$.) exercise. Training on the day of the laboratory assessment was standardised to 12,000m low-intensity (≤2 $mmol \cdot l^{-1}$.), steady-state ergometer rowing in order to help meet weekly training mileage demands. This session was completed >3hrs prior to the laboratory test to allow ample time for rest and refuelling. Athlete avoided caffeine consumption prior to testing.

Athletes completed a 10 minute warm-up on the test ergometer at a fixed intensity (1:51.0 per 500m for men; 2:10.0 for women). Athletes then completed 5 x 4 minute incremental steps with 30s rest between efforts. The senior men's team 1st step was set at 270W with each stage increased by 25 watts. Senior women completed one of 2 starting loads (180W or 200W) which increased by 20W with each step. Development squad athletes were prescribed starting loads based on 55% of their 2,000m ergometer test average power, with 5% increases for each of the subsequent 4 steps. On completion of the 5th and final step, all athletes rested for 150s before completing a 4 minute maximal effort to establish $\dot{V}O_{2peak}$. Time per 500m (split), power (2.80/500m split^2), and stroke rate (SPM) were recorded from the ergometer computer.

Capillary blood lactate samples were taken during the 30s rest interval between stages. Blood was analysed for blood lactate concentration using a Biosen C-Line lactate analyser (EKF Diagnostics, Magdeburg, Germany [Coefficient of Variation 1.5% at 12 mmol·l]). Lactate was regressed against power and the watts produced at 2 mmol·l^{-1} ($W_{2mmol \cdot l^{-1}}$) and 4 mmol·l^{-1} ($W_{4mmol \cdot l^{-1}}$) of blood lactate were calculated by polynomial interpolation and internally verified by experienced reviewers.

Inspired/expired air was analysed using an Oxycon Pro 'breath-by-breath' metabolic system (Jaeger, Viasys Healthcare, Yorba Linda, CA). Tests were conducted using a mouthpiece to limit dead space. The gas analysers were calibrated using gases of a known concentration and the flow volume was calibrated using a standardised 3 litre syringe prior to every test. Values of oxygen consumption ($\dot{V}O_2$, calculated using the differential-paramagnetic principle, [Coefficient of Variation 3% or 0.05 l·min^{-1}]), carbon dioxide expiration ($\dot{V}CO_2$, calculated using the infared absorption principle

[Coefficient of Variation 3% or 0.05 l·min^{-1}]), ventilation, ($\dot{V}_{E,}$ measured via a flat turbine digital volume sensor, [Coefficient of Variation 2% or 0.05 l·min^{-1}]), breathing frequency (BF) and respiratory exchange ratio (RER, [Coefficient of Variation 4%]) were monitored during the test and averaged for the last minute of each stage. $\dot{V}O2_{peak}$ was defined as being the highest 15s average oxygen consumption measured during the 4 minute maximum effort.

3.3.2.3 250m speed (Female Specific Test)

Both women's squads completed a 250m ergometer test using the previously described Concept II ergometer at the same squad specific drag used for the 2000m performance. Rowers were requested to row 250m between 40-44 strokes·min^{-1}. Data were recorded for average power, total time and stroke rate, m·s^{-1} was used for analysis. The men's squad did not complete this particular test due to coach preference.

3.3.2.4 1RM (Male Specific Test)

One repetition maximum strength tests were conducted for SNR_{men}. Power clean ($1RM_{clean}$), Bench Press ($1RM_{press}$) and Bench Pull ($1RM_{pull}$) were chosen as the most rowing specific tests of strength. Athletes were permitted 3 attempts at each chosen weight, with their result being the heaviest lift deemed acceptable by the UKSCA accredited strength and conditioning coach. The women's squad did not complete these particular tests due to coach preference.

3.3.3 Calculations

The power associated with $\dot{V}O2_{peak}$ ($W\dot{V}O2_{peak}$) was calculated by solving the regression equation describing the power and $\dot{V}O_2$ from the 5 sub-maximal steps.

3.3.4 Statistics

Using SPSS 17 (IBM, New York, USA), Pearson's product-moment correlation was performed to examine the relationship between measured variables, and 2000m ergometer performance for SNR_{men}, SNR_{women}, DEV_{men}, DEV_{women}, and combined squads (see Table 3.2). Given the aim of the study was to identify the strength of relationships between physiological status and performance, greater emphasis was placed on the magnitude of the correlation coefficient, rather than the significance of relationships. Significance was accepted at the $p<0.05$ level. Regression relationships to examine the degree of shared variance between physiological status and performance were examined using standard bivariate regression. Although multiple regression could facilitate identification of the combined variance in performance explained by physiological status, it has also been shown to be problematic with small sample sizes. Tabachnick and Fidell (1996) recommend using a ratio of at least 5:1, hence with over 10 predictor variables**,** the sample size would need to be 50; an unrealistic figure when examining elite squads. Data were screened to identify data points lying more than 3 standard deviations from the line of best fit.

3.4 Results

Table 3.1 includes the average 2,000m speed for all groups. Using a T-test, there were significant differences between all groups ($p<0.05$). Table 3.2 reports mean values, standard deviations and Pearson's product-moment coefficients for 2,000m ergometer performance and measured physiological variables across the individual and combined squads. Significant correlations ($p<0.05$) were recorded for height, body mass, $\dot{V}O2_{peak}$, $W\dot{V}O2_{peak}$ $W_{2mmol \cdot l^{-1}}$, and $W_{4mmol \cdot l^{-1}}$ when the squads were combined. For SNR_{men}, significant relationships ($p<0.05$) were noted for body mass, $W_{4mmol \cdot l^{-1}}$and power clean, and for the SNR_{women} squad, significant relationships were found between body mass, $\dot{V}$

$O2_{peak}$, $W\dot{V}O2_{peak}$ $W_{2mmol \cdot l^{-1}}$, $W_{4mmol \cdot l^{-1}}$, and 250m speed. For DEV_{men}, significant relationships were found for $\dot{V}O2_{peak}$, $W\dot{V}O2_{peak}$ $W_{2mmol \cdot l^{-1}}$, $W_{4mmol \cdot l^{-1}}$, and $1RM_{clean}$, $1RM_{press}$ and $1RM_{pull}$. For DEV_{women}, $\dot{V}O2_{peak}$ and $W_{4mmol \cdot l^{-1}}$ were significantly related to 2,000m ergometer performance. Table 3.2 also shows the standard bivariate regression explanations of variance for each correlate of 2000m performance for all 4 squads individually and combined.

For the combined group the variance in 2000m ergometer performance was over 85% for the following variables: $\dot{V}_{O2peak}$ (94%), $W\dot{V}O2_{peak}$ (96%, see figure 3.1), $W_{2mmol \cdot l^{-1}}$ (89%) and $W_{4mmol \cdot l^{-1}}$ (92%). Independently, body mass (35%), $W_{4mmol \cdot l^{-1}}$ (27%), and $1RM_{clean}$ (25%) were the strongest predictors of SNR_{men} performance. For the SNR_{women}, $W\dot{V}O_{2peak}$ (71%), $\dot{V}_{O2peak}$ (69%), $W_{2mmol \cdot l^{-1}}$ (61%) and $W_{4mmol \cdot l^{-1}}$ (58%), and W_{250m} (53%) best explained 2000m performance. In the development squads, $1RM_{pull}$ (79%), $1RM_{press}$ (72%) and $W_{4mmol \cdot l^{-1}}$ (59%) were the best predictors for DEV_{men}, and $W_{4mmol \cdot l^{-1}}$ (43%) $\dot{V}O2_{peak}$ (41%) and 250m speed (35%) for DEV_{women}. Figure 3.1 demonstrates the relationship between $W\dot{V}O2_{peak}$ and 2000m ergometer speed for SNR_{men}, SNR_{women}, DEV_{men}, and DEV_{women} when combined.

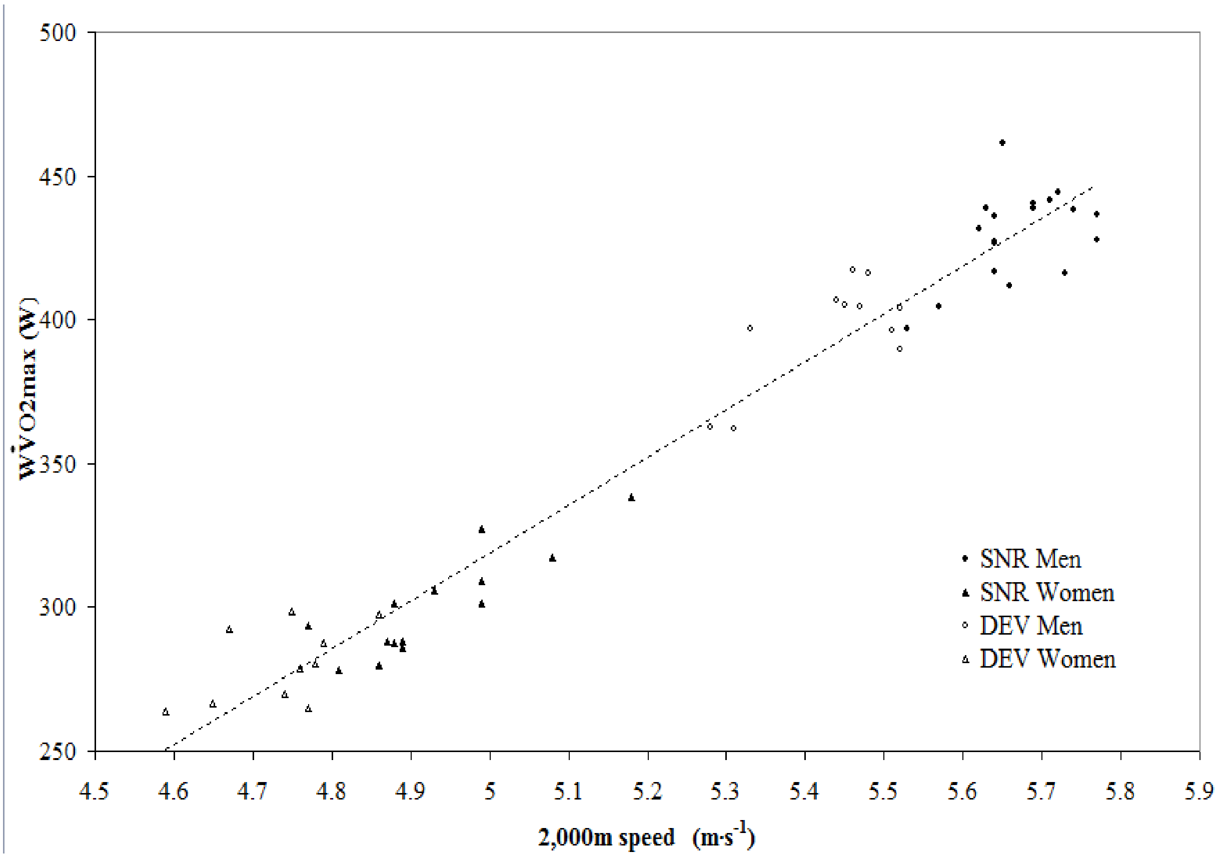


Figure 3.1. The relationship between W$\dot{V}$ O2 $_{peak}$ and 2000m ergometer speed for SNR$_{men}$, SNR$_{women}$, DEV$_{men}$, and DEV$_{women}$ when combined.

Squad	N	Statistical Analysis	Height (m)	Weight (kg)	$\dot{V}$ O2 $_{peak}$ (l.min^{-1})	$\dot{V}$ O2 $_{peak}$ (ml.kg^{-1}.min^{-1})	W$\dot{V}$ O2 $_{peak}$ (W)	$W_{2mmol\cdot l^{-1}}$ (W)	$W_{4mmol\cdot l^{-1}}$ (W)	W_{250m} (m/s)	$1RM_{clean}$ (kg)	$1RM_{press}$ (kg)	$1RM_{pull}$ (kg)
SNR_{men}	**18**	$\overline{X}$	194.9 *±4.2*	97.0 *±4.4*	6.5 *±0.3*	66.9 *±2.8*	429.7 *±15.7*	342.3 *±21.5*	389.7 *±20.8*	-	103.6 *±10.8*	106.3 *±10.7*	101.0 *±6.4*
		R	0.41	0.64**	0.38	-0.22	0.48*	0.44	0.54**	-	0.50*	0.40	0.37
		r^2	0.11	0.37	0.11	-0.02	0.19	0.15	0.25	-	0.21	0.11	0.08
SNR_{women}	**14**	$\overline{X}$	182.3 *± 5.7*	76.1 *± 4.0*	4.4 *± 0.3*	58.3 *± 3.3*	300.1 *± 18.0*	245.8 *± 21.9*	275.7 *± 22.8*	5.7 *± 0.2*	-	-	-
		R	0.10	0.69**	0.83**	0.19	0.86**	0.78**	0.76*	0.73*	-	-	-
		r^2	0.01	0.44	0.69	-0.04	0.71	0.61	0.58	0.53	-	-	-
DEV_{men}	**11**	$\overline{X}$	194.3 *± 3.6*	93.1 *±3.7*	6.0 *± 0.3*	64.4 *± 2.7*	396.4 *± 18.7*	294.7 *± 22.6*	333.3 *± 20.4*	-	99.7 *± 10.8*	94.9 *± 11.2*	98.3 *± 8.7*
		R	-0.18	0.59	0.71*	0.34	0.70*	0.68*	0.77**	-	0.67*	0.85**	0.88*
		r^2	0.03	0.35	0.50	0.12	0.50	0.46	0.59	-	0.46	0.72	0.79
DEV_{women}	**10**	$\overline{X}$	181.8 *± 3.6*	79.3 *± 6.2*	4.2 *± 0.2*	53.1 *± 3.8*	280.1 *± 13.5*	211.8 *± 21.1*	242.8 *± 20.0*	5.4 *± 0.2*			
		R	0.49	0.30	0.64*	0.10	0.52	0.41	0.66*	0.59	-	-	-
		r^2	0.24	0.09	0.41	0.01	0.27	0.17	0.43	0.35	-	-	-
Combined Squads	**53**	$\overline{X}$	188.8 *± 7.8*	87.3 *± 10.3*	5.4 *± 1.0*	61.5 *± 6.1*	360.3 *± 66.5*	282.3 *± 55.1*	320.2 *± 61.7*	5.5 *± 0.2*†	102.1 *± 10.8*$	101.9 *± 12.1*$	100.0 *± 7.3*$
		R	0.78**	0.89**	0.97**	0.85**	0.98**	0.94**	0.96**	0.79†**	0.45$*	0.67$**	0.48$*
		r^2	0.62	0.79	0.94	0.71	0.96	0.89	0.92	0.63†	0.20$	0.45$	0.23$

Table 3.2. Mean values and standard deviations, Pearsons Product-Moment Correlations, and Individual regression explanation values physiological variables and 2km ergometer performance.

* = $p<0.05$ ** = $p<0.01$

$\overline{X}$ = Group mean (including standard deviation) R=Pearsons Product Moment Correlation value, r^{2} = bivariate regression explanation of variance value

† = SNR men & Women only $ = SNR Men & DEV Men only

3.5 Discussion

This paper represents the first study to explore the strength of relationships between monitored physiological variables and 2000m ergometer rowing performance in elite homogeneous groups of male and female, senior and development squad rowers.

Using a stepwise regression analysis, Ingham et al (2002) reported W$\dot{V}$ O2 $_{max}$, W_{max}, W$\dot{V}O_{2LTLSS,}$ and $W_{4mmol}{}^{-1}$ together as able to explain 98.3% of the variance in 2000m performance in a similar group of elite male and female rowers. A limitation of stepwise multiple regression is that it is unstable with small sample sizes and the resultant model can be an artefact of the relationships between independent variables (Tabachnick & Fidell, 1996) as demonstrated in Figure 1 when squads are combined. The main finding from the present study is that when different groups of rowers are combined, the resulting heterogeneous spread is responsible for the strong correlations and explanation of variance in rowing performance explained by physiological variables. As Table 3.2 and Figure 3.1 demonstrate, analysing individual groups separately provided weaker correlations than the combined squad, exposing the frailties of using correlation with a heterogeneous group with wide ranging performances and physiological attributes. Therefore, we suggest that researchers and practitioners interested in examining factors influencing performance for elite athletes only examine data collected from similar, homogenous, gender specific groups of comparable experience, skill level and performance as the variables explaining performance may be different in these groups.

Previous single variable and multi-factoral analyses have demonstrated that elite rowing performance relies on aerobic indices of performance such as maximal oxygen consumption ($\dot{V}O_{2max}$) and sub-maximal markers of efficient oxygen consumption (Cosgrove et al., 1999, Ingham et al., 2002). This conclusion is supported in the present study to differing degrees. When squads were combined, W$\dot{V}$ O2 $_{peak}$ explained 96% of the variance in 2000m ergometer performance alone. This value is an extrapolated product of the sub-maximal oxygen consumption/power production relationship and maximal oxygen consumption, historically reported as variables crucial to endurance performance (Maestu & Jurimae, 2001). In contrast, when squads were analysed individually, power at 4mmol·l^{-1} ($W_{4mmol}{}^{-1}$) was the only variable significantly related to 2,000m performance in all 4 groups. $\dot{V}_{O2peak}$ was significantly related to performance in 3 squads, with the exception of the SNR_{men}, whereas the same was true for $W\dot{V}_{O2peak}$ with the exception of the DEV_{women}.

Previous rowing research also highlights strength and power (in various forms) as important, although less impactful determinants of performance (Reichmann et al., 2002, Nevill et al., 2009). Strength was measured directly for the men's squads and 1RM power clean was able to explain 21% (SNR_{men}) and 46% (DEV_{men}) of the variance in 2000m speed – supporting the notion of rowing as a 'strength endurance' sport. The increased explanation of variance for all 3 strength markers in the DEV_{men} and lower contribution from aerobic markers may be indicative of the lower aerobic training volume (in comparison to the SNR_{men}) completed by this group. The capacity to produce an average 2,000m speed 0.24 m/s^{-1} slower than the SNR_{men} with such a difference in physiological determinants demonstrates the importance of strength to DEV_{men} performance. However, in order to further improve performance and match that of SNR_{men} it is likely that developments in aerobic performance will be most influential.

For the women's squads, strength was not measured directly, but 250m speed (a product of strength application and anaerobic metabolism) was able to explain 53% (SNR_{women}) and 35% (DEV_{women}) of the variance in 2000m speed. It is therefore recommended that the assessment of strength and its application in a rowing specific measure is an integral component of an elite rower's physiological testing battery.

Throughout the results, the explanation of variance in the SNR_{men} 2000m speed, based on physiological variables, was much weaker than in the other squads. This finding is in contrast to previous research investigating the determinants of performance in rowers. Ingham et al. (2002) reported significant correlations ($p<0.01$) between 2000m ergometer performance and the above variables for senior men, senior women and the combined squads. However, this result may be due to the inclusion of lightweight athlete data. For example, male lightweight rowers in the current senior GB Rowing Team have an average $\dot{V}O2peak$ 89% of the heavyweight men (unpublished data). In the Ingham et al. (2002) study, 4 of the 23 (17%) men and 5 of the 18 (28%) women studied were lightweights which would have increased the spread of physiological data and therefore improved correlation values.

The differences in the strength of relationship between squads could therefore be explained by the increased homogeneity within the SNR_{men}. For example, based on the large range of aerobic abilities in the SNR_{women} squad, incremental step-tests started at one of two power outputs (180W or 200W) to ensure athletes did not complete the first step above $W_{2mmol}{}^{-1}$, and to guarantee they achieved $W_{4mmol}{}^{-1}$ during the final stage(s) of the test. In contrast, the SNR_{men} squad all started at 270W. This spread is further demonstrated in 2000m ergometer performance. The difference between the fastest and slowest women included in this analysis was 33.2 seconds over 2 km, whilst in the SNR_{men} squad there was a 14.8 seconds difference. Finally, 28% of the SNR_{women} tested won gold or silver medals at the 2011 Rowing World Championships, where as 61% of the men achieved the same result, suggesting a more heterogeneous performance ability in the SNR_{women} team at this time.

The inability of bivariate regression to explain the variance in this group of SNR_{men} rowers suggests that, when working with small elite groups, such statistical analysis is inappropriate and subtle differences in physiology allow for similar performance outcomes. For example, an athlete who excels in aerobic indices of performance may meet the demands of 2,000 m with a greater reliance on this determinant and a reduced contribution from, for example, strength. The opposite may be true of an exceptionally strong rower. Therefore, athletes should be individually profiled and areas of meaningful change identified to further improve performance without compromising current strengths.

Due to coach preference, it was not possible to perform the same tests on all athletes. Future studies should include identical test batteries for all squads (male and female; heavyweight and lightweight; development and senior). The addition of strength measures may add important information for the explanation of variance in the women's squads together with the inclusion of a more specific marker of anaerobic capacity (i.e. 250m speed) in the men's squads. Furthermore, the inclusion of a peak power test as employed by Ingham et al. (2002) may be a valuable addition to the current testing battery.

3.6 Conclusion

In conclusion, this study highlights the importance of separating elite athletes into homogenous groups in order to analyse key performance predictors. The strong relationship between aerobic indices and 2000m ergometer performance previously reported in the literature is supported in the findings from SNR_{women} rowers in the present study, with the addition of 250 m speed (an indication of strength and anaerobic capacity) also deemed to significantly contribute to performance. In contrast, the relationship between physiological indices and 2,000m ergometer performance is less straightforward in SNR_{men} rowers. The variation in speed was poorly explained by the tested variables, the strongest of which were body mass, sub-maximal aerobic efficiency ($W_{4mmol \cdot l^{-1}}$), and maximum strength ($1RM_{clean}$). Weak relationships were attributed to wide ranging physiological profiles in the small group, whereas the women followed a more homogenous physiological profile. The 2000m performance of DEV_{men} demonstrated an increased reliance on strength over aerobic determinants; likely a reflection of their training model, while DEV_{women} followed a similar, but weaker pattern to their senior counterparts. In conclusion, this study has identified differences in the strength of relationships between currently monitored variables and 2,000m ergometer rowing performance using small groups of elite level rowers. The results from the present study are valuable for coaches and practitioners aiming to improve the performance of their squad or individuals within it. Identifying the strongest physiological correlates of performance, alongside individual profiling, will provide the data to support the implementation of training interventions aimed at addressing weaknesses in an athlete's profile.

CHAPTER 4:

THE LONGITUDINAL DEVELOPMENT OF SUB-MAXIMAL AEROBIC CAPACITY IN ELITE ROWERS

4.1 Abstract

This study investigated the longitudinal development of sub-maximal aerobic capacity in a group (n=23) of elite rowers. Changes in the power associated with 4mmol·l^{-1} of blood lactate ($W_{4mmol·l}$$^{-1}$) using an incremental step-test were analysed in order to investigate progression rates and differences between Olympians (OLY, n=14) and non-Olympians (NON, n=9). OLY athletes improved significantly ($p<0.05$) during the first 3 years of elite level training (+2.99% years 1-2, +3.16% years 2-3). Changes following years 3-4 (-0.25%) and 4-5 (+1.02%) were not significant ($p>0.05$) however; the results of a case series analysis of individual athletes, including a double Olympic gold medallist with >12 years of international experience, suggested a clear upward trend in $W_{4mmol·l}$$^{-1}$ throughout an Olympians career despite fluctuations in individual seasons and Olympiads. Improvements were attributed to the physiological adaptations associated with a consistent and well executed high volume/low intensity training model. Differences in the development of $W_{4mmol·l}$$^{-1}$ between OLY and NON were not significant until the 3rd year of elite level training ($p<0.05$). The stagnation in $W_{4mmol·l}$$^{-1}$ observed in NON athletes following 3 years of elite training was ascribed to a ceiling of aerobic development or an inability to effectively polarise training in order to maximise adaptation. In conclusion, 3 years of elite level training appears to be the key time-point in which to evaluate an elite rower's aerobic development. At this point, alternative training methods could be introduced in order to avoid stagnation in development and subsequent performance. Physiological profiling during the early stages of an athletes career could also identify those more likely to thrive in a high volume/low intensity training programme.

4.2 Introduction

Olympic Rowing training involves the systematic, often concurrent development of aerobic endurance, muscular strength/power and anaerobic capacity in order to sustain the highest average power output during a race (Ingham et al., 2002; Shimonda et al., 2009). Traditionally, the training of elite rowers has focused on the development of the aerobic system through high volume/low intensity training, polarised with short duration high intensity efforts above the anaerobic threshold (Fiskerstrand & Seiler, 2004).

Physiological adaptations result from this approach to training. Central adaptations include an increased cardiac output via an augmented stroke volume and arterio-venous oxygen difference (Levine, 2008). At the muscle, morphological adaptations involve hypertrophy of (and conversion to) type 1 muscle fibres (Spina et al., 1996), increased capillary density, increased size and number of mitochondria, and an augmented concentration of the enzymes involved in ATP re-synthesis (Jones & Carter, 2000). Changes to the acid-base status of skeletal muscle include an increased turnover and oxidation of lactate (Hawley & Steptoe, 2001). There is also a change in the balance of fuel supply, due to an increased utilisation of fat (Hawley & Steptoe, 2001).

Such adaptations are reflected in the development of key determinants of rowing performance such as maximal aerobic capacity ($\dot{V}O_{2max}$), and measures of sub-maximal aerobic capacity including the power associated with 2mmol·l^{-1} ($W_{2mmol\cdot l^{-1}}$), 4mmol·l^{-1} ($W_{4mmol\cdot l^{-1}}$) and the anaerobic threshold (AT). Maximal aerobic capacity ($\dot{V}O_{2max}$) is limited by central cardiovascular function and research examining elite athletes (including rowers) supports the notion that although $\dot{V}O_{2max}$ is a fundamental requirement for endurance performance in heterogeneous groups (Ingham et al., 2002), homogenous athletes with the same $\dot{V}O_{2max}$ can achieve a range of performance scores (Vollard et al., 2009). At sub-maximal exercise intensities, $W_{4mmol\cdot l^{-1}}$ is commonly measured in elite rowers (Altenburg et al., 2012) rather than AT, and has been found to correlate well with ergometer performance (Ingham et al., 2002).

Studies examining the longitudinal development of these physiological parameters in elite athletes, including rowers, are limited to case studies (*i.e.* Jones, 1998; Lacour et al., 2009; Mikulic, 2011a). Alongside improvements in performance, case studies report an initial improvement followed by a plateau in $\dot{V}O_{2max}$, combined with a continuous improvement in anaerobic threshold (AT) (Jones, 1998; Mikulic, 2011a) and $\dot{V}O_2$ at

$4mmol \cdot l^{-1}$ (Lacour et al., 2009). These examples, alongside cross-sectional analyses (including Study 1 of this thesis) do not include development trends in groups of elite athletes who follow the same training programme.

Elite performer case studies typically focus on the physiological development of successful individuals (Lacour et al., 2009; Mikulic 2011a) as their story is of interest to athletes, coaches and practitioners working towards future success. Limited information is reported that analyses the progression of individuals who join elite level programmes, but fail to achieve the highest levels of performance *i.e.* do not achieve Olympic success despite achieving a pre-requisite selection standard. Study 1 of this thesis identified $W_{4mmol \cdot l^{-1}}$ as the strongest correlate of 2,000m ergometer performance in a homogenous group of elite male rowers ($r=0.54$, $p<0.05$) (and was the only variable significantly related to performance in other all other groups measured; open-weight women, development women and development men). It was also the strongest single determinant of performance measured using bivariate regression, explaining 25% of the variation in 2,000m ergometer speed (43-59% in other groups). In terms of physiological determinants, further longitudinal analysis of this variable may discriminate ‘successful’ athletes from those that fail to reach the upper echelon of the sport. A comparative analysis of ‘successful’ and ‘non-successful’ individuals/groups has implications for development to senior squad transition, selection/de-selection and could also help optimise progression rates within a squad.

The aim of the present study was to investigate the development rates of sub-maximal aerobic performance in two groups of elite rowers - Olympians and elite (international squad) rowers who failed to achieve selection for the Olympic Games during their careers. This distinction allows the differences in progression rates following induction to the senior squad to be analysed. Such trends may help improve the identification of sub-standard aerobic development in order to provide interventions at the earliest possible opportunity. A Case study of a double Olympic champion is also used to provide more detailed information regarding the development of a successful elite rowing athlete.

4.3 Methods

4.3.1 Participants

During the Athens, Beijing and London Olympiads (2000 - 2012), 60 open-weight male rowers represented the Great Britain Rowing Team internationally. Of these, 42 athletes began their international careers during this time. This study only included athletes if they had at least 2 years of continuous senior team training (in order to increase the power of analysis), and were excluded if they had not completed a minimum of one sub-maximal aerobic assessment during each one of the years they were a part of the team. When these conditions were applied, 23 athletes fulfilled the criteria for inclusion. Athletes were then divided into those that had represented Great Britain at the Olympic Games, all of whom had completed at least 5 years of senior team training (OLY, n=14, all Olympic medallists), and those that failed to achieve Olympic selection during their time in the senior team, all of whom had at least 3 years of senior team training (NON, n=9). From the OLY group, a double Olympic champion with 12 continuous years of senior team training (Athlete C) was also analysed as an individual case study.

4.3.2 Training

In order to be selected for the GB Rowing Team men's squad, athletes must train as part of a centralised squad that follows an identical training programme. The same chief coach has been in post since 1992, which has led to a consistency of training methodology and volume throughout the time period analysed here. This allows for the comparison of athletes starting their senior training at different time points, but does not consider the different stages of an Olympiad that this may have occurred (see discussion).

4.3.3 Testing Protocols

Multiple sub-maximal aerobic step-tests are completed during a season as part of an ongoing physiological monitoring service. All tests were performed using Concept II model D machines (Nottingham, UK). The drag factor was set according to squad specific guidelines (138) and the computer set to record average stroke power (watts).

The generic squad training programmes did not include intensive exercise 24 hours prior to laboratory assessment Sessions were limited to steady-state (≤2 $mmol{\cdot}l^{-1}$.) exercise. Training on the day of the laboratory assessment was standardised to 12,000m low-intensity (≤2 $mmol{\cdot}l^{-1}$.), steady-state ergometer rowing in order to help meet weekly training mileage demands. This session was completed >3hrs prior to the laboratory test to allow ample time for rest and refuelling. Athlete avoided caffeine consumption prior to testing.

A 10-minute warm-up was completed on the test ergometer at a fixed intensity of 255W. Athletes then rowed 5 x 4 minute incremental steps with 30s rest between efforts. The 1st step was set at 270W or 295W (based on historical tests, in order to ensure athletes achieved $W_{4mmol{\cdot}l}{}^{-1}$) with each stage increased by 25 watts.

Concept II power and stroke rate (SPM) were recorded from the ergometer computer. Capillary blood lactate samples were taken during the 30s rest interval between stages. Blood was analysed for blood lactate concentration using a Biosen C-Line lactate analyser (EKF Diagnostics, Magdeburg, Germany, Coefficient of Variation 1.5% at 12 mmol·l]). Lactate was regressed against power and the watts produced at 2$mmol{\cdot}l^{-1}$

($W_{2mmol \cdot l^{-1}}$) and $4mmol \cdot l^{-1}$ ($W_{4mmol \cdot l^{-1}}$) of blood lactate were calculated by polynomial interpolation and internally verified..

4.3.4 Data analysis

The highest $W_{4mmol \cdot l^{-1}}$ scores achieved during each year of senior training were used for analysis. T-tests were used to investigate the year-on-year changes in $W_{4mmol \cdot l^{-1}}$ in the two groups and the differences in $W_{4mmol \cdot l^{-1}}$ between OLY and NON groups during years 1, 2 and 3. Raw data of all recorded 2,000m ergometer performance tests and measures of aerobic performance parameters ($W_{4mmol \cdot l^{-1}}$ and $\dot{V}O_{2peak}$) are included graphically for all individuals (although not included in statistical analysis). Data in these graphs are expressed via chronological time in order to demonstrate the unequal distribution of measurements. A linear regression trend line was included to analyse the relationship of variables across time. Data were also presented in terms of intra-year and Olympiad trends in one individual, Athlete C, an Olympic Champion in 2008 and 2012.

Smith and Hopkins (2012), in a review of measures of rowing performance, provide Standard Error Estimates (SEE) for studies which examine the relationship between (amongst others) physiological variables and rowing performance - including $W_{4mmol \cdot l^{-1}}$. The SEE for $W_{4mmol \cdot l^{-1}}$ for a group of elite male rowers (including lightweight men) based on Nevill et al. (2011) was calculated as 2.4%. The 'smallest meaningful change' in $W_{4mmol \cdot l^{-1}}$ (calculated using one standard deviation of the squad average (Hopkins, 2005) observed using step-test data from the current GB Rowing Team is 6 watts, or 1.6% of the squad average $W_{4mmol \cdot l^{-1}}$. Table 4.1 includes the percentage year-on-year changes in $W_{4mmol \cdot l^{-1}}$ for OLY & NON.

4.4 Results

Table 4.1 includes raw $W_{4mmol \cdot l^{-1}}$ for OLY (5 years) and NON (3 years) alongside percentage change between years. OLY $W_{4mmol \cdot l^{-1}}$ significantly improved from years 1 to 2 (+2.99%, $P<0.05$), and 2 to 3 (+3.16%, $P<0.05$), but not years 3 to 4 (-0.25%, $P>0.05$) or 4 to 5 (+1.02%, $P>0.05$). NON $W_{4mmol \cdot l^{-1}}$ failed to improve significantly from years 1 to 2 (+1.91%, $P>0.05$) or 2 to 3 years (-1.87%, $P>0.05$) of senior team training. There was no significant difference ($p>0.05$) between OLY and NON $W_{4mmol \cdot l^{-1}}$ following 1 or 2 years of elite senior squad training (379±21 & 373±17W). OLY $W_{4mmol \cdot l^{-1}}$ was significantly greater than NON following the 3rd year of training (391±25 & 366±18W).

Using the SEE and smallest worthwhile change calculations, the improvement in $W_{4mmol \cdot l^{-1}}$ for OLY between years 1-2, and 2-3 were classified as meaningful. The improvement in NON between years 1-2 was also considered meaningful, while the decrement during years 2-3 was considered a meaningful decrease. Figure 4.1 demonstrates the changes in $W_{4mmol \cdot l^{-1}}$ in OLY and NON related to years of senior squad training. Figures 4.2$^{(A-N)}$ and 4.3$^{(O-W)}$ demonstrate the changes in W_{2000m} when available) alongside $W_{4mmol \cdot l^{-1}}$ and $\dot{V}O_{2peak}$ for all participants (when available).

Figure 4.4 demonstrates the changes in $W_{4mmol \cdot l^{-1}}$ during 3, 4 year Olympic cycles (Athens, Beijing & London) for athlete C, an Olympic Champion in Beijing 2008 and London 2012. Linear regression trend lines explain the relationships between $W_{4mmol \cdot l^{-1}}$ and time. Figure 4.5 shows the changes in $W_{4mmol \cdot l^{-1}}$ during the 2002, 2006 and 2008 season (chosen as typical examples from each Olympiad) for the same athlete. Second-order polynomial trend lines highlight the pattern of change over the course of these individual seasons.

Years in Senior Squad	OLY $W_{4mmol \cdot l^{-1}}$		NON $W_{4mmol \cdot l^{-1}}$	
1	368±33	~	366±17	~
2	379±21*‡	+2.99%	373±17	+1.91%
3	391±25*‡†	+3.16%	366±18	-1.87%
4	390±24*	-0.25%	~	~
5	394±28*	+1.02%	~	~

Table 4.1. Annual changes in best $W_{4mmol \cdot l^{-1}}$ associated with increased year's senior squad training

*=significantly different to year 1 ($p<0.05$), ‡ = significantly different to previous year,† = significantly different to NON (same year).

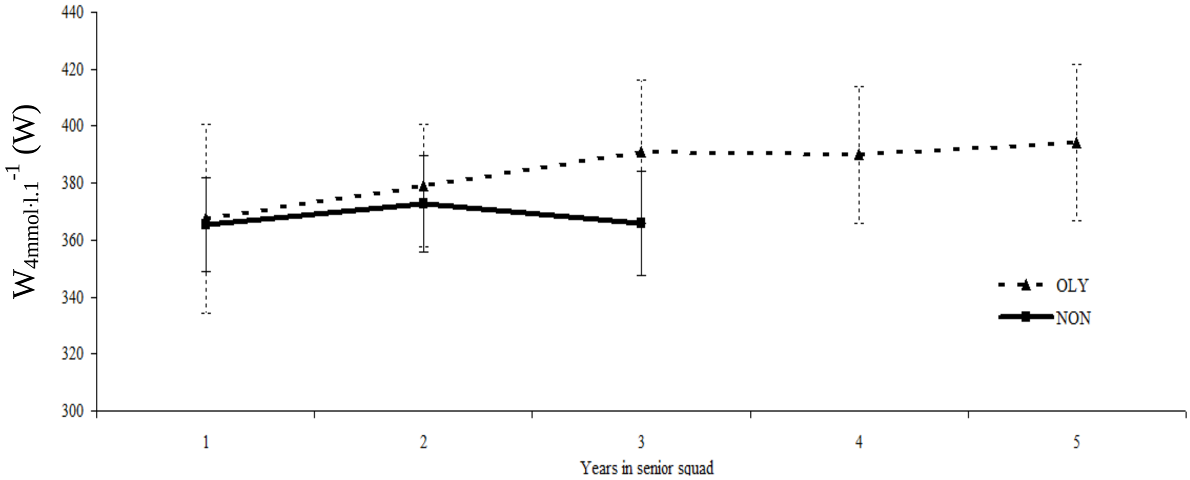
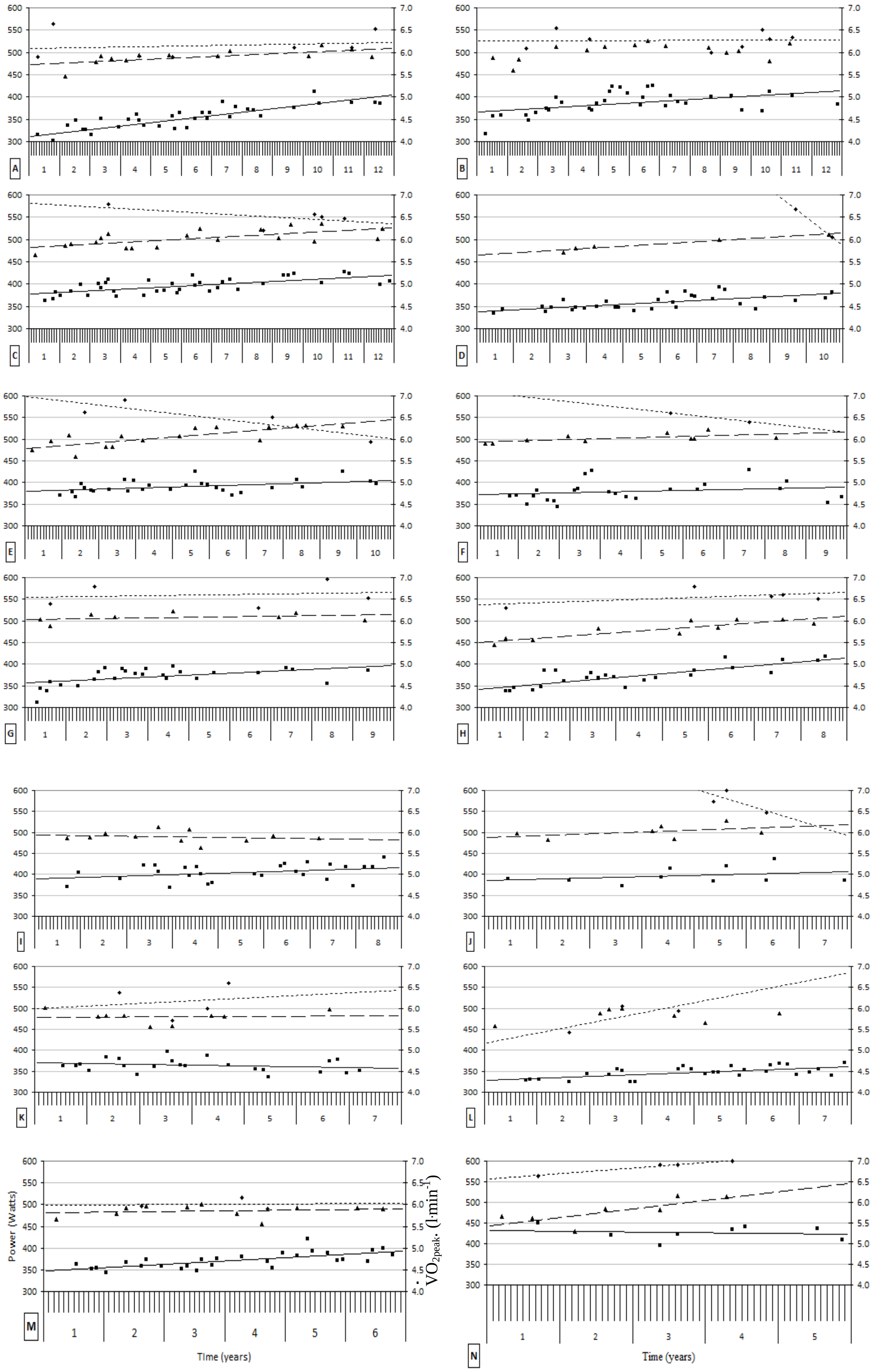


Figure 4.1. Annual changes in $W_{4mmol \cdot l^{-1}}$ associated with increased years of senior squad training in OLY and NON.



■ $W_{4mmol \cdot l^{-1}}$ ▲ W_{2000m} ♦ $\dot{V}O_{2peak}$

Figure 4.2. (A-N) OLY Individual athlete longitudinal plots of W_{2000m}, $W_{4mmol \cdot l^{-1}}$ and $\dot{V}O_{2peak.}$

Linear trend lines indicate the relationship between variables and time.

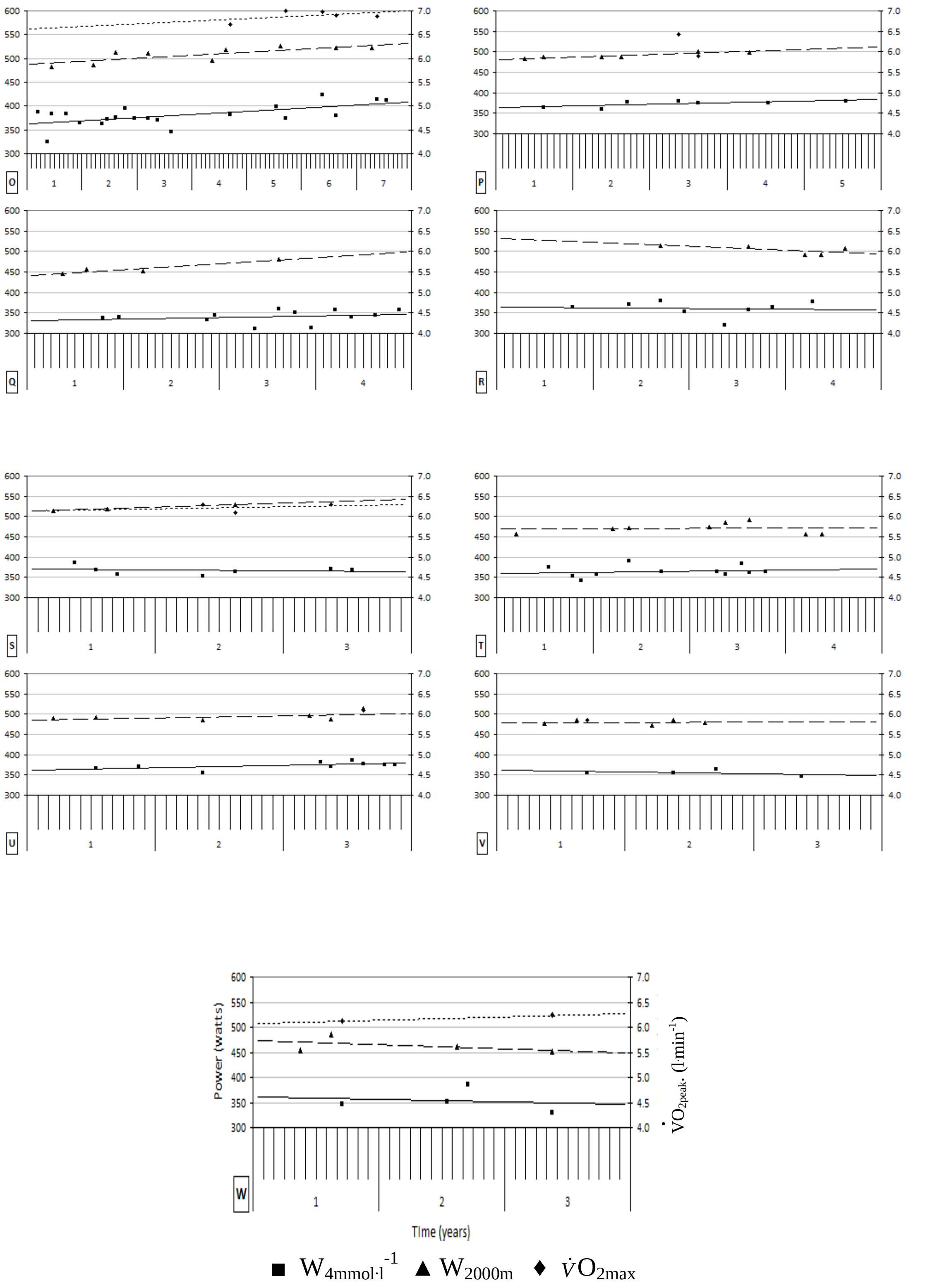


Figure 4.3. (O-W) NON Individual athlete longitudinal plots of average W_{2000m}, $W_{4mmol \cdot l^{-1}}$ and $\dot{V}O_{2peak}$.
Linear trend lines indicate the relationship between variables and time.

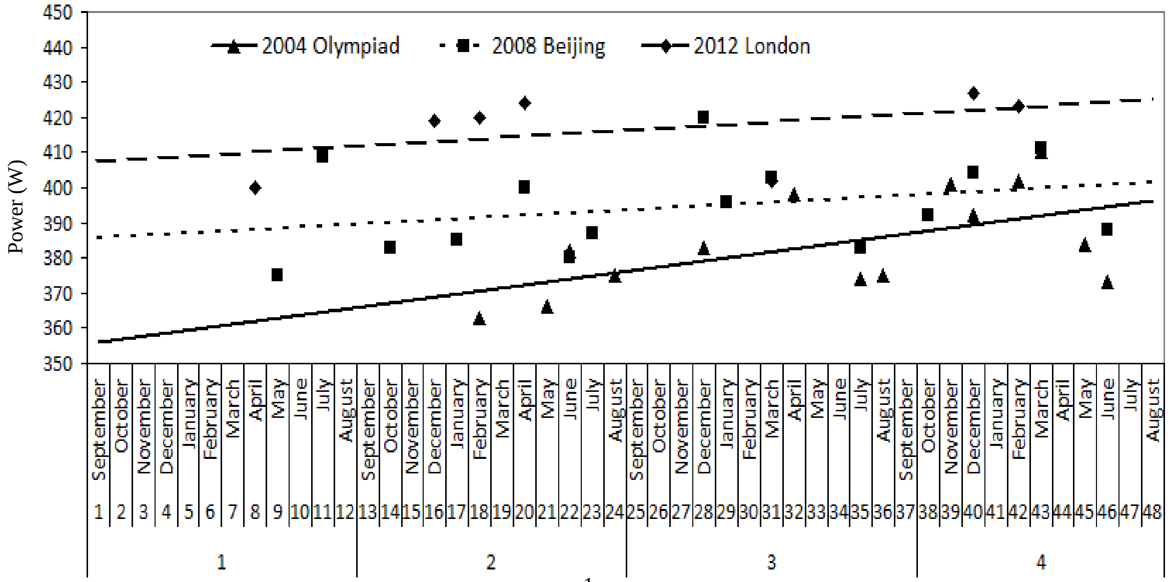


Figure 4.4. Athlete C - Changes in $W_{4mmol \cdot l^{-1}}$ during 3 discreet Olympiads

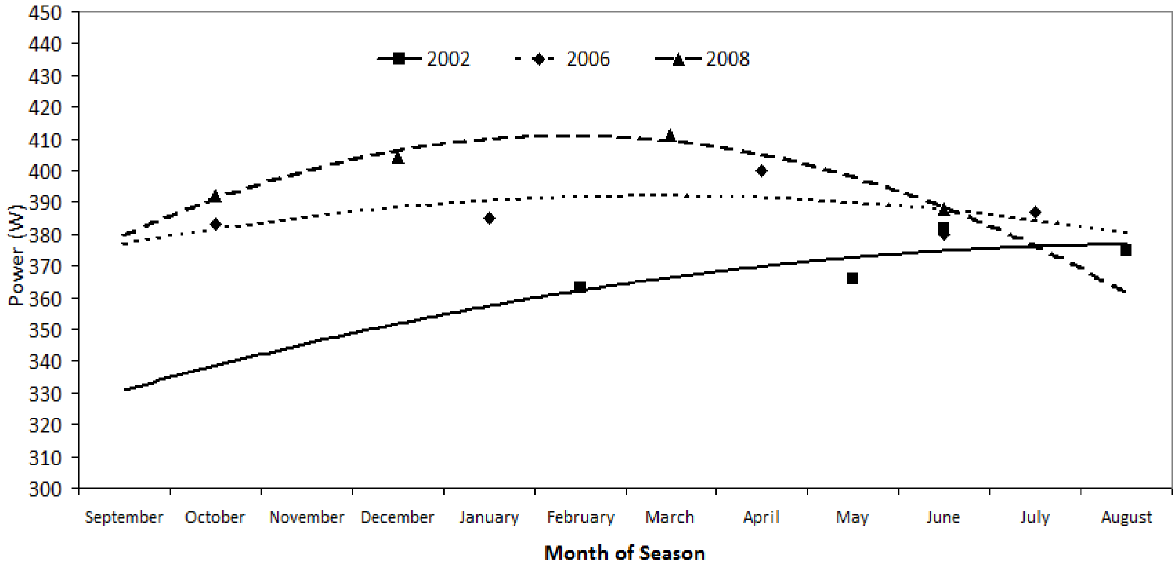


Figure 4.5. Athlete C - Changes in $W_{4mmol \cdot l^{-1}}$ during 3 individual seasons from 3 Olympic cycles.

5.5 Discussion

The present study represents the first to report longitudinal physiological data from an elite squad of athletes. The GB Men's Rowing Team is one of the most successful rowing programmes of the modern era, winning at least one gold medal at each of the last 8 Olympic Games, and multiple World Championship Gold medals in between. The same chief coach has been in place since 1992 leading to a consistent training approach for 20 years. Implementing strict criterion, 2 sample groups from a large elite level population were analysed in order to investigate the aerobic development patterns of successful athletes in comparison to their less successful counterparts. The aim of this research was to identify trends that may lead to the early identification of sub-standard aerobic improvement, and possible windows for training interventions to improve the chances of success for more athletes. The inclusion of 23 individual W_{2000m} and $\dot{V}O_{2peak}$ data (where available), in individual plots of an athletes career alongside changes in $W_{4mmol \cdot l^{-1}}$ also provides useful information on the requirements for sustained success in elite rowing.

4.5.1 Sub-maximal aerobic capacity development

Results from study 1 of this thesis identified $W_{4mmol \cdot l^{-1}}$ as an important determinant of performance in highly homogenous groups (open weight men & women, development men & women) of elite rowers. This result was expected, due to the wealth of previous research highlighting the importance of sub-maximal aerobic capacity to rowing ergometer performance, and the use of this particular measurement by the GB Rowing Team over the previous 3 Olympic cycles. The main finding of the current study is that Olympic Rowers significantly improve $W_{4mmol \cdot l^{-1}}$ during the first 3 years of their elite careers. $W_{4mmol \cdot l^{-1}}$ improved significantly in years 1 to 2, and 2 to 3. $W_{4mmol \cdot l^{-1}}$ appears to slow in years 3 to 4, and 4 to 5 with no significant improvement recorded. However, individual data, including multiple Olympic medallists (*i.e.* Athlete C, a double gold medallist) suggests that in subsequent years, there is an upward trend in $W_{4mmol \cdot l^{-1}}$ (see figure 4.2). Statistical analysis of changes in the first 5 years of $W_{4mmol \cdot l^{-1}}$ allowed for the inclusion of 14 OLY athletes. As Figure 4.2 demonstrates, a decreasing number of athletes have an increasing number of years experience. However, given the small number of participants, statistical power would be very low and so traditional statistical analysis could be considered inappropriate. It is possible that athletes experience a period of stabilisation during this period before a continued improvement.

Figure 4.2 also includes all the available W_{2000m} data from the OLY group, alongside $W_{4mmol \cdot l^{-1}}$ and $\dot{V}O_{2peak}$ data. A trend evident throughout these plots is the consistent improvement in $W_{4mmol \cdot l^{-1}}$ alongside W_{2000m} throughout an individual rower's career. These results are in agreement with previous research highlighting long-term improvements in the sub-maximal aerobic capacity of elite athletes (Jones 1998; Lacour et al., 2009) and provide a link between ergometer and on-water performance due to the use of Olympic selection as a success criteria in this study.

The reason for this consistent improvement is likely the training programme followed by these Olympians, and their approach to it. All athletes completed a high volume of low intensity training interspersed with high intensity, short duration efforts above $W_{4mmol \cdot l^{-1}}$ for 5 or more years. Such a programme will result in cardiovascular/respiratory and muscular adaptations, including an increased concentration of the enzymes involved in ATP resynthesis amplified blood flow, peripheral capillarisation, and mitochondrial biogenesis (Jones & Carter, 2000). These changes result in an increased oxygen delivery and uptake, a reduction in the rate of lactate production, an ability to clear lactate more effectively, a lower rate of glycogen depletion, and speeded oxygen kinetics (Jones & Carter, 2000).

Although measured much less frequently in the GB Rowing Team system, $\dot{V}O_{2peak}$ does not appear to follow the same pattern as $W_{4mmol \cdot l^{-1}}$ and remains stable throughout a career (see figure 4.2[A-N]). Variations in the $\dot{V}O_{2peak}$ of athletes in the present research are consistent with Messonier et al. (1998) and Rusko (1987) suggesting that maximal oxygen uptake plateaus with increased age in well trained rowers. However, Lacour et al. (2009) in a case study of an Olympic Champion rower reported a 2.4% increase in

$\dot{V}O_{2max}$ over a 6 year period from the age of 26 to 32 years, when the athlete was already well trained. In this study, Athlete N demonstrates a similar trend in $\dot{V}O_{2peak}$ during a comparable time frame (5 years), suggesting continuous improvement is possible, while Athlete C registered his highest $\dot{V}O_{2peak}$ during the 3rd year of his elite rowing career (6.8l·min^{-1}) while values from years 10 and 11 averaged 6.5l·min^{-1}. Such differences highlight the varied individual responses to the same training programme, even in aerobic indices. Such variation can be caused by genetic differences, disparity in the homeostatic stress experienced by athletes during and after training sessions, sleep, psychological stress and nutritional factors. (Mann et al.,2014).

Additional analysis of the individual data provides information regarding the fluctuations in $W_{4mmol \cdot l}{}^{-1}$ across seasons and Olympiads. For example, Athlete C trained over 3 consecutive Olympiads. Systematic improvements in $W_{4mmol \cdot l}{}^{-1}$ during the three Olympiads (see Figure 4.4) are evident despite the fluctuations that occur within a season and Olympic cycle (Figure 4.5). It is impressive, and testament to the training programme, that this athlete can continue to make improvements to their sub-maximal aerobic fitness following 10+ years of elite level training, a finding rarely possible in studies of elite athletes.

Figure 4.5 demonstrates the pattern of $W_{4mmol \cdot l}{}^{-1}$ change within individual years in 3 Olympic cycles, where multiple step-tests were completed at distinct phases of the season. There is a trend that suggests $W_{4mmol \cdot l}{}^{-1}$ is at its greatest in March/April. This finding is in contrast to Mikulic (2012) who reported the highest values of endurance capacity ($\dot{V}O_{2max}$ $W\dot{V}O_{2max}$ and power output at the anaerobic gas exchange threshold) at the end of the season in a crew of elite rowers. Traditionally, April marks the end of ‘winter training’ where athletes compete in the final selection trials. Following selection, athletes spend the remainder of the season in crew boats with significantly less ergometer training. The focus of training shifts to the effective technical delivery of peak and mean power alongside race-specific anaerobic parameters - which may explain the slight reduction in $W_{4mmol \cdot l^{-1}}$ during this time.

4.5.2 Olympians vs. Non-Olympians

Another major finding from this research is the differences in $W_{4mmol \cdot l^{-1}}$ between athletes that go on to attain Olympic success, and those that fail to achieve Olympic selection. There was no significant difference in $W_{4mmol \cdot l^{-1}}$ improvement between OLY and NON following the first and second years of senior level training. However, following the third year, the OLY group had a significantly higher $W_{4mmol \cdot l^{-1}}$ than the NON group who regressed back to their first year average.

Possible explanations for this difference in $W_{4mmol \cdot l^{-1}}$ development include the physiological profiles of athletes when they join the senior team, and their subsequent individual execution/responsiveness to training, including factors such as rest and nutrition (Mann et al., 2014). Using bivariate regression analysis, Study 1 of this thesis reported differences in the relationships between measures of strength, endurance and W_{2000m} of elite senior and development athletes. For example, in male development squad athletes, one repetition maximum bench press (72%) and bench pull (79%) could better explain performance than $W_{4mmol \cdot l^{-1}}$ (59%). In senior team rowers, the importance of strength was much weaker (Bench press 11%, Bench Pull 8%) with $W_{4mmol \cdot l^{-1}}$ (25%) being (relatively) the more effective descriptor. This suggests that development rowers have alternative predictors of performance to their senior counterparts, rather than the same, but relatively weaker determinants. This is due to the years required to develop endurance capacity (as seen in this study).

Therefore, rowers joining the senior team could have physiological profiles not suited to thriving in a training programme which has a primary focus on high volume/low intensity endurance training aimed at improving aerobic energy production. Alternatively, following an initial improvement in the response to such training, it may be that NON athletes reach a ceiling in their aerobic development and stagnation in $W_{4mmol \cdot l}{}^{-1}$.

Coping with a large increase in volume and intensity requires a controlled approach to training. Studies investigating the training methods of elite endurance athletes suggest that a polarised approach is the most popular method, whereby large volumes of training are conducted at low intensities, interspersed with short duration high intensity sessions (Seiler, 2010). The volume of training prescribed by elite rowing coaches (5000-6000 km per year) may force rowers to train at low intensities in order to complete their mileage (Driller 2009). However, it is possible to maintain an unsuitably high training intensity for short periods in such a voluminous programme.

Athletes who fail to adhere to prescribed training zones will spend too much time training in mid-range intensities, eager to impress coaches or unable to correctly judge intensity. Subsequently, this can produce athletes too fatigued to train appropriately at high intensities progressing to a stagnation in training adaptation as demonstrated by the NON group in the current study. In support of this, Guillich et al. (2009) demonstrated that junior international rowers who went on to achieve senior international success had similar training volumes, but demonstrated greater polarisation of intensity than those not successful at senior level.

Evidence describing how individual athletes approached training is not available here, so attributing a lack of improvement to poor polarisation is not possible. However, athletes Q, R, S, and T (see figure $4.2^{O\text{-}W}$), all demonstrate a limited improvement in $W_{4mmol \cdot l}{}^{-1}$ over several years in comparison to all OLY athletes (figure $4.2^{A\text{-}N}$) with the exception of athletes K and N, who appear to demonstrate a lack of improvement during their time in the senior squad, while still enjoying success at the highest level. This highlights the multitude of factors (including technical) that determine elite rowing performance.

4.5.3 Implications for Training

This study provides useful guidance regarding $W_{4mmol \cdot l}^{-1}$ development norms in a group of elite male rowers. Of interest to coaches and scientists is the possibility of averting the stagnation in $W_{4mmol \cdot l}^{-1}$ development observed in NON in order to increase their chances of Olympic success. The rapid increase in training volume and intensity from club/university to elite senior rowing may be problematic for newly selected individuals, particularly those with a physiological profile which favours markers of strength and power. The problems associated with a rapid increase in training volume include an increased risk of under recovery, illness and injury. Improved physiological profiling of athletes before they are selected for the senior team would allow for improved integration when necessary. Providing young athletes with a graded introduction to senior team training combined with targeted training to address (previously identified) weaknesses in key determinants of performance may help them to enhance their training response and avoid such problems.

Furthermore, more detailed control of training intensity distribution may improve adaptation to training stimulus. Guellich and Seller (2010) monitored elite junior track cyclists endurance physiology and performance, and noted that ‘responders’ to a 15 week typical high volume/low intensity training programme spent more time below $2mmol \cdot l^{-1}$ than ‘non-responders’ who spent increased time in the $3\text{-}6mmol \cdot l^{-1}$ range.

Alternatively, training interventions that provide an alternative aerobic adaptation stimulus may lead to further improvement and associated success in athletes that appear to have stagnated or reached a ceiling in their physiological development. Low volume/high intensity training has been compared to high volume/low intensity training in an attempt to investigate the most effective model of adaptation. Gaskill et al. (1999) took cross-country skiers who did not respond to a high volume/low intensity training programme, reduced the low intensity volume and doubled the high intensity training. This resulted in significant improvements in maximal and sub-maximal aerobic markers and competitive results. Removing athletes with sub-standard $W_{4mmol\cdot l}{}^{-1}$ development (identified through a standardised profiling strategy) from the senior squad programme and implementing such an intervention could quickly improve $W_{4mmol\cdot l}{}^{-1}$ and allow athletes to return to the generic programme with a greater ability to polarise and maximise their potential.

While potentially more powerful than the results of a single case study analysis, conclusions drawn from the statistical analysis of small groups should be treated with caution. For example, the standard deviation of the data presented in table 4.1 and figure 4.1 suggest an athlete could follow an altogether different pattern of $W_{4mmol\cdot l}{}^{-1}$ development and still achieve Olympic selection/success. Therefore, the interrogation of individual data alongside group trends can provide more detailed insight.

While athletes completed up to 4 aerobic step-tests per year during their careers, this study chose to use the single best measure of $W_{4mmol\cdot l}{}^{-1}$ from each season rather than an average value. As discussed, $W_{4mmol\cdot l}{}^{-1}$ tended to peak in March-April. If athletes did not complete a test at this time, it is possible that results for a given year did not reflect their highest possible power output at $4mmol\cdot l^{-1}$.

Figure 4.5 shows the pattern of $W_{4mmol\cdot l}{}^{-1}$ during 3 discreet Olympic cycles. A limitation of the previous group comparison is its failure to consider the stage of the Olympiad an athlete joins the senior team, and the effect this may have on training and subsequent adaptation. Olympic training programmes aim to produce peak performance at the

Olympic Games and therefore include subtle annual differences in volume and intensity. Although not significant, the improvements seen in athlete C during the Athens 2004 Olympiad mirror the development of the OLY group. During the Beijing 2008 and London 2012 Olympiads, consistent improvements are evident but at a slower rate.

4.6 Conclusion

This study is the first to examine the development rates of a group of world class male rowers during their first 3-5 years of elite senior training. It appears difficult to identify those likely to succeed after 1 or 2 years of senior team training, but progress in the 3rd year of elite training is more marked in those who go on to achieve Olympic selection. This information can be used to identify those that are unlikely to reach the standards required for Olympic selection. This may be due to an inability to improve, or the need for a change in aerobic training stimulus that may result in improved performance. A physiological profiling system in the GB Rowing Team development squads would provide a more detailed explanation of the relative strengths and development rates of athletes before they join the senior team. Interventions could be implemented to identify whether an athlete is likely to continue developing within the senior training programme. Finally, this study may provide evidence to change the training model of athletes who’s aerobic fitness stagnates after 1, 2 or 3 years in the senior team in order to give them the best chance of Olympic selection and subsequent success.

CHAPTER 5:

THE PHYSIOLOGICAL PROFILING OF DEVELOPMENT SQUAD ROWERS: PROJECT SPIDER

5.1 Abstract

This study involved the conception, implementation and presentation of a physiological profiling system for British international development squad rowers. Its aim was to investigate the differences between a range of development rowers, their senior counterparts (SNR, N=15) and a theoretical Olympian standard (OLY). 20 under twenty-three age group, club based rowers, completed a battery of performance tests and physiological measurements to identify previously identified determinants of performance. Athletes were divided into groups for analysis based on international selection - under 23 internationals (U23, N=6), under 23 non-internationals (NON, N=14). Athletes completed 250m (W_{250m}), 2,000 (W_{2000m}) and 5,000m (W_{5000m}) time trials, a sub-maximal incremental test to identify the power associated with 2 and 4mmol·l^{-1} blood lactate ($W_{2mmol \cdot l}{}^{-1}$ and $W_{4mmol \cdot l}{}^{-1}$), one repetition maximum bench press, bench pull ($1RM_{press}$ and $1RM_{pull}$) and an unloaded counter-movement jump (CMJ_{mean}). The resulting profile provided a comprehensive analysis of each athlete's relative strengths and weaknesses. Results demonstrated that U23 possessed significantly greater W_{2000m}, W_{5000m}, $W_{2mmol \cdot l}{}^{-1}$ and $W_{4mmol \cdot l}{}^{-1}$ power than NON (P>0.05). SNR athletes performed significantly better than NON in all parameters except for CMJ_{mean}, but only outperformed U23 significantly in W_{5000m}, $1RM_{press}$ and $1RM_{pull}$. It was therefore suggested that development athletes should increase the training focus on the improvement of aerobic indices of performance rather than strength and power development, and the identification of potential athletes should be weighted more towards endurance factors than maximal strength and power production.

5.2 Introduction

As stated previously, elite rowing is a complex 'power-endurance' sport with a range of anthropometric, physiological and technical requirements. (Study 1 of this thesis, Ingham et al., 2002; Cosgrove et al., 1999). Athletes are tall, heavy, and have a high sub-maximal and maximal aerobic capacity. Strength and peak power are also essential to enable crews to produce ~240 powerful strokes throughout a standard 2,000m race.

The GB Rowing Team men's squad is among the most successful rowing nations of the modern era, winning multiple medals at the Beijing 2008 (1 gold, 1 silver, 1 bronze) and London 2012 (1 gold, 3 bronze) Olympic Games. Athletes in this team train centrally, following squad specific programmes which aim to maximise the physical and technical capabilities of team members. Aspiring rowers are based at one of 9 ‘High performance’ clubs or Universities and generally train part-time for 10-14hrs per week. The GB Rowing Team also runs a well established talent identification system (START) whereby athletes are selected for further development based on a series of anthropometric and physiological test results. These athletes are placed in small training groups and train full-time. Senior team selection is based on club or university performance at national regattas (e.g. Henley Royal Regatta), a well developed trialling system, and Junior (<18yrs)/Under 23 international selection/performance.

The physiological attributes of these development athletes is not monitored, with data limited to ergometer/water performance scores and a small amount of training information. The competition between clubs (such as the Henley Royal Regatta) is intense and the sharing of rower information limited to international selection training camps and trials. Therefore, no ‘pathway’ model for the physiological development of elite rowers exists to judge the progress of potential Olympians.

During the 2012/13 season, the need to standardise physiological testing parameters throughout the national system was recognised by the GB Rowing Team. Pressure from funding bodies and a high retirement count following the London 2012 Olympic Games, increased the need to characterise the athletes making the transition from club to international selection and ensure all development athletes maximise their potential.

The analysis and interpretation of this information needed to be simple and visually appealing in order to easily highlight an athletes strengths and weaknesses in comparison to their peers (other development athletes), and their ultimate target (the senior team) concisely.

The aim of this study was to compare the physiological determinants of performance in GBRT international development rowers with both non-internationals and senior team athletes, using Olympic standards as a guide.

5.3 Methods

5.3.1 Participants

Athlete profiling took place between December 2012 and March 2013. The service was offered to all Development coaches nationwide, and 14 different programmes had at least one athlete profiled. A complete profile required the completion of 7 individual measurements. Due to the nationwide and therefore remote nature of testing, the author was dependent on coach and athlete cooperation to complete and submit all the necessary data. This led to 57 athletes having incomplete profiles (PART) due to illness, injury or coach preference. Complete data profiles were collected for 20 athletes, including 6 selected to represent GBRT at the 2013 U23 Rowing World Championships. 15 senior squad athletes (including 7 athletes who subsequently won medals at the 2013 World Rowing Championships) were profiled during the same time period and included for statistical analysis.

Squad	**Age (yrs)**	**Height (cm)**	**Weight (kg)**	**W_{2000m} (W)**
U23 (n=6)	20.2 ±0.9	193.0±5.3	94.7±4.1	472.8±15.4
NON (n=14)	21.3±0.7	193.0±5.5	91.8±4.6	443.0±27.7
PART (n=57)	21.3±2.5	192.6±5.4	92.6±5.2	432.1±30.1
SNR (n=15)	25.4±2.9	194.0±4.5	96.3±5.2	495.6±19.8

Table 5.1. Participant information.U23=under twenty-three international rowers, NON=under twenty-three non-international rowers, PART=under twenty-three non-international rowers with partially complete profiles, SNR=Elite senior team rowers.

5.3.2 Testing Protocols

The aim of this study was to deliver a complete assessment of physiological rowing determinants by deploying the following test battery. Testing took place in the athlete's training environment, with the aerobic step-test conducted by a GBRT affiliated sports scientist.

5.3.2.1 Performance Tests ($W_{250m,}$ W_{2000m}, W_{5000m})

250m, 2000 and 5000m ergometer time-trials were performed using Concept II model D machines (Nottingham, UK). The drag factor was set according to squad specific guidelines (Men = 138, Women = 130, Lightweight Men = 135, Lightweight Women = 125) and the computer set to record average power (W) and stroke rate. The 250m test was performed between 40-44 strokes.min^{-1} to ensure good technique.

5.3.2.2 Aerobic 'Step-test' ($W_{2mmol \cdot l}{}^{-1}$and $W_{4mmol \cdot l}{}^{-1}$)

Athletes completed a 10 minute warm-up on the test ergometer at a fixed intensity (1:51.0 per 500m). Athletes then completed 5 x 4 minute incremental steps with 30s rest between efforts. Starting loads were based on 55% of the athletes most recent 2,000m ergometer test average power (W_{2000m}) with 5% increases for each of the subsequent 4 steps. Capillary blood lactate samples were taken during the 30s rest interval between stages. Blood was analysed for blood lactate concentration using a Biosen C-Line lactate analyser (EKF Diagnostics, Magdeburg, Germany). Lactate performance curves were plotted and the power produced at 2mmol·l^{-1} ($W_{2mmol \cdot l}{}^{-1}$) and 4mmol·l^{-1} ($W_{4mmol \cdot l}{}^{-1}$) of blood lactate was identified.

5.3.2.3 Strength ($1RM_{press}$ $1RM_{pull}$)

One repetition maximum strength tests were conducted for Bench Press and Bench Pull - chosen as the safest and most rowing specific and reliable tests of strength. Athletes were permitted 3 attempts at each chosen weight, with their result being the heaviest lift deemed acceptable by the UKSCA accredited strength and conditioning coach.

5.3.2.4 Counter-movement Jump (CMJ_{mean}):

Athletes completed an unloaded counter movement jump using a Gymaware linear position transducer, attached to an unloaded bar of minimal weight (Kinetic Performance, Melbourne). Athletes were allowed three attempts and the average power (CMJ_{mean}) from a single jump was recorded in watts.

5.3.3 Data Analysis

Differences between groups was analysed using a one-way ANOVA with post-hoc Tukey for W_{2000m} and all morphological and physiological variables. The results of this statistical analysis are included in table 5.2.

5.3.4 Spider Profile

The ‘Spider Profile’ is a graphical representation of the above physiological parameters (see figures 5.1 & 5.2) which highlight the strengths and weaknesses of individual athletes or group averages. Data is presented as percentages of the Olympic standard (a series of theoretical parameters decided by coach experience and historical data) which are included in the GB Rowing Team Olympic strategy document and due to confidentiality agreements with GBRT, the absolute data is not included in this thesis. Senior team averages are also included to provide context for coaches and athletes.

5.4 Results

Table 5.2 includes a summary of results for ergometer performance, morphological and measured physiological variables. In total, data was collected from 77 athletes. However, due to the remote nature of testing, injury and illness, it was not always possible to complete the full battery of tests for each individual. 57 athletes had partially completed profiles (PART). This data is included in table 5.2, but not included in statistical analysis. The mean scores for each variable are reported in table 5.2 (alongside the number of participants included in the group average). Complete profiles were collected from 20 athletes. This group was further divided into those that were selected for the U23 International squad for the 2013 U23 Rowing World Championships (U23), and those that were not selected (NON). Senior team data from the same testing period is also included (SNR). Figure 5.1 is a Spider Profile of all 4 groups, presented as percentages of the senior squad 'Olympic Standard'. Figure 5.2(A-F) are individual athletes Spider profiles for each member of U23.

Group	Age (yrs)	Height (m)	Weight (kg)	W_{2000m} (W)	W 2mmol·l-1 (W)	W 4mmol·l-1 (W)	W_{5000m} (W)	W_{250m} (W)	1RM press (kg)	1RM pull (kg)	CMJ Mean (W)
U23 (N=6)	20.2†	193.0	94.7	472.8‡	308.8‡	352.8‡	379.2†	731.2	92.1†	85.8†	3049.2
NON (N=14)	21.3†	193.0	91.8	443.0*†	278.4*†	321.4*†	360.8	711.1	93.6	90.4	3418.1
PART	21.3 (N=57)	192.6 (N=57)	92.6 (N=57)	437.9 (N=57)	283.0 (N=24)	321.0 (N=24)	362.8 (N=50)	712.8 (N=10)	95.4 (N=20)	92.7 (N=21)	3502.2 (N=18)
SNR (N=15)	25.4*‡	194.0	96.3	496.5‡	333.2‡	381.8‡	409.9*‡	777.6‡	112.2*‡	102.0*‡	3704.6

Table 5.2. Physiological testing data *=significantly different to U23 ($p<0.05$), ‡=significantly different to NON ($p<0.05$), †=significantly different to SNR ($p<0.05$)

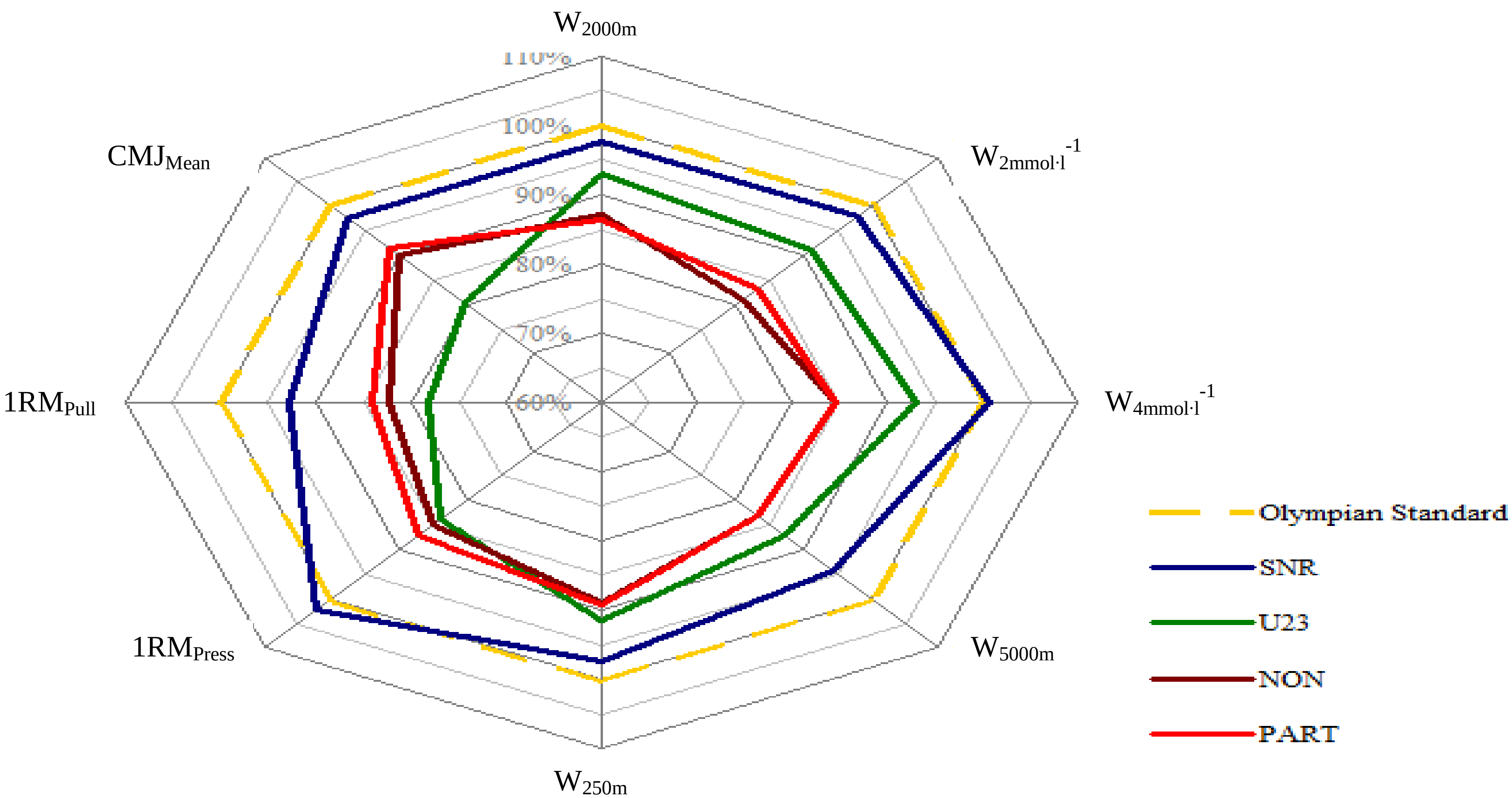


Figure 5.1. Spider profile of group average data as a percentage of "Olympian Standard"

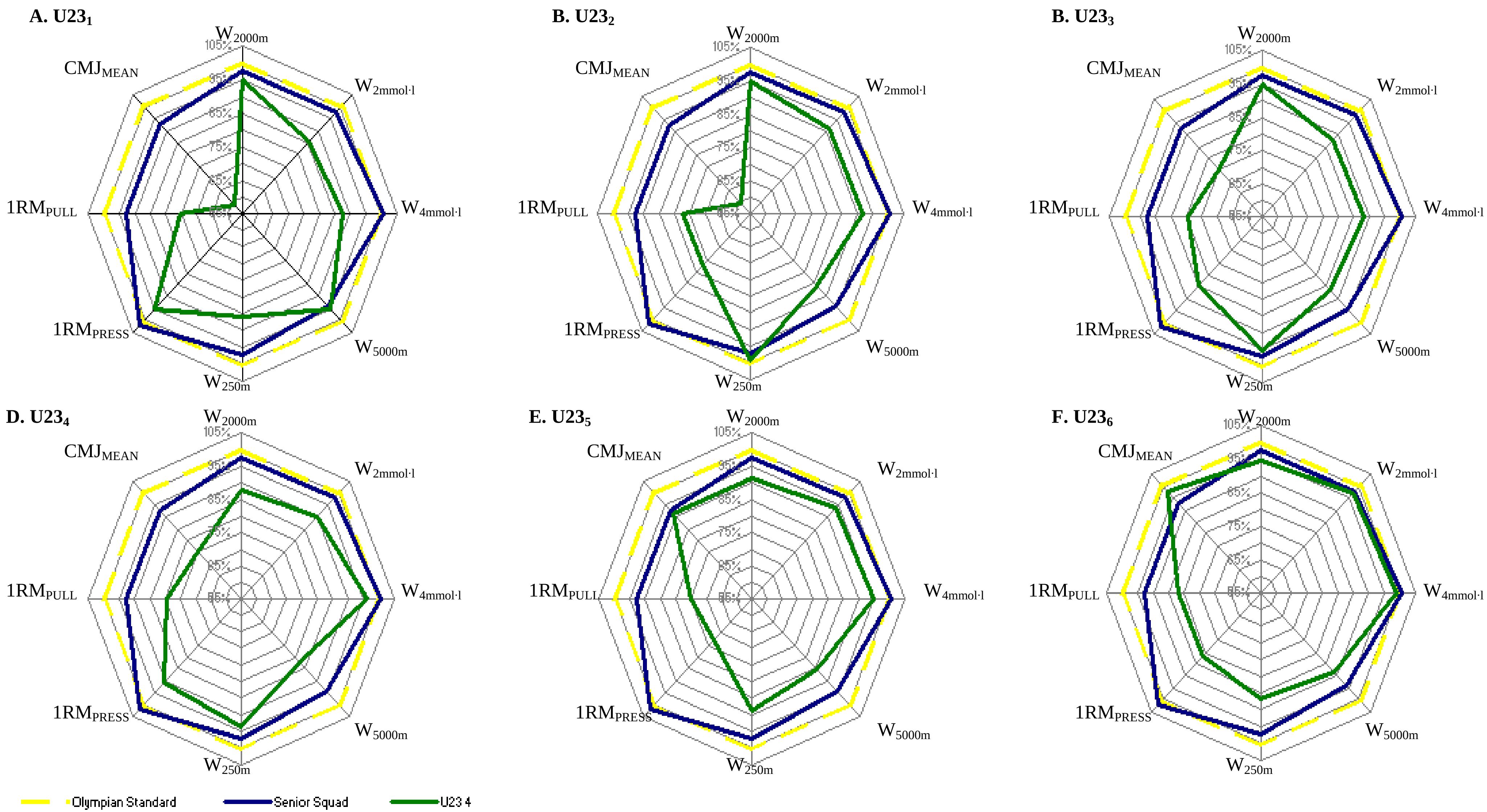


Figure 5.2. (A-F) Individual Spider Profiles for U23 international athletes

5.5 Discussion

5.5.1 SNR & U23/DEV profiles

The primary aim of this study was to compare the physiological determinants of rowing performance in the GBRT 'sub-elite' development programme with senior team athletes using 'Olympic Standards' as a guide. SNR athletes achieved significantly better results than NON athletes in all tested variables with the exception of CMJ_{mean} In comparison to U23, SNR achieved significantly better results in W_{5000m} and $1RM_{press,}$ $1RM_{pull}$, but no other variables, including 2,000m performance (W_{2000m}).

Study 1 of this thesis attempted to explain the variation in 2,000m based on differences in the currently measured physiological determinants of rowing performance. Squads were analysed in homogenous gender and competitive level groups, and this was suggested as a reason for the poor explanation of variance reported. The strongest predictor of performance for senior open weight men in study 1 was $W_{4mmol \cdot l}{}^{-1}$ (25%). In agreement, the results of the current research suggest that aerobic indices such as $W_{2mmol \cdot l}{}^{-1}$, and in particular $W_{4mmol \cdot l}{}^{-1}$ are key determinants in the international selection of developmental rowers as U23 athletes could not be statistically separated from SNR athletes in terms of these variables.

Senior athletes were significantly stronger than both development groups in 1RM markers ($p<0.05$). This is in contradiction to Study 1. This could be explained by the ability of these athletes to dedicate more time to weight lifting in their weekly training programme. Senior team athletes will lift weights (on average) 3 times per week during the season. Garcia-Pallares and Izquiendo (2011) suggest 3 weight training sessions as optimal to achieve positive adaptations in muscle strength and power. Development athletes, with less time available for training will, at most, lift weights 1-2 times per week.

The profile of U23 athletes in this study appears different to the findings of Study 1, which suggested that DEV_{men} (not distinguished by international selection) had increased reliance on strength markers to explain performance. This was attributed to the time frame required to develop sub-maximal aerobic capacity in elite athletes. By comparing means, study 1's data suggests that DEV_{men} are stronger than the U23 athletes in this study, but weaker in aerobic indices such as $W_{2mmol \cdot l^{-1}}$ and $W_{4mmol \cdot l^{-1}}$. It therefore appears that the isolation of international development athletes, as in this study, provides useful information regarding the determinants of success at a development level.

5.5.2 U23 & NON profiles

A comparison of International (U23) and non-international (NON) development athletes was also included. U23 recorded a significantly higher average power output during a 2,000m ergometer test than NON. Endurance indices ($W_{2mmol \cdot l^{-1}}$, $W_{4mmol \cdot l^{-1}}$ and W_{5000m}) also set U23 athletes apart from NON athletes. There were no significant differences between U23 and NON athletes for $W_{250m,}$ $1RM_{press}$, $1RM_{pull}$ or $W_{CMJ.}$ Mean values (displayed in table 5.2 and figure 5.1) suggest NON outperform U23 in these variables (with the exception of $W_{250m,}$). NON (and other non-international athletes with incomplete profiles - PART), appear to exhibit an increased reliance on strength and power determinants to achieve a performance, as in the DEV_{men} group from study 1. This is reflected in the shape of the U23 spider profile (figure 5.2) which highlights the 'skew' towards endurance indices ($W_{2mmol \cdot l^{-1}}$, $W4_{mmol \cdot l^{-1}}$ and W_{5000m}) in U23.

The ability to differentiate between international and non-international development athletes using sub-maximal aerobic indices suggests that aerobic determinants outweigh strength and maximum power production in developmental rowers. This is of no surprise due to the large emphasis placed on aerobic training in rowing (Fiskerstrand &

Sieler, 2004) and the previously reported relationships between maximal and sub-maximal markers of aerobic capacity in both senior (Ingham et al., 2002) and junior athletes (Mikulic, 2008). The shift in profile shape towards indices of strength and power, seen in the NON group Spider Profile suggests that excelling in these indices is not sufficient to achieve international selection. As highlighted in study 2 of this thesis, aerobic variables such as $W_{4mmol \cdot l^{-1}}$ will continue to improve throughout an athlete's career and differentiate between Olympians and non-Olympians. NON athletes should seek to develop their endurance capacity as it appears that markers of this parameter are more conducive to success in rowing than the limited effect of strength and power training.

A further explanation for the difference in W_{2000m} and international selection of U23 athletes is technical proficiency. The U23 group performed better in the rowing specific elements of the Spider Profile including W_{2000m}, W_{5000m} and the sub-maximal rowing assessments of aerobic capacity $W_{2mmol \cdot l^{-1}}$ and $W_{4mmol \cdot l^{-1.}}$. The rowing stroke (on water or ergometer) requires the accurate and well timed application of force (Soper & Hume 2004). Although inferior in markers of absolute strength and power, it is possible that the U23's were 'strong enough' and performance in rowing specific tests is an indication of a superior ability to apply force and load the posterior chain, in order to achieve a more effective stroke and avoid 'leaking' power unnecessarily. From the results presented here, it could be suggested that a large number of the athletes tested more than fulfil the strength and power requirements of an U23 international athlete, but struggle to translate the power to the rowing stroke. Therefore, more time should be spent improving the delivery of power at the expense of improving these variables.

In terms of talent identification, it is possible that the recruitment of athletes via University or the GBRT START programme is skewed towards stronger athletes with the ability to produce large amounts of power explosively. Phase 1 of the GBRT talent identification involves nationwide recruitment drives alongside the systematic testing of school/university students who fulfil a simple height requirement. Phase 2 involves a series of physiological tests designed to identify those with the potential to succeed in elite rowing. Successful athletes are then assigned to rowing clubs where their skills can be developed and their training managed. An increased emphasis on aerobic indices of performance and their trainability during recruitment may alter the physiological profile of GBRT development rowers and their subsequent 2,000m performance (a known correlate of performance at international regattas – Mikulic et al., 2009a).

Although difficult, a measure of the ability to effectively apply power in a rowing specific situation would be a beneficial recruitment test for potential rowers. It appears that the counter-movement jump is not an appropriate assessment as NON athletes were able to out perform U23 internationals. Although replicating the movement pattern of a rowing stroke, this measure does not include an element of ‘timing’ or ‘feel’ necessary when moving an oar through the water.

5.5.3 The use of Spider Profiles

The parameters selected for inclusion on the spider profile were initially based on the results of Study 1 of this thesis. The physiological markers tested then were those already used as regular assessments with the GBRT. The results of study 1, study 2 and previous research (Ingham et al 2002, Nevill et al 2011) have suggested that $W_{4mmol \cdot l^{-1}}$ is essential due to the importance of sub-maximal aerobic capacity. $\dot{V}O2_{peak}$ was not included in the testing battery. Although previous research has highlighted its importance to rowing performance (Seiler, 2006) it was felt that the spider profile should be accessible to coaches and athletes nationwide, rather than only those with access to a laboratory. Lactate profiling, although still requiring specialist input, is possible in a field environment.

The influence of 250m speed on SNR_{women} performance in Study 1 suggested it was a useful addition to a physiological profile in terms of assessing anaerobic capacity – a quality reported to be of significant importance to rowing performance (Reichman et al., 2002; Ingham et al., 2002). While senior athletes were significantly more powerful than NON, no difference was observed between NON and U23. The aerobic contribution to a ~45s effort and rowing specific nature of the test is a possible explanation for U23 athletes achieving a similar average score to the NON, unlike other markers of strength and power.

The assessment of strength via 1RM was a controversial topic in coach/scientist discussions. It was felt that maximum lifts were inappropriate for a large percentage of the development rowers who have different degrees of weight room technical competency. Therefore, the safer exercises - bench press and bench pull were retained, but the more technical power clean was removed. Instead, an unloaded counter-movement jump was included in an attempt to assess raw power production. The distribution of results from this measure suggest that it has little impact on rowing performance as U23 are deficient in comparison to non-selected individuals and the senior team. As previously mentioned, the mean power from a counter movement jump may involve no ‘rowing specific’ technique as it does not include technical factors such as timing at the catch position or loading of the posterior chain. It is also possible that the measurement of CMJ_{mean} using a linear position transducer has limitations caused by the displacement of the cable during a jump. Although less practical, the use of a force platform may provide more accurate results. The inclusion of a maximum ‘rowing power' test could also provide a more valid measure and provide a marker to assess the transfer of raw power to a rowing environment.

For each development rower tested during the initial year of this study, their coach was issued with a spider profile spreadsheet. This was intended to provide them with an analysis of their athlete's physiological status and their development relative to the previous years U23 team, and the senior rowers. Coaches reported that the spider profile provided a useful visual representation of their athletes and prompted both individual and squad based training interventions to address weaknesses highlighted by the shape of the graph.

The method is not without its limitations. Using the percentage difference between development athletes and an 'Olympic Standard' could be misleading, and the relationship between SNR scores and OLY standards highlight this. As postulated in Study 1, individual differences in athlete profiles appear to differentiate 2,000m ergometer performances in homogenous groups. Failing to achieve an Olympic Standard in one determinant of performance is not necessarily critical to success. These values are based on historical values and coach experience/expertise and may misrepresent the demands of elite rowing performance. The use of an absolute data 'power profile' (plotting power output data at various points between a maximal effort and endurance test) could provide a more straightforward representation of an athlete's physiological profile.

5.6 Conclusion

In conclusion, this study collected physiological profiles of GBRT development rowers using a battery of tests designed to represent the demands of elite rowing performance. This data, presented via a Spider Profile suggested that those athletes who are selected for international competition at the end of the season rely on aerobic indices of performance rather than strength and power markers. This has implications for the identification and training of new and already established young rowers.

CHAPTER 6:

THE INDIVIDUALISATION OF AN ELITE ROWING CREW'S PHYSICAL TRAINING PROGRAMME

6.1 Abstract

Based on previously identified physiological determinants of rowing performance, this study involved profiling and adapting a generic training programme in order to address individual weaknesses. 6 members of an international rowing crew, preparing for a long-course regatta, completed a battery of physiological tests adapted from the previous studies included in this thesis. Measurements of maximal aerobic capacity ($\dot{V}O_{2peak}$), the rowing power associated with it ($W\dot{V}O_{2peak}$), sub-maximal aerobic capacity via the power associated with 2&4mmol·l^{-1} blood lactate ($W_{2mmol \cdot l^{-1}}$ and $W_{4mmol \cdot l^{-1}}$), maximum rowing power (W_{max}) and an unloaded counter-movement jump (CMJ_{mean}) were conducted. Athletes were assigned to either an endurance (END, N=4) or maximal power (MAX, N=2) group depending on the results of their profile. All rowers completed a generic rowing training programme (an average of 131 km per week) with 2/14 sessions per week comprising either high intensity aerobic interval training or additional weight lifting. Results were analysed as a case series with individual responses discussed as the lack of control group made the relative impact of training interventions difficult to assess. 3/4 END athletes improved aerobic indices, in particular $\dot{V}O_{2peak}$, but made no improvements in markers of power production. MAX athletes improved their maximum power and aerobic performance. This was attributed to increased mechanical efficiency, muscle coordination and recruitment, strength related technical improvements or the reduced relative intensity of sub-maximal work leading to a conservation of energy. In conclusion, the minor adaptation of a generic rowing training programme, based on individual profiling, can have a marked effect on the physiological adaptation of athletes struggling to make progress in a traditional high-volume/low-intensity system.

6.2 Introduction

Endurance training methods have evolved over the last 50 years leading to the identification of more effective strategies to produce high performing athletes (Seiler, 2010). As with other endurance sports, a common distribution of 80:20 (low intensity:high intensity training) is employed with elite rowing teams (Guellich et al., 2009, Fiskerstrand & Seiler, 2004). Such a training model places emphasis on peripheral and central adaptations to endurance training, and helps reduce the sympathetic stress, muscle damage, and blood lactate accumulation associated with high intensity training (Gulstrand, 1996).

There is evidence to suggest that this method of training will not work for all endurance athletes (Gaskill et al 1999). Ingjer (1991) amongst others (*i.e.* Mikulic, 2011a) report performance plateaus following multiple years of endurance training using this 80:20 model. Study 2 of this thesis reported a 3rd year stagnation in the power associated with a blood lactate of 4mmol·l^{-1} ($W_{4mmol \cdot l^{-1}}$) in rowers failing to be selected for the Olympic games, while 'successful' Olympians continued to develop this parameter following identical training programmes. Gaskill et al. (1999) postulated that athletes that plateau may have reached a 'ceiling' of development, or may require a change in training stimulus to improve performance. In an attempt to address this performance plateau, Gaskill et al. (1999) assigned cross-country skiers to a one-year high-intensity, low volume regime based on their poor response to a one-year high-volume/low-intensity programme. The authors reported significant improvements in $\dot{V}O_{2peak}$, lactate threshold and competitive performance. In contrast, the improvement in the control group was similar to that experienced after the initial high volume/low intensity one-year training programme.

Changes in cellular signalling caused by a shift in training intensity may allow athletes to improve endurance performance via the development of other contributing factors. While large volumes of low intensity training may be best suited to the development of factors such as increased mitochondrial density and capilarisation, higher intensity 'interval training' may be more effective in developing factors such as cardiac function and buffering capacity (Seiler & Tonnessen, 2009).

Another limitation of high volume/low intensity endurance training is its effects on strength and subsequent maximum power development. Athletes can struggle to improve strength due to the demands of high volume aerobic training and the interference phenomenon (Garcia-Pallares & Izquierdo, 2011, Izquierdo-Gabarren et al., 2010, Docherty & Sporer, 2000). Acutely, when completing several training sessions in a day, residual fatigue can lead to reduced capability of the muscle to maximally contract during a weight training session (Leveritt et al., 1999). Also, depleted glycogen levels can cause disruption in optimal signalling responses (Creer et al 2005) and a catabolic state reduces total protein synthesis rate (Nader, 2006). Chronically, the difference in muscle recruitment patterns and shift in fibre type instigated through endurance training places opposite metabolic and morphologic demands on the muscle which cannot be met, and the adaptations resulting from strength training are compromised (Leveritt et al., 1999).

An optimal training programme will seek to develop the physiological factors that dictate performance. Previous research has investigated the determinants of performance in elite rowers (Ingham et al., 2002; Mikulic, 2008; Jurimae et al., 2010). Anthropometric indices, $\dot{V}O_{2max}$, the power associated with $\dot{V}O_{2max}$ ($W\dot{V}O_{2max}$), $W_{4mmol \cdot l^{-1}}$ and various strength/maximum power markers have all been recognised in studies using heterogenous groups of rowers. The usefulness of these studies to the training of elite homogenous groups is limited. Individual differences in performance and its determinants are small. Study 1 of this thesis reported limited explanation of variance using a range of recognised physiological tests in groups of Great Britain Rowing Team (GBRT) senior and development, male and female rowers. It was postulated that while high values are necessary for success at the highest level, once a minimum level for each determinant is reached, differences in performance are based on relative strengths, suggesting that individual interventions may be significant in optimising the training and subsequent performance of these endurance athletes.

In response to this, GBRT have adopted the physiological ‘Spider Profile’ system of athlete profiling as described in Study 3 of this thesis. A battery of tests which assessed the major physiological determinants of rowing performance was refined to provide an analysis tool for coaches and practitioners. This system was introduced throughout the GBRT development system to help inform bespoke programming and enhance performance. To date, this approach has not been undertaken with elite, senior rowers.

Based on previous studies, the first aim of this study was to physiologically profile an elite, senior rowing crew. Second, based on individual results, athletes were to be prescribed individual training sessions within a generic training programme in order to improve weaknesses that contribute to performance.

6.3 Methods

6.3.1 Experimental Design

Six elite level rowers from a senior men’s 8+ (age: 24.4 ± 0.4 years, height: 196.5 ± 5.8 cm, mass: 96.6 ± 3.7 kg) completed a 7 week training programme in preparation for the E. ON Hanse Cup rowing regatta (the 2 athletes completing the M8+ crew were unavailable for the beginning of the training period and therefore not included in this study). Participants reported to the laboratory following 14 days ‘active recovery’. On commencement of the training block (day 1 and 2), athletes conducted a series of physiological tests in order to profile each individual and identify physiological strengths and weaknesses. This test data was presented in ‘Spider profiles’ (see Figure 6.1). Tests were repeated within 7 days following the regatta.

6.3.1.1 Anthropometry:

Height (cm) and body mass (kg) were recorded using a stadiometer (Holtain, Crymych, Pembrokshire) and electronic scales (Marsden, Rotherham, England) respectively. Sum of seven skinfolds was assessed by the same experimenter using callipers (Harpenden, West Sussex, England) according to ISAK guidelines. The total score of Tricep, Sub-Scapular, Bicep, Supra-Spinale, Abdominal, Quadriceps and Calf were reported in millimetres.

6.3.1.2 Counter-movement Jump (CMJ_{mean}):

Athletes completed an unloaded counter movement jump using a Ballistic Measurement System force platform (Innervations, Australia). Athletes were allowed three attempts (verified by a UKSCA accredited coach) and average power (CMJ_{mean}) from a single jump were recorded in watts.

6.3.1.3 Maximum Rowing Power (W_{max}):

Athletes warmed-up for 2 minutes at a fixed intensity (1:51.0 per 500m) then rowed 7 strokes at a stroke rate of 34 strokes.min^{-1}, increasing the intensity with each stroke, culminating in 2 maximal rowing stroke efforts. The highest power (W_{max}) measured via the CII PM3 monitor during a single stroke was recorded.

6.3.1.4 250m Rowing Power (W_{250m}):

Athletes warmed-up for 2 minutes at a fixed intensity (1:51.0 per 500m) then rowed a maximal effort 250m at a stroke rate of 40-44 strokes.min$^{-1.}$ The average power (W_{250m}) measured via the CII PM3 monitor was recorded.

6.3.1.5 Aerobic Step-Test ($W_{2mmol\cdot l^{-1}}$, $W_{4mmol\cdot l^{-1}}$, $\dot{V}O_{2peak}$, $W\dot{V}O_{2peak}$)

Tests were conducted in an air conditioned laboratory (18°C, RH = 35%). The generic squad training programmes did not include intensive exercise 24 hours prior to laboratory assessment Sessions were limited to steady-state (≤2 $mmol\cdot l^{-1}$.) exercise. Training on the day of the laboratory assessment was standardised to 12,000m low-intensity (≤2 $mmol\cdot l^{-1}$.), steady-state ergometer rowing in order to help meet weekly training mileage demands. This session was completed >3hrs prior to the laboratory test to allow ample time for rest and refuelling. Athlete avoided caffeine consumption prior to testing.

Athletes completed a 10 minute warm-up on the test ergometer at a fixed intensity (1:51.0 per 500m). Athletes then completed 5 x 4 minute incremental steps with 30s rest between efforts. The 1st step was set at 270W with each stage increased by 25 watts. On completion of the 5th and final step, all athletes rested for 150s before completing a 4 minute maximal effort in order to identify $\dot{V}O_{2peak}$.

CII power and stroke rate (SPM) were recorded from the ergometer computer for all 6 steps. Capillary blood lactate samples were taken during the 30s rest interval between stages. Blood was analysed for blood lactate concentration using a Biosen C-Line lactate analyser (EKF Diagnostics, Magdeburg, Germany, Coefficient of Variation 1.5% at 12 mmol·l]). Lactate was regressed against power and the watts produced at 2$mmol\cdot l^{-1}$ ($W_{2mmol\cdot l^{-1}}$) and 4$mmol\cdot l^{-1}$ ($W_{4mmol\cdot l^{-1}}$) of blood lactate were calculated by polynomial interpolation and internally verified.

Inspired/expired air was analysed using an Oxycon Pro ‘breath-by-breath’ metabolic system (Jaeger, Viasys Healthcare, Yorba Linda, CA). The gas analysers were calibrated using gases of a known concentration and the flow volume was calibrated using a standardised 3 litre syringe prior to every test. Values of oxygen consumption ($\dot{V}O_2$, calculated using the differential-paramagnetic principle, [Coefficient of Variation 3% or 0.05 $l{\cdot}min^{-1}$]), carbon dioxide expiration ($\dot{V}CO_2$, calculated using the infared absorption principle [Coefficient of Variation 3% or 0.05 $l{\cdot}min^{-1}$]), ventilation, ($\dot{V}_E$, measured via a flat turbine digital volume sensor, [Coefficient of Variation 2% or 0.05 $l{\cdot}min^{-1}$]), were monitored during the test and averaged for the last minute of each stage. $\dot{V}O2_{peak}$ was defined as being the highest 15s average oxygen consumption measured during the 4 minute maximum effort. The power associated with $\dot{V}O2_{peak}$ ($W\dot{V}O2_{peak}$) was calculated by regressing $\dot{V}O2_{peak}$ in the equation for power and $\dot{V}O_2$ from the 5 sub-maximal steps.

6.3.1.6 Further Measures:

A regularly monitored endurance training session within the GB Rowing Team requires athletes to row the furthest distance possible in 30 minutes at 20 strokes per minute (W_{30min}). Distance (m), time per 500m (split), CII power and stroke rate were recorded. This test was completed in week 1, post-intervention, and as training sessions on 3 further occasions during the 7 week training block.

6.3.2 Programme selection

On completion of the testing protocol and the construction of Spider Profiles (Figure 6.1), athletes were assigned to one of two training groups based on coach and scientist discussion: Endurance (END, n=4) or Maximum Power (MAX, n=2). Athletes then followed a generic rowing training programme plus the addition of two group specific sessions per week based upon their group assignment.

6.3.2.1 Baseline Programme:

The baseline training programme was written in conjunction with the crew coach and considered a standard 8 week preparation for the E.On Hanse Cup (Appendix A). All athletes completed an average of 131km per week of rowing and ergometer training which followed a traditional elite rowing structure based on an 80-20 distribution of low-high intensity training. Three gym based weight training sessions were included per week, with the aim of increased load, volume and speed of movement leading to increased lean muscle mass and rate of force production (see Table 6.3 and Appendix C for a summary of athletes MAX_1 and END_2 weight training). The timing of sessions for 'individual training' was designed to have minimal negative impact on crew based water training.

6.3.2.2 Endurance Programme:

Athletes in the Endurance group (END) completed 13 (2 per week, 1 in week 7) group specific training sessions during the 7 week training block (see Appendix B for session examples). Athletes completed a 3km warm-up prior to a series of high intensity intervals and were prescribed active recovery between repetitions and sets of repititions. Athletes were given instructions as to the intensity of the repetitions in each session in the form of percentage of maximum effort, RPE and the training zones used by the GB Rowing Team.

6.3.2.3 Maximum Power Programme:

Athletes in the maximum power development group (MAX) completed 30 (4 to 5 sessions per week) weight training sessions during the 7 week training block (see Appendix C) compared with END athletes who completed 18 sessions (2 to 3 sessions per week). The emphasis of this training was increased lean muscle mass, followed by neuromuscular conditioning and rate of force development. A summary of the distribution of strength training for END_1 and MAX_2 can be found in Appendix C.

6.3.3 Training adherence

Athletes were asked to complete an online training diary which recorded training adherence, volume, intensity and rate of perceived exertion for each session. Blood lactate samples were taken during key endurance sessions to monitor intensity.

6.4 Results

Table 6.1 provides information regarding the intensity zones used for training prescription. Table 6.2 includes the distribution of rowing/ergometer kilometres for END & MAX groups during the 7 week programme. Table 6.3 explains the differences in weight training for END and MAX during the 7 week programme. The session-by-session training programme is available in Appendix A.

Training Zone	Heart Rate (% of Max)	Blood Lactate (mmol·l-1)	Stroke Rate (SPM)
1	59-67%	<2.0	17-18
2	67-75%	2.0 - 4.0	19-23
3	75-85%	~4.0	24-28
4	85-100%	~4.0 - 8.0	28-36
5	~	~8.0 +	>36
6	~	~	>26

Table 6.1. Rowing/Ergometer Training Zone Physiological Parameters distribution

Week	Rowing/Ergometer Training Zone Distribution (km/%)													
	1		2		3		4		5		6		Total Mileage (km)	
	MAX	END	MAX	END	MAX	END	MAX	END	MAX	END	MAX	END	MAX	END
1	118	126	17	17	10	22	1	1	1	1	0	0	**147**	**167**
	80.3%	*75.4%*	*11.6%*	*10.2%*	*6.8%*	*13.2%*	*0.7%*	*0.6%*	*0.7%*	*0.6%*	*0.0%*	*0.0%*	***100%***	***100%***
2	149	157	12	12	10.5	27.5	1	1	0.25	0.25	1	1	**173.8**	**198.8**
	85.8%	*79.0%*	*6.9%*	*6.0%*	*6.0%*	*13.8%*	*0.6%*	*0.5%*	*0.1%*	*0.1%*	*0.6%*	*0.5%*	***100%***	***100%***
3	108	108	0	0	2	11.5	2	4.5	8.3	0	2	2	**122.3**	**126**
	88.3%	*85.7%*	*0.0%*	*0.0%*	*1.6%*	*9.1%*	*1.6%*	*3.6%*	*6.8%*	*0.0%*	*1.6%*	*1.6%*	***100%***	***100%***
4	97	105	8	8	4	5	1	8	0	1	0	0	**110**	**127**
	88.2%	*82.7%*	*7.3%*	*6.3%*	*3.6%*	*3.9%*	*0.9%*	*6.3%*	*0.0%*	*0.8%*	*0.0%*	*0.0%*	***100%***	***100%***
5	119	127	8	8	13	13	1	4.5	0	6.5	0	0	**141**	**159**
	84.4%	*79.9%*	*5.7%*	*5.0%*	*9.2%*	*8.2%*	*0.7%*	*2.8%*	*0.0%*	*4.1%*	*0.0%*	*0.0%*	***100%***	***100%***
6	100	108	8	8	9	11	4	6.5	1	7.5	1	1.1	**123**	**142.1**
	81.3%	*76.0%*	*6.5%*	*5.6%*	*7.3%*	*7.7%*	*3.3%*	*4.6%*	*0.8%*	*5.3%*	*0.8%*	*0.8%*	***100%***	***100%***
7	83.5	87.5	0	0	0	1	0	2	17.7	18.7	0	0	**101.2**	**109.2**
	82.5%	*80.1%*	*0.0%*	*0.0%*	*0.0%*	*0.9%*	*0.0%*	*1.8%*	*17.5%*	*17.1%*	*0.0%*	*0.0%*	***100%***	***100%***

Table 6.2. Weekly rowing/ergometer training volume and intensity distribution for MAX and END

Week	Strength/Power Training Zone Distribution (%)					
	Strength Intensity		Strength Volume		Loaded Power	
	MAX	END	MAX	END	MAX	END
1	*0.0%*	*0.0%*	*80.9%*	*84.2%*	*19.1%*	*15.8%*
2	*17.2%*	*0.0%*	*78.3%*	*78.2%*	*4.6%*	*21.8%*
3	*49.5%*	*57.0%*	*37.0%*	*0.0%*	*13.4%*	*43.0%*
4	*54.2%*	*58.7%*	*35.9%*	*20.8%*	*10.0%*	*20.5%*
5	*63.4%*	*66.6%*	*21.6%*	*14.2%*	*15.0%*	*19.2%*
6	*64.8%*	*69.5%*	*26.0%*	*10.5%*	*9.2%*	*20.0%*
7	*70.1%*	*70.8%*	*21.5%*	*29.2%*	*8.4%*	*0.0%*

6.3. Weekly strength/power training distribution for MAX and END

Athletes reported 100% adherence to the training programme. No illnesses were encountered during the 7 weeks. When athletes suffered minor injuries that prevented them from rowing, sessions were completed on a static bicycle with a power display (Wattbike, Nottingham England). Table 6.4 summarises the cross-training sessions completed per week for all 6 participants for strength and endurance sessions.

	Week 1		**Week 2**		**Week 3**		**Week 4**		**Week 5**		**Week 6**		**Week 7**	
END_1	Row Ergo	Gym	Row Ergo	Gym	Row Ergo	Gym	Row Ergo	Gym	Row Ergo	Gym	Row Ergo	Gym	Row Ergo	Gym
END_1	– *12*	– *2*	– *15*	– *3*	– *14*	– *3*	– *11*	– *3*	– *11*	– *3*	– *10*	– *3*	– *10*	– *1*
END_2	2 *12*	– *2*	– *15*	– *3*	– *14*	– *3*	– *11*	– *3*	– *11*	– *3*	– *10*	– *3*	– *10*	– *1*
END_3	– *12*	– *2*	– *15*	– *3*	– *14*	– *3*	– *11*	– *3*	– *11*	– *3*	– *10*	– *3*	– *10*	– *1*
END_4	– *12*	– *2*	– *15*	– *3*	– *14*	– *3*	4 *11*	– *3*	– *11*	– *3*	– *10*	– *3*	– *10*	– *1*
MAX_1	4 *10*	– *4*	– *13*	– *5*	– *12*	– *5*	1 *9*	– *5*	– *9*	– *5*	– *8*	– *5*	– *9*	– *2*
MAX_2	1 *10*	– *4*	– *13*	– *5*	2 *12*	– *5*	1 *9*	– *5*	– *9*	– *5*	– *8*	– *5*	– *9*	– *2*

Table 6.4. Cross-training sessions per week for all 6 participants. Italic text represents the programmed sessions per week divided into rowing/ergometer (Row/Ergo) and weight training (Gym).

Table 6.5 includes pre and post intervention data for all 6 individual athletes, the percentage change between tests, and pre-intervention personal bests where available. Figure 6.1$^{(a-f)}$ includes Spider Profiles for each athlete, and were used (alongside raw data) during coach-scientist discussions during the allocation of athletes to END and MAX training groups.

		Weight (kg)	Sum of skinfolds (mm)	Gluteal Girth (cm)	Mid Thigh Girth (cm)	W_{30min} (W)	W_{4min} (W)	$W_{2mmol \cdot l^{-1}}$ (W)	$W_{4mmol \cdot l^{-1}}$ (W)	Max Lactate ($mmol \cdot l^{-1}$)	$\dot{V}O_{2peak}$ (l.min)	$W\dot{V}O_{2peak}$ (W)	W_{max} (W)	CMJ_{mean} (W)	W_{250m} (W)
END_1	**Pre-intervention**	97.3	70.8	104.0	56.5	305.6	325.7	283.0	316.0	8.37	5.6	341.1	829.6	3816.9	907.1
	Post-intervention	99.0	67.3	105.4	59.7	308.5	373.7	322.0*	347.0	7.7	6.3*	380.0	797.2	4046.5	937.7
	Pre-post difference	*1.7%*	*-5.0%*	*1.3%*	*5.7%*	*0.9%*	*14.7%*	*13.8%*	*9.8%*	*-8.0%*	*11.5%*	*11.4%*	*-3.9%*	*6.0%*	*3.4%*
END_2	**Pre-intervention**	94.9	60.2	101.5	56.0	316.6	434.4	285.0	334.0	7.98	5.9	392.1	797.2	4631.6	760.7
	Post-intervention	96.4	69.7	101.2	59.4	343.8*	472.8	325.0*	363.0*	9.09	6.4*	420.4	766.6	4528.3	775.7
	Pre-post difference	*1.6%*	*15.8%*	*-0.3%*	*6.1%*	*8.6%*	*8.8%*	*14.0%*	*8.7%*	*13.9%*	*7.3%*	*7.2%*	*-3.8%*	*-2.2%*	*2.0%*
END_2	**Pre-intervention**	92.7	53.5	104.0	58.5	298.1	381.8	278.0	318.0	11.50	6.3	362.3	737.5	3952.0	896.0
	Post-intervention	95.0	55.6	103.9	59.3	335.6*	454.5	318.0	359.0	8.8	7.0*	387.5	737.5	4106.7	933.7
	Pre-post difference	*2.5%*	*3.9%*	*-0.1%*	*1.4%*	*12.6%*	*19.0%*	*14.4%*	*12.9%*	*-23.5%*	*11.2%*	*7.0%*	*0.0%*	*3.9%*	*4.2%*
END_4	**Pre-intervention**	95.6	58.6	105.2	56.5	295.5	403.8	255.0	294.0	12.5	6.1	373.5	766.6	4351.2	800.5
	Post-intervention	99.6	66.0	106.3	59.0	315.6	444.3	275.0	311.0	13.5	6.3*	406.4	766.6	3991.3	823.0
	Pre-post difference	*4.2%*	*12.5%*	*1.0%*	*4.4%*	*6.8%*	*10.0%*	*7.8%*	*5.8%*	*8.0%*	*3.4%*	*8.8%*	*0.0%*	*-8.3%*	*2.8%*
MAX_1	**Pre-intervention**	103.4	83.3	106.0	63.0	313.8	442.8	298.0	337.0	12.39	6.3	383.5	797.2	3744.8	797.2
	Post-intervention	106.4	83.7	109.1	65.0	337.6	472.8	329.0	373.0	9.2	6.6	421.7	829.6	4511.4	836.2
	Pre-post difference	*2.9%*	*0.5%*	*2.9%*	*3.2%*	*7.6%*	*6.8%*	*10.4%*	*10.7%*	*-25.7%*	*5.1%*	*10.0%*	*4.1%*	*20.5%*	*4.9%*
MAX_2	**Pre-intervention**	95.6	67.1	109.0	57.2	290.6	387.7	292.0	323.0	11.47	6.0	379.0	766.6	3381.5	729.1
	Post-intervention	97.3	55.0	107.9	58.8	316.6	454.5	312.0	345.0	5	6.1	378.9	737.5	4092.0	769.6
	Pre-post difference	*1.8%*	*-18.0%*	*-1.0%*	*2.8%*	*8.9%*	*17.2%*	*6.8%*	*6.8%*	*-56.4%*	*2.2%*	*0.0%*	*-3.8%*	*21.0%*	*5.6%*

Table 6.5. PB, Pre-Post physiological testing data (including Personal Best scores where available)* = New personal Best

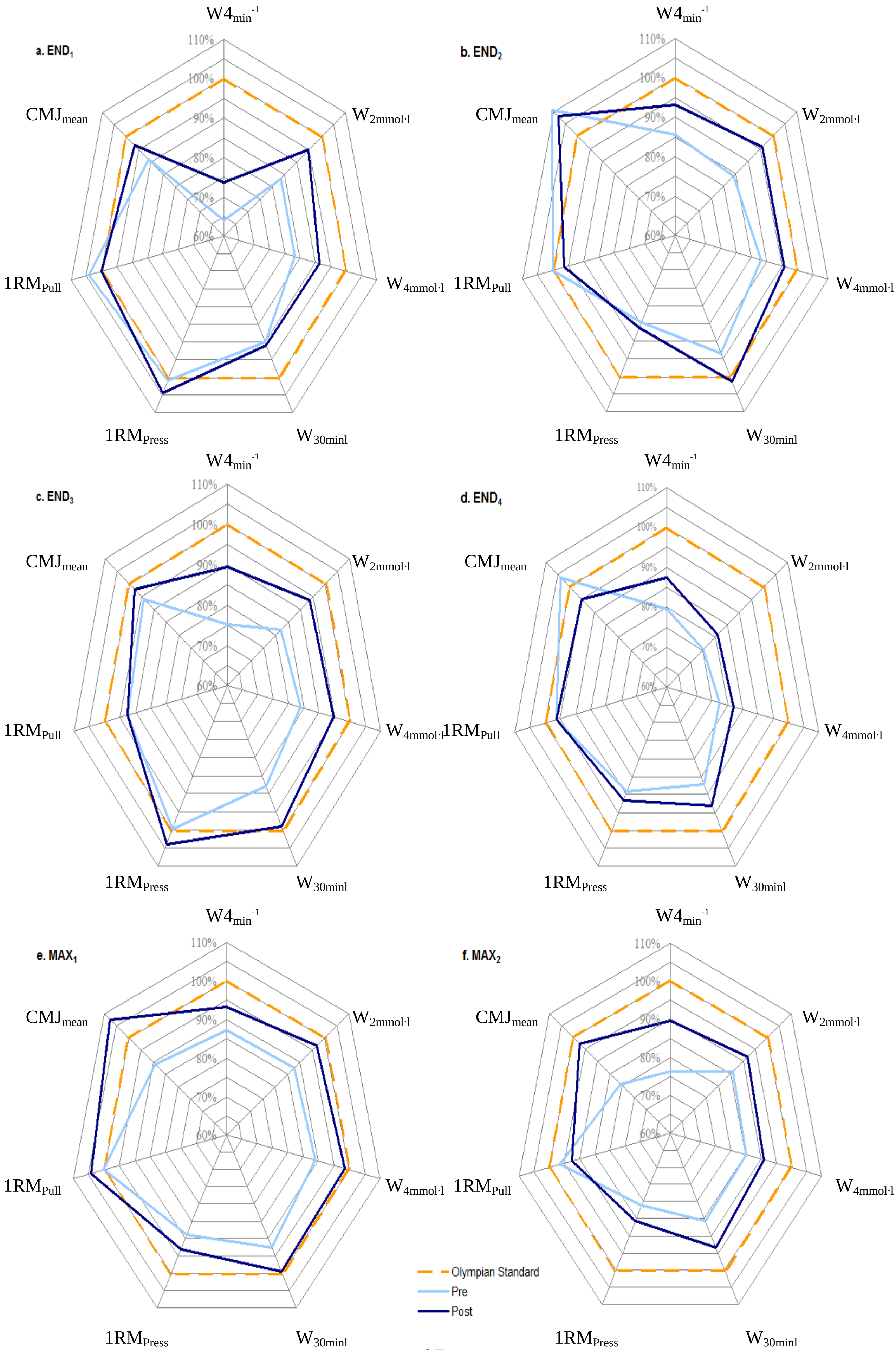


Figure 6.1.(A-F) Individual Spider Profiles for all athletes

6.5 Discussion

The primary aim of this study was to investigate the effectiveness of profiling elite rowers, and introducing individual changes to their squad based training programme. This was intended to identify and improve physiological weakness in the build-up to an international long-course regatta. Individual programmes focused on aerobic adaptations through mixed intensity interval training, and peak power production via increased lean muscle mass, strength, and rate of force production.

6.5.1 Training Periodisation

A key finding from this training intervention study is the feasibility of incorporating an element of individualised programming into a team sport environment, which traditionally adopts a centralised training approach to physiological development. The manipulation of 2 training sessions per week (total sessions = 13, over a 7 week intervention) led to a clear change in focus towards the development of aerobic endurance or maximum power indices, while retaining many of the characteristics of an elite rowing training programme.

6.5.2 Endurance Training Group (END)

In order to address weaknesses in aerobic determinants of rowing performance, 4 athletes were assigned to the END training group. This group completed a total of 13 high intensity interval training sessions, including a 96% increase in the work done above $W_{4mmol \cdot l^{-1}}$ each week (in comparison to MAX, see Table 6.2). Analysing mean scores, this group improved 12.5% in $W_{2mmol \cdot l^{-1}}$, 9.4% in $W_{4mmol \cdot l^{-1}}$, 8.3% in $\dot{V}O2_{peak}$, and 8.5% in $W\dot{V}O2_{peak}$ (see table 6.3 for individual changes). There was also a 7.2% improvement in W_{30min}, including 2 personal best scores.

Of note, MAX athletes also improved in all aerobic indices despite completing a volume based programme with reduced >$W_{4mmol \cdot l^{-1}}$ intensity training. There does appear to be a group dependent difference in $\dot{V}O2_{peak}$ improvement with END athletes generally improving more. Rusko (1992) in a review of elite cross-country skiing training suggested that training at or above the anaerobic threshold is more effective in developing maximal oxygen consumption, while lower intensity training is more effective in developing sub-maximal endurance determinants. This observation could be an indication of minor changes to the intracellular signalling caused by increased training intensity. Increased stroke volume, cardiac output, blood volume & pulmonary diffusion (Garcia-Pallares & Izquierdo 2011) combined with changes in mitochondrial size and density, increased aerobic enzyme activity and lactate handling, could have contributed to the improved $\dot{V}O2_{peak}$ seen here.

Guellich & Seiler (2010) reported a -17.5 to +20% change in $W_{4mmol \cdot l^{-1}}$ amongst a group of elite junior track cyclists following a 15 week endurance training programme. The mode improvement was 7.5%. The 9.4% average increase noted in this study (following a shorter intervention) may have been enhanced by the 14 day active recovery and its subsequent effect on the starting point of these athletes. Ingham et al., (2008) manipulated training intensity by comparing the effects of low-intensity training (100% < lactate theshold) with mixed training (30% > halfway between $\dot{V}O2$ at lactate threshold and $\dot{V}O2_{peak}$) Improvements in 2,000m performance and $\dot{V}O2_{peak}$ occurred independent of training group. However, the participants used were sub-elite, and the training volumes used not relevant to elite endurance athletes. This study attempted to provide an ecologically valid scenario whereby a high training volume was retained alongside the inclusion of interval training above $W_{4mmol \cdot l^{-1}}$.

Although these improvements are clear in 3 of the END athletes, END_4 failed to show any meaningful improvement in aerobic indices of performance. This alternative result highlights the benefit of a case series approach to analysing the responses to training interventions. Heterogeneous responses to the same training highlight the range of factors that can affect adaptation such as genetic factors, disparity in the homeostatic stress experienced by athletes during and after training sessions, sleep, psychological stress and nutritional factors. (Mann et al., 2014).

The 6 athletes participating in this study did so as they were not selected for the 2013 World Rowing Championships. The reasons for this could include technical, tactical or team cohesion related factors. However, the failure to improve physiological determinants of performance during the previous seasons training could also be a factor. Providing an alternative training stimulus may be a means of improving the determinants of performance in such athletes.

Although including 1-2 high intensity interval training sessions in a voluminous training programme had a positive effect on the majority of this group of athletes, there are obvious risks involved in such a strategy. Increasing training stress can lead to an increased risk of injury and illness, and requires extended recovery time. Indeed, although anecdotal feedback suggests that the athletes enjoyed the variation in training, the average RPE from the $>W_{4mmol \cdot l^{-1}}$ sessions in this study was 18, suggesting a high physiological and psychological demand. It is recommended that while the model employed in the current study can provide effective results, it should remain a carefully monitored short-term intervention. More research is required to investigate the longer term development of athletes who follow a traditional rowing training programme, while including periods of increased intensity training.

6.5.3 Maximum Power Training Group (MAX)

Strong evidence supporting the notion of individualised training within an elite squad programme is provided by the power test results of the MAX group. Increasing the weight training exposures from 3 (standard GBRT practice) to 5 (while END completed their high-intensity interval sessions) had a demonstrable effect on the peak and average power production measured through a counter movement jump and maximum rowing power, as well as potentially assisting improvements in anaerobic capabilities (W_{250m}) aerobic indices ($W_{2mmol \cdot l^{-1}}$, $W_{4mmol \cdot l^{-1}}$, $\dot{V}O2_{peak}$ and $W\dot{V}O2_{peak}$).

The CMJ is a semi-specific measure of peak and mean power production in rowers. However, the power output of a single rowing stroke is a more applicable measure of the application of force. While both athletes saw improvements in the CMJ measures, athlete MAX_1 improved W_{max} by 4.1% while MAX_2 saw a 3.8% decrease. This may demonstrate a heterogeneous response to the same stimulus (highlighted by the small population used in this study) or may demonstrate difference in the ability to translate power to rowing specific situations through effective technique – as discussed in Study 3 of this thesis.

Garcia-Pallares and Izquiendo (2011) suggest 3 weight training sessions as optimal to achieve positive adaptations in muscle strength and power. END athletes in this study failed to make noticeable improvements in markers of power production (See table 6.2) following 3 sessions per week. This may be due to the residual fatigue experienced by this group caused by the high intensity interval sessions.

Study 1 of this thesis highlighted 250m speed as a key contributor to 2km performance in elite women. W_{250m} improved by 5.6% and 4.9% in athletes MAX_1 and MAX_2 respectively,. This highlights the importance of strength and power training on explosive rowing performance. Improved aerobic indices may also have contributed to this positive change.

Anthropometrically, the two MAX athletes increased their body mass (MAX_1 = 3kg; MAX_2 = 1.6kg) with either a decrease (MAX_2 = -12.1mm) or no change (MAX_1 = 0.4mm) in the sum of 7 skinfolds, indirectly suggesting an increase in lean muscle mass. Athlete MAX_1 increased lower body girth measurements alongside a stable body fat, supporting this proposal. MAX_2 demonstrated smaller changes in girths, which may have been affected by the marked reduction in fat mass counteracting any increases in lean muscle mass seen with this measurement.

An additional finding of this study was the improvement in performance tests and aerobic indices recorded by MAX athletes. This result is in agreement with previous research noting improvements in kayak paddling speed and power output at maximal and sub-maximal intensities (Izquierdo-Gabarren et al., 2010, Garcia-Pallares et al., 2010). Garcia-Pallares & Izquiendo (2011) summarised that this may be due to increased mechanical efficiency, muscle coordination and recruitment, strength related technical improvements or the reduced relative intensity of sub-maximal work leading to conservation of energy. This, combined with a sufficient aerobic stimulus, stimulated the related adaptations in these two athletes.

The practical application of this intervention study is that athletes with deficiencies in maximum power production (a known correlate of rowing performance, Ingham et al., 2002) can dramatically increase peak power production by increasing weight training from 3 to 5 sessions per week, within a high volume endurance programme. In this very small group, it appears that such training was also beneficial to aerobic performance as key indicies improved, possibly due to the benefits of increased peak power output.

Future research should expand the number of participants in both groups, particularly MAX.

6.6 Conclusion

In conclusion, this study challenges the traditional model of elite rowing training whereby all athletes follow a generic high volume, low intensity training programme with limited high intensity efforts and weight training. While such a programme is historically successful as it focuses on arguably the most trainable determinants of rowing performance (e.g. sub-maximal aerobic capacity), it will not be optimal for all athletes. Those with a limited history of strength and power training can dramatically benefit from an increase in gym work aimed at increasing lean mass and the rate of force production, at the expense of aerobic training and a reduction in the interference phenomenon. Athletes with a deficiency in aerobic capacity, or experiencing stagnation in aerobic development could benefit from a well monitored, short-term block of interval training. More research is needed examining the long-term effects of such training blocks on elite athletes and their effect on performance.

CHAPTER 7:

GENERAL DISCUSSION

7.1. Discussion

This thesis had four main aims. First, to describe the physiological determinants of elite rowing performance and investigate gender and experience level differences. Based on the results of study 1, it's second aim was to describe the longitudinal changes in sub-maximal aerobic capacity in a large group of elite male rowers based on success criteria. This added to the design and implementation of a physiological profiling system in order to analyse the relative status of development athletes in the GBRT system. Finally, using a refined version of this profile, a partially individualised training programme aimed at developing the key physiological determinants of performance in an elite crew was devised. Data regarding British development rowers was previously limited to key performance tests and occasional training data, while interventions using elite level rowers in a high performance environment are rarely reported. The findings of this research have a high degree of applied value and could be used to transfer research findings to practice. We argue that they should be used to help improve young rowers chances of international and Olympic success.

Despite always competing over a 2,000m course, elite international rowers are a heterogeneous group of athletes. Rowers compete in one of 14 Olympic boat types, divided into men and women, open-weight and lightweight, and rowing and sculling categories. Previous research describing determinant models of rowing performance have often used sub-elite rowers (Cosgrove et al 1999) where a spread of physiological variables is more evident, or grouped genders and weight categories together (Ingham et al., 2002) which will undoubtedly increase the range of values used to explain variation in 2,000m rowing performance. Seiler (2006) in his analysis of the Oxford-Cambridge

Boat Race and M1x World Championships times, states that there has been a 25-30% increase in average velocity over the last 150 years of competitive rowing. This suggests that the physiological profile of an elite rower should be regularly updated in order to track such enhancements.

In both rowing literature and the Great Britain Rowing Team (GBRT) developmental system there is a lack of standardised physiological testing that allows longitudinal and cross-sectional intra/inter-athlete comparisons. This information could help the developing athlete, coach and scientist to plan their training in order to best achieve optimal performance and senior team selection.

Elite rowing training has evolved in a similar fashion to other endurance sports where a model of voluminous training composed of 80% low to moderate intensity work is complimented by 20% of work done at a high intensity. Research suggests that this training system will not work for all athletes (Stepto et al 1999). Therefore, alternative methods of training should be investigated in order to provide options for those not thriving when following a high mileage training programme.

Study 1 of this thesis attempted to explore the strength of relationships between monitored physiological variables and 2,000m ergometer rowing performance in elite homogenous groups of male, female, senior and development rowers. The main finding of this research was the need to examine data from athletes of the same gender with comparable experience and skill level when investigating the factors influencing performance in elite rowers.

Results demonstrated that the strength of correlation and bivariate regression differed amongst groups and was significantly affected by the compact spread of physiological variables and 2,000m ergometer performance. When squads were analysed individually, power at 4mmol·l^{-1} ($W_{4mmol \cdot l^{-1}}$) was the only variable significantly related to 2,000m performance (W_{2000m}) in all 4 groups. $\dot{V}O_{2peak}$ was significantly related to performance in 3 squads, with the exception of the senior men (SNR_{men}), whereas the same was true for $W\dot{V}_{O2peak}$ with the exception of the development women (DEV_{women}).

Strength was measured directly for the men's squads and $1RM_{clean}$ clean was able to explain 21% (SNR_{men}) and 46% (development men; DEV_{men}) of the variance in 2000m speed – supporting the notion of rowing as a 'strength endurance' sport. The increased explanation of variance for all 3 strength markers in the DEV_{men} and lower contribution from aerobic markers may be indicative of the lower aerobic training volume (in comparison to the SNR_{men}) completed by this group. The capacity to produce an average 2,000m power 61.1W lower than the SNR_{men} with such a difference in aerobic determinants demonstrates the importance of strength to DEV_{men} performance. However, in order to further improve performance and match that of SNR_{men} it is likely that developments in aerobic performance will be most influential.

Throughout the results, the explanation of variance in the SNR_{men} 2000m time-trial speed based on physiological variables was much weaker than in the other squads. This was attributed to an increased homogeneity within the group demonstrated by smaller range in physiological variables, performance times (14.8s compared to 33.2s for SNR_{women}) and the amount of 2011 World Championship medallists within the group (61% compared to 28% of the SNR_{women}). Therefore, the inability of bivariate regression to explain the variance in performance suggests that a robust 'model' of rowing physiology based on statistical analysis is not appropriate in such groups. Instead, athletes should be individually profiled and areas of meaningful change identified to improve performance without compromising already developed strengths.

The observation that $W_{4mmol \cdot l^{-1}}$ ^{e}is a key descriptor of ergometer performance in all groups formed the basis of the longitudinal investigation considering the changes in sub-maximal aerobic capacity in Olympians and non-Olympians in Study 2. Previous research examining longitudinal aerobic development is limited to case studies of successful individuals (Lacour et al 2009, Mikulic 2011). These studies demonstrate improved performance alongside a continued improvement in the lactate threshold (LT). $\dot{V}O_{2max}$, widely regarded as the most important physiological determinant of rowing performance, appears to plateau – suggesting its contribution to improved performance is limited once maximum aerobic capacity is reached.

Study 2 involved a retrospective analysis of 23 athletes who began their international rowing career between 2000 and 2007. The group was divided according to whether they achieved selection for the Olympic Games (the pinnacle of the rowing calendar) during their time in the sport. Annual changes in $W_{4mmol \cdot l^{-1}}$ were tracked for each group over 3 to 5 years and compared. Analysis of individual data was also discussed alongside less frequently measured W_{2000m} and $\dot{V}O_{2peak}$ scores. Results suggested that successful Olympians (all members of this group won Olympic medals) improved their $W_{4mmol \cdot l^{-1}}$ significantly and meaningfully following the second and third years of senior team training. After this, improvement slowed, but the analysis of individuals with up to 12 years of senior team experience suggested an upward trend in $W_{4mmol \cdot l^{-1}}$ throughout a career. Non-Olympians made a non-significant improvement in $W_{4mmol \cdot l^{-1}}$ between years 1 and 2 that could not be separated statistically from the OLY group, but regressed following their third year of senior team training and were significantly lower than OLY.

It therefore appears difficult to identify those likely to succeed after 1 or 2 years of senior team training, but progress in $W_{4mmol \cdot l^{-1}}$ in the 3rd year of elite training is more marked in those who go on to achieve Olympic selection. This information can be used to identify those that are unlikely to reach the standards required for Olympic selection.

This may be due to an inability to improve or the need for a change in aerobic training stimulus that may result in improved performance. Interventions could be implemented to identify whether an athlete is likely to continue developing within the senior training programme. Finally, this study may provide evidence to change the training model of athletes who's aerobic fitness stagnates after 1, 2 or 3 years in the senior team in order to give them the best chance of Olympic selection and subsequent success.

A limitation of Study 2 was the inability to monitor changes in $W_{4mmol \cdot l^{-1}}$ during the 1st year of senior team training due to the lack of a pre-senior team test. This meant the 'starting point' for $W_{4mmol \cdot l^{-1}}$ in the athletes tracked was unknown. Such data may provide useful information regarding future development and subsequent success. Therefore, physiological profiling in the GBRT development squads was suggested to provide a more detailed record of $W_{4mmol \cdot l^{-1}}$ and other key variables in rowers before they join the senior team, and made the basis of Study 3.

The nationwide collection and analysis of physiological data required a battery of simple, reliable and most importantly valid measures of rowing physiology. Of equal importance was the method used to display this information to coaches in order to best highlight senior team and 'Olympic standards' alongside the relative strengths and weakness of their athletes. Based on the findings of Study 1, measures of ergometer performance, sub-maximal aerobic capacity, anaerobic capacity, strength and power production were collected from development athletes and displayed using a 'Spider profile'. Comparisons were then made with senior team (SNR) athletes based on selection for the U23 international squad using 'Olympian standards' as a guide.

Senior team athletes recorded significantly better results than rowers who failed to achieve selection for the U23 squad (NON) in all performance and physiological indices apart from the unloaded counter-movement jump (CMJ_{mean}). SNR were significantly better than U23 in W_{5000m},, $1RM_{press}$ and $1RM_{pull}$. There were no significant differences between SNR & U23 in W_{2000m}, sub-maximal aerobic capacity ($W_{2mmol \cdot l^{-1}}$,$W_{4mmol \cdot l^{-1}}$), or CMJ_{mean} In terms of a comparison between development athletes, performance (W_{2000m} and W_{5000m}) and endurance indices ($W_{2mmol \cdot l^{-1}}$,and $W_{4mmol \cdot l^{-1}}$) set U23 athletes apart from NON ($p<0.05$) and PART athletes Finally, there were no significant differences between U23 and NON/PART in measures of strength and power ($1RM_{Press}$ and $1RM_{Pull}$) or $CMJ_{mean.}$

The ability to differentiate between international and non-international development athletes using sub-maximal aerobic indices, suggests that aerobic determinants outweigh strength and maximum power production in developmental rowers. This is of no surprise due to the emphasis placed on aerobic training (Fiskerstrand & Sieler 2004) and the previously reported relationships between maximal and sub-maximal markers of aerobic capacity in both senior (Ingham et al 2002) and junior (Mikulic 2008) rowers. The shift in profile shape towards indices of strength and power, seen in the NON group Spider Profile suggests that excelling in these indices is not sufficient to achieve international selection. As highlighted in study 2 of this thesis, aerobic variables such as $W4_{mmol \cdot l^{-1}}$ will continue to improve throughout an athlete’s career and differentiate between Olympians and non-Olympians. NON athletes should seek to develop their endurance capacity as it appears that markers of this parameter are more conducive to success in rowing than the limited effect of strength and power training.

A further explanation for the difference in W_{2000m} and international selection of U23 athletes is technical proficiency. The U23 group performed better in the rowing specific elements of the Spider Profile including W_{2000m}, W_{5000m} and the sub-maximal rowing assessments of aerobic capacity $W_{2mmol \cdot l^{-1}}$,$W_{4mmol \cdot l^{-1}}$. The rowing stroke (on water or ergometer) requires the accurate and well timed application of force (Soper & Hume

2004). Although inferior in markers of absolute strength and power, it is possible that the U23's performance in rowing specific tests is an indication of a superior ability to apply force and load the posterior chain, in order to achieve a more effective stroke and avoid 'leaking' power unnecessarily. From the results presented here, it could be suggested that a large number of the athletes tested fulfil the strength and power requirements of an U23 international athlete, but struggle to translate the power to the rowing stroke. Therefore, more time should be spent improving the delivery of power at the expense of improving these variables.

The validity of upper body exercises such as the bench press and bench pull should therefore be questioned at this point. According to Gee et al (2011) these exercises are a core inclusion of rowing strength training programmes. However, Lawton et al (2011) report a poor relationship between such non-specific tests and W_{2000m}. Exercises included in a programme will improve over the course of a training block, but if they are not related to rowing performance, any such improvements will not influence 2,000m power

Furthermore, it is possible that the recruitment of athletes via University or the GBRT START programme is skewed towards stronger athletes with the ability to produce large amounts of power explosively. An increased emphasis on aerobic indices of performance and their trainability during recruitment may alter the physiological profile of GBRT development rowers and their subsequent 2,000m performance (a known correlate of performance at international regattas; Mikulic et al 2009a).

The test battery selected to profile athletes in this study dispensed with the measurement of maximal aerobic capacity in favour of sub-maximal parameters only. Research suggests that this parameter is one of the best descriptors of rowing performance (Seiler 2006), but will plateau in well trained individuals (Mikulic 2011a). Previous studies have shown that a plateau in $\dot{V}O_{2max}$ will occur at 20-22 years in well trained endurance athletes (Rusko, 1987; Legaz Arrese et al., 2005). Also, the need for a time consuming laboratory based measurement requiring expensive equipment and controlled conditions was considered logistically difficult, while capillary blood lactate samples can be taken relatively easily and reliably in a field environment.

The influence of 250m speed on SNR_{women} performance in Study 1 suggested it was a useful addition to a physiological profile in terms of assessing anaerobic capacity – filling the gap between endurance and strength markers. Although not significant, the average values forU23 athletes (as with other rowing specific tests) were higher than those of NON & PART. The assessment of strength via 1RM was a controversial topic in coach/scientist discussions. It was felt that maximum lifts were inappropriate for a large percentage of the development rowers who have different degrees of weight room technical competency. Therefore, the safer (but less valid – Lawton et al 2011) exercises - bench press and bench pull were retained, but the more technical lift – power clean was removed.

Instead, an unloaded counter-movement jump was included in an attempt to assess raw power production. The distribution of results from this measure suggest that it has little impact on rowing performance as U23 are deficient in comparison to non-selected rowers and the senior team. The mean power from a counter movement jump (CMJ_{mean}) may involve no 'rowing specific' technique as it does not include technical factors such as timing at the catch position or loading of the posterior chain. It is also possible that the measurement of CMJ_{mean} using a linear position transducer has limitations caused by the displacement of the cable during a jump. Although less practical, the use of a force platform may provide more accurate results. The inclusion of a maximum 'rowing power’ test could also provide a more valid measure and provide a marker to assess the transfer of raw power to a rowing specific environment.

For each development rower tested during the initial year of this study, their coach was issued with a ‘Spider Profile’ spreadsheet (see study 3, Figures 5.1 and 5.2). This was intended to provide an analysis of an athlete’s physiological status and their development relative to the previous year’s U23 team, and the senior rowers. Coaches reported that the spider profile provided a useful visual representation of their athletes and prompted both individual and squad based training interventions to address weaknesses highlighted by the shape of the chart.

Study 3 and the implementation of ‘Project Spider’ filled a gap in the GBRT development system physiology service. Due to the standardised nature of testing, an added bonus of the data and its presentation was the option for senior team coaches to easily analyse athletes nationwide in a format they are familiar with. Until this point, awareness of development rowers was limited to ergometer and on-water performances. ‘Project Spider’ provided them with an in-depth understanding of potential athlete’s physiological strengths and weakness – useful information in terms of their possible integration into the senior team.

Elite rowing training includes the completion of extremely high weekly volumes interspersed with high intensity efforts (Seiler and Kjerland, 2010). The results of Study 3 indicate that the best U23 rowers (i.e. those on the fringes of senior team selection) have 2,000m ergometer scores not significantly slower than senior internationals. Having a performance comparable to elite rowers might suggest that such athletes are ready to make the step to senior team training and competition. However, the physiological development necessary to improve these scores requires the correct execution of an already successful training programme (and the capacity to further improve with such a training stimulus). However, the inability to adapt to a large increase in volume, or complete it effectively, will reduce the potential adaptations to training. Therefore, 'Project Spider' provides an means of assessing the suitability for senior training through its inclusion of training measures such as $W_{2mmol \cdot l^{-1}}$,$W_{4mmol \cdot l^{-1}}$, and strength/power.

The main aim of Study 4 was to refine and utilise the physiological profiling adopted in Study 3 (based on Study 1 and the longitudinal investigation of study 2) and employ training methods to improve individual weaknesses in the physiological determinants of rowing performance. The participants in this study were those not selected in GBRT crews at the 2013 World Rowing Championships (Chung Ju, South Korea). Accordingly, the athletes employed in Study 4 could be considered most in danger of following the same pattern of development as the NON athletes from Study 2 – an inability to complete the programme, or improve within it.

The profiling used in Study 3 was adapted slightly to include a 7 stroke test of maximal rowing power in order to increase the specificity of power production not fully explained via CMJ_{mean} This test was retained, but measured using a force platform. Additional tests such as $\dot{V}O2_{peak}$ $W\dot{V}O2_{peak}$ and W_{30min} were also included due to the small group size and access to a laboratory. Six athletes from an M8+ crew were divided into END and MAX groups and completed 13 group specific training sessions over the course of the 7 week programme. The generic training was a realistic 'high volume/low intensity' rowing programme averaging 131km per week with 3 weight lifting sessions. END athletes completed a series of ergometer interval sessions in an attempt to improve $W_{2mmol \cdot l^{-1}}$ and $W_{4mmol \cdot l^{-1}}$, while MAX athletes completed two additional weight training exposures aimed at developing maximum rowing power.

Analysing mean scores, END improved in all indices of endurance performance without a fall in maximum rowing power. Both MAX athletes improved in all markers of power production and aerobic determinants. Differences between groups was evident in $\dot{V}O_{2\,peak}$ possibly suggesting that training at or above the anaerobic threshold is more effective in developing maximal oxygen consumption, while lower intensity training is more effective in developing sub-maximal endurance determinants. This observation could be an indication of minor changes to the intracellular signalling caused by increased training intensity. An increase in adaptations, including increased stroke volume, cardiac output, blood volume & pulmonary diffusion (Garcia-Pallares & Izquierdo 2011) combined with changes in mitochondrial size and density, increased aerobic enzyme activity and lactate handling, could have contributed to the improved $\dot{V}O_2$ peak seen here.

Whilst mean results demonstrated a general trend for improvement, individual athletes in END showed different degrees of improvement in the variables measured. For example, END_4 showed lower percentage improvements in the majority of indices. This example highlights the individual differences in the responses to different training methodologies described previously. The improvements in anaerobic capacity and maximum power alongside aerobic improvements demonstrated by MAX are likely attributed to increased mechanical efficiency, muscle coordination and recruitment, strength related technical improvements or the reduced relative intensity of sub-maximal work leading to conservation of energy.

Study 4 challenged the traditional model of elite rowing training whereby all athletes follow a generic high volume, low intensity training programme with limited high intensity efforts and weight training. While such a programme is historically successful as it focuses on arguably the most trainable determinants of rowing performance (e.g.

sub-maximal aerobic capacity), it will not be optimal for all athletes. Those with a limited history of strength and power training (and an already well developed aerobic system) can dramatically benefit from an increase in gym work aimed at increasing lean mass and the rate of force production, at the expense of aerobic training and a reduction in the interference phenomenon. Athletes with a deficiency in aerobic capacity, or experiencing stagnation in aerobic development could benefit from a well monitored, short-term block of interval training which leads to minor changes to the intracellular signalling caused by increased training intensity.

The application of scientific process within sport and its ability to influence performance is a complex subject. Researchers have limited access to elite populations and coaches are understandably reluctant to experiment with successful methods. This often results in practitioners relying on the findings of well designed research studies and attempting to translate them to everyday practice (Bishop, 2006). However, the experience level of participants, length of interventions, and training volumes used (plus more) reduce ecological validity and the possible application of findings to elite competitors.

When possible, the alternative is to attempt research within an elite applied environment. Such experimentation reverses the pros and cons of the above method. Using highly motivated, elite level participants can provide evidence that is applicable to the homogenous group of athletes tested. However, small sample size, a lack of control group and an inability to control many influencing variables reduces the more widespread relevance of findings.

The applied sports scientist must be focused on performance improvement while being imaginative, adaptable, and able to “embrace the complexity of the sporting world” (Bishop, 2008). Importantly, they must implement rigorous scientific method where possible, know the limitations of their investigation, and understand what represents a meaningful change in performance. The performance effect of interventions within elite sport are likely to be small, with a high degree of individuality among results. In elite populations, case series analyses can provide powerful conclusions without the need for complex statistics that often lead to the misinterpretation of findings (Whyte 2012).

This thesis has described (via cross-sectional and longitudinal) the determinants of performance in elite groups of rowers using established routine tests and a wealth of underutilised historical data. Rigorous control was employed where possible, particularly within a laboratory situation (Study 1). An intervention with realistic constraints was then conducted in the elite environment. The analysis of elite rowers within their training and competition environment has resulted in findings highly applicable to the GBRT and development of athletic performance within it. Identifying and understanding the limitations of such research are important when discussing the accuracy, reliability and validity of findings.

7.2. Limitations

It is acknowledged that in **Study 1**, it was not possible to standardise the testing protocols between groups. Due to coach preferences regarding testing protocols, the two women's squads did not complete 1RM tests. The same is true of W_{250m} with the men's team. Using the same testing battery across squads would have allowed a more complete investigation of performance determinants.

The division of participants in **Study 2** into Olympians and non-Olympians did not consider factors such as direct competition for particular seats in a boat that could affect Olympic selection. Individual rowers specialise in either sweep (1 oar per person) or sculling (2 oars per person) events. In sweep rowing, athletes either favour bow side (oar on the left) or stroke side (oar on the right). Also, injury and illness at key points in the season were not considered.

There was no aerobic step-test in order to assess the $W_{4mmol \cdot l}{}^{-1}$ of athletes prior to joining the senior team. The first measurements were taken during the 1^{st} year of senior training making a comparison of year zero to year one impossible. This limitation was a further advantage of Project Spider's initiation.

While potentially more powerful than the results of a single case study analysis, conclusions drawn from the statistical analysis of small groups should be treated with caution. For example, the standard deviation of the data presented in table 4.1 and figure 4.1 suggest an athlete could follow an altogether different pattern of $W_{4mmol \cdot l}{}^{-1}$ development and still achieve Olympic selection/success. Therefore, the interrogation of individual data alongside group trends can provide more detailed insight.

While athletes completed up to 4 aerobic step-tests per year during their careers, this study chose to use the single best measure of $W_{4mmol \cdot l}{}^{-1}$ from each season rather than an average value. As discussed, $W_{4mmol \cdot l}{}^{-1}$ tended to peak in March-April. If athletes did not complete a test at this time, it is possible that results for a given year did not reflect their highest possible power output at $4mmol \cdot l^{-1}$.

A further limitation is the failure to consider the stage of the Olympiad an athlete joins the senior team, and the effect this may have on training and subsequent adaptation. Olympic training programmes aim to produce peak performance at the Olympic Games and therefore include subtle annual differences in volume and intensity.

Study 3 used coach and scientist selected 'Olympic standards' as a basis for the Spider profile comparisons of U23, NON and SNR athletes. These standards are based on historical data and the coaches interpretation of what is required to become an

Olympian. It is possible that the values used were not correctly judged, leading to a misleading skew in favour of, or against, a given variable. Changing these standards could have a quite dramatic effect on the profile.

Finally, **Study 4** did not include a control group which made the relative effects of the END and MAX programmes difficult to assess. Also, due to the stage in the season that the investigation took place, the option of completing a 2,000m performance test before and after the training intervention was not available. Instead, the 4 min maximum step which followed the sub-maximal step-test was used

7.3. Recommendations for further research

This findings of this thesis have led to the identification of further research questions regarding the determinants of rowing performance in senior and development rowers. The following list is a summary of possible future investigations.

The determinants of on-water rowing performance:

Study 1 investigated the relationship between physiological variables and 2,000m ergometer performance. The inclusion of technical/biomechanical factors, measured on-water would provide a more complete picture of the demands of elite rowing

An examination of the relationship between adherence to training prescription and development of sub-maximal aerobic capacity:

Study 2 did not provide information regarding the training adherence of OLY & NON during their first 3-5 years of senior team training. An analysis of volume and intensity (in relation to the prescribed training programme) would provide additional evidence to explain the differences between successful and non-successful individuals.

Project Spider: Performance Pathway:

Study 3 provided a standardised testing battery and means of presenting data within the GBRT senior and development system. However, the data presented was (at this point) a 'snapshot' of athletes at one point in time. Ideally, athletes would be tracked from novice to elite. This would provide norm data regarding the 'performance pathway' of developing rowers that could be used as the basis for interventions when athletes stray from 'ideal' development.

Crew interventions based on Spider Profiles:

Study 4 suggested that subtle training interventions can be effective in altering the focus of training for individual athletes. When rowing as part of a crew, there are often common physiological deficiencies in the selected athletes that may affect the key determinants of performance in particular events. The individualised training schedule adopted in this study could be applied to a crew in order to improve a variable that is specific to them or their event.

7.4. Conclusions

Aim 1: Describe the physiological determinants of elite 2000m ergometer rowing and investigate gender differences.

Using bivariate regressions, Study 1 investigated the relationships between the currently measured markers of physiological development in the GBRT. Sub-maximal aerobic capacity (in this case $W_{4mmol \cdot l^{-1}}$) was a key determinant of elite rowing performance in homogenous groups of male and female senior and development rowers. The results of this study highlight the need for individual assessment of elite athletes over statistical analysis of group means.

Aim 2: Describe the longitudinal changes in sub-maximal aerobic capacity in elite male rowers.

Differences in $W_{4mmol \cdot l}^{-1}$ are evident between Olympian's and non-Olympian's following 3 years of elite senior team training. $W_{4mmol \cdot l}^{-1}$ continues to improve during an Olympians rowing career whereas non-Olympians appear to stagnate or regress after this point. Possible explanations for these differences include non-Olympians reaching a physiological ceiling of development, and/or differences in the training polarisation of the two groups.

Aim 3: Design and implement a physiological profiling tool to analyse the physiological strengths and weaknesses of GBRT 'development' rowers.

Study 3 provided evidence to suggest that selected U23 athletes differ to their senior team peers in strength, power and anaerobic capacity determinants, but not performance or aerobic indices such as $W_{4mmol \cdot l}^{-1}$. This was attributed to full-time senior team rowers being able to dedicate more time to strength and power training than their part-time counterparts. Non-successful development rowers are strong and powerful but lack aerobic capacity and technical delivery in comparison to successful U23's and elite senior rowers. It was suggested that the talent identification and training of potential rowers is skewed towards strength and power at the expense of aerobic qualities.

Aim 4: Based on physiological profiling, design and implement a partially individualised training programme aimed at improving the key physiological determinants of rowing performance.

Study 4 suggested that individualising 2 sessions per week of a high volume rowing training programme could have a positive effect on physiological weaknesses in elite rowers. When strength/power training was increased, improvements were made in both maximum power output and aerobic indices. When aerobic interval training was introduced, in order to improve $W_{4mmol \cdot l^{-1}}$, aerobic indices (particularly $\dot{V}O_{2peak}$) increased. Such training blocks should be short and well monitored.

In conclusion, this body of work has highlighted the need for specificity in the analysis of elite rowing athletes as gender and experience level dramatically affect the physiological determinants of performance. Sub-maximal aerobic capacity is an influential determinant in all groups, and its development can determine those that achieve Olympic success. The need to convey this message to coaches and athletes in the GBRT development system has led to the inception of a profiling system which provides a platform for intra and inter athlete and squad comparisons. Finally, this profile can help to identify bespoke interventions aimed at developing weaknesses and maximising an individuals chance of success in this complex ‘power endurance’ sport.

CHAPTER 8:

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APPENDICIES

Appendix A: Study 4, Hanse Cup training programme 2013

Hanse Cup Training Programme

														1						
Active Recovery							Active Recovery							Home Training (+Testing)					Elite DEV camp	
15/07/13 Mon	16/07/13 Tue	17/07/13 Wed	18/07/13 Thu	19/07/13 Fri	20/07/13 Sat	21/07/13 Sun	22/07/13 Mon	23/07/13 Tue	24/07/13 Wed	25/07/13 Thu	26/07/13 Fri	27/07/13 Sat	28/07/13 Sun	29/07/13 Mon	30/07/13 Tue	31/07/13 Wed	01/08/13 Thu	02/08/13 Fri	03/08/13 Sat	04/08/13 Sun
														Bish S&C Testing	Lab test or UT2 ergo12km	Weights	Weights	UT2 20km	UT2 16km	UT2 12km
														Lab Test or	UT2 ergo 12km or	UT2/1 20km(2x4km)	AT Ergo 30' TEST	Individual Training	Individual Training	Video Session
														UT2/1 20km (4x2km)	UT2/1 20km (4x2km)	UT2 12km				UT2 12km
2							3							4						
Elite Development Camp											Sculling Festival			Squad Training UL						
05/08/13 Mon	06/08/13 Tue	07/08/13 Wed	08/08/13 Thu	09/08/13 Fri	10/08/13 Sat	11/08/13 Sun	12/08/13 Mon	13/08/13 Tue	14/08/13 Wed	15/08/13 Thu	16/08/13 Fri	17/08/13 Sat	18/08/13 Sun	19/08/13 Mon	20/08/13 Tue	21/08/13 Wed	22/08/13 Thu	23/08/13 Fri	24/08/13 Sat	25/08/13 Sun
UT2 16km	UT2/1 16km(3x2km)	UT2 16km	UT2 ergo 18km	UT2 16km	UT2 12km	UT2/1 16km(3x2km)	UT2 16km	UT2 16km	UT2 12km	UT2 8km pre-paddle	UT2 ergo 18km	NWSC Racing	NWSC Racing		Weights	UT2 20km	Weights	UT2 16km	UT2 12km	Off
UT2 12km	UT2 12km	AT Ergo 30 mins	UT2 ergo 16km	12km UT2 inc bursts	UT2/AT/TR 12km (1.5/1/250m)	Individual Training	UT2 12km inc bursts	UT2 12km inc bursts	Individual Training	UT2/TR/AC 12km (4x1000m)	Individual Training	TBC	TBC	UT2 20km	20k UT2/1 2x4km 21,23	Individual Training	UT2 16km	Individual Training	14k UT2/AT/TR 2x2k AT R24, 26 / 1k TR R28	
Weights	Weights		Weights	Individual Training			Weights	Weights		Weights				Weights			UT2 12km			
5							6							7						
Squad Training UL							Squad Training							Squad Training			Hanse Cup			
26/08/13 Mon	27/08/13 Tue	28/08/13 Wed	29/08/13 Thu	30/08/13 Fri	31/08/13 Sat	01/09/13 Sun	02/09/13 Mon	03/09/13 Tue	04/09/13 Wed	05/09/13 Thu	06/09/13 Fri	07/09/13 Sat	08/09/13 Sun	09/09/13 Mon	10/09/13 Tue	11/09/13 Wed	12/09/13 Thu	13/09/13 Fri	14/09/13 Sat	15/09/13 Sun
Weights	Weights	UT2 20km	Weights	UT2 20km	UT2 16km	Off	Weights	Weights	UT2 20km	Weights	20 k UT2/AP inc 10x15s R28/36	UT2 16km	Off	Weights inc testing	UT2 12km	UT2 12km	Travel	TBC	Hanse Cup Sprints	Hanse Cup Race
UT2 12km	UT2/1 20km(4x2km)	Individual Training	UT2 16km	Individual Training	16k UT2/AT/TR 2x2k R24/26, 1x2k R28		UT2/1 20km(4x2km)	AT ergo 30 mins	Individual Training	UT2 12km	Individual Training	14km UT2/TR/AC 2x2km 30/32, 32/34, 1x1km 34/34+		10km UT2/AC 2x1k first&pace	Individual Training	10km UT2/AC 2x250m,2x500m		TBC		
AT ergo 30 mins	UT2 12km						UT2 12km							UT2 12km						

Appendix B: Study 4, END Individual Training sessions

Week	Session 1	Session 2
1	3x2km **AT** 2 mins rest 1. R24 2. R24 3. R24	2x3km **AT** 3 mins rest 1. R24 2. R24
2	4x2km **AT** 2 mins rest 1. R24 2. R24 3. R26 4. R26	3x3km **AT** 3 mins rest 1. R24 2. R26 3. R26
3	2x1500m R24, 26 (*1 min rest between*) **AT** *5 mins rest* 2x1500m R26, 28 (*1 min rest*) **AT**/**TR**	2km R24 **AT**, 1km R26, **AT** (*3 mins rest between*) 5 mins rest 2km R26 **AT**, 1km R28, **TR** (*3 mins rest between*)
4	8x500m R24, 26, 28, 30, 30, 28, 26, 24 (*30s rest between*) **AT**/**TR**/**AC**	5x1000m R28 **TR** *Start a new 1000m every 4 minutes* (eg 3:07 work = 0:53 rest)
5	6x250m, R40-44 (*10s rest*) max effort **AC** *5 min rest* 6x250m, R40-44 (*10s rest*) max effort **AC** *5 min rest* 4x500m, R30-32 **AC** *starting a new rep every 3 mins* (eg 1:30 work, 0:30 rest)	4x500m R28 **TR** *(45s rest between)* *5 mins rest* 3x500m R28 **TR** *(45s rest between)* *5 mins rest* 2x500m R30 **AC** *(45s rest between)* *5 mins rest* 1x500m Free rate **AC**
6	2km R26 **AT** *4 mins rest* 1.5km R28 **TR** *3 mins rest* 1km R30 **TR** *2 mins rest* 750m R32 **AC** *1 min rest* 500m R34 **AC** *30s rest* 250m R36 **AC** *15s rest* 100m Free Rate / max effort **AP**	6x250m, R40-44 (*10s rest*) max effort **AC** *5 min rest* 6x250m, R40-44 (*10s rest*) max effort **AC** *5 min rest* 4x500m, R30-32 **AC** *starting a new rep every 3 mins* (eg 1:30 work, 0:30 rest)
7	8x500m R26, 28, 30, 32, 32, 30, 28, 26 (*30s rest between*) **AT**/**TR**/**AC**	

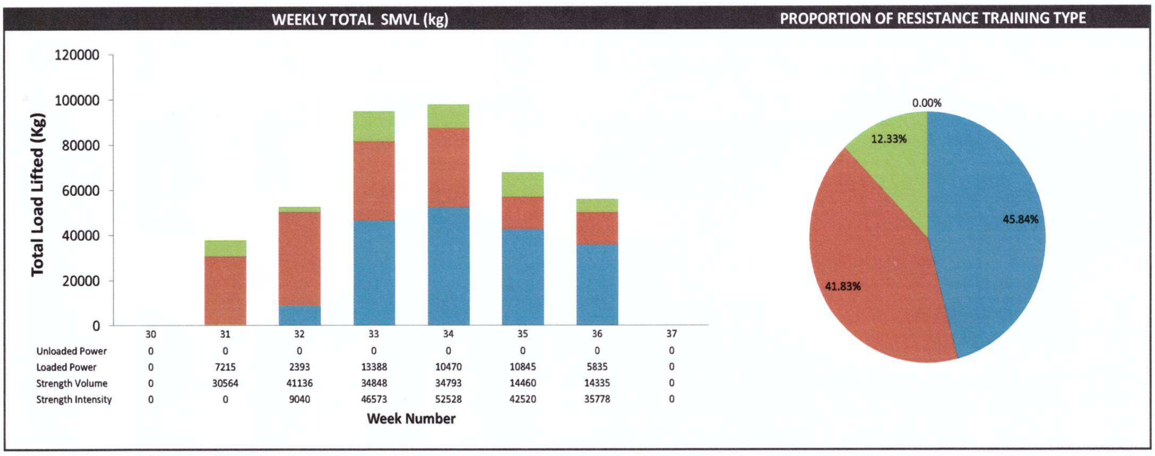
Appendix C: Study 4, Individual weight training summaries for MAX_1 and END_2

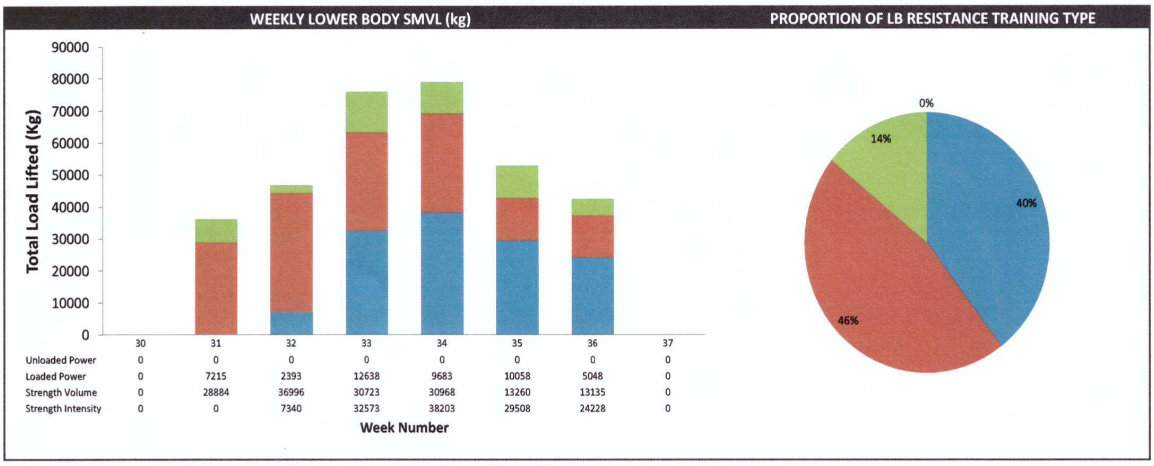
GBROWINGTEAM

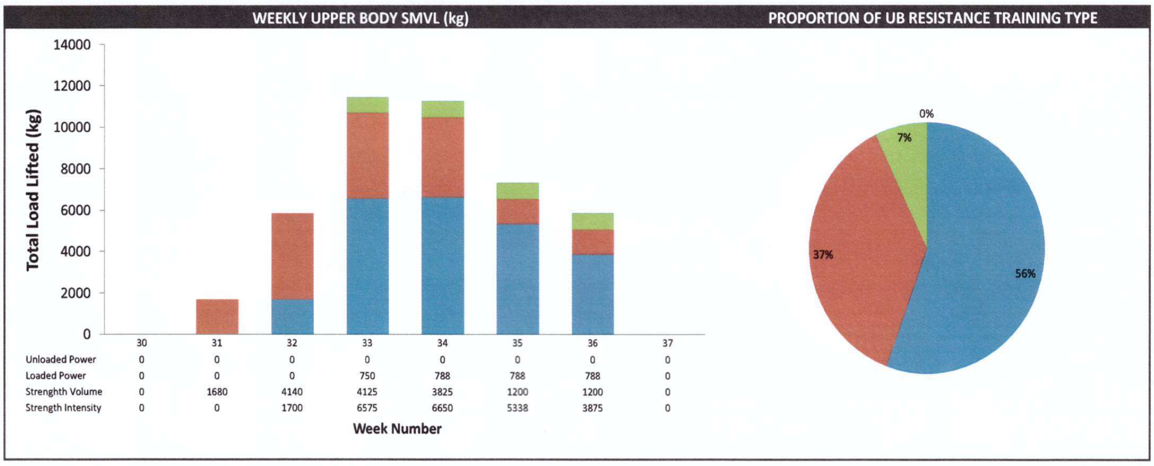
Name: MAX_1
Start Date: 22/07/2013
End Date: 15/09/2013

Type of Resistance Training
Strength Intensity (reps 6 <)
Strength Volume (reps 8 >)
Loaded Power
Unloaded Power

Acronyms
SMVL: System Mass Volume Load (kg)
LB: Lower Body
UB: Upper Body





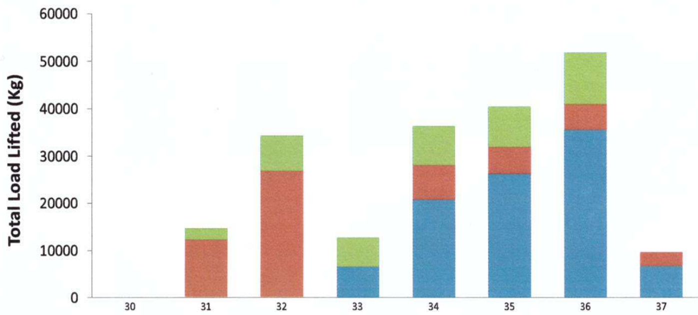


ENGLISH INSTITUTE OF SPORT

GBROWINGTEAM

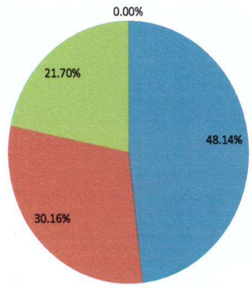
Name:	END2	**Type of Resistance Training**	**Acronyms**
Start Date:	22/07/2013	Strength Intensity (reps 6 <)	**SMVL:** System Mass Volume Load (kg)
End Date:	15/09/2013	Strength Volume (reps 8 >)	**LB:** Lower Body
		Loaded Power	**UB:** Upper Body
		Unloaded Power	

WEEKLY TOTAL SMVL (kg)

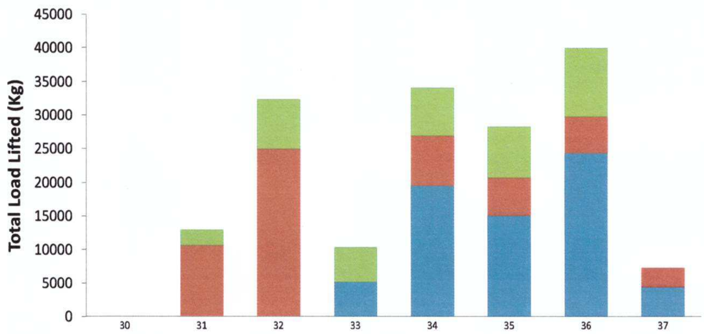


Week Number	30	31	32	33	34	35	36	37
Unloaded Power	0	0	0	0	0	0	0	0
Loaded Power	0	2313	7464	5976	8139	8469	10940	0
Strength Volume	0	12287	26794	0	7326	5605	5355	2810
Strength Intensity	0	0	0	6738	20727	26248	35499	6830

PROPORTION OF RESISTANCE TRAINING TYPE

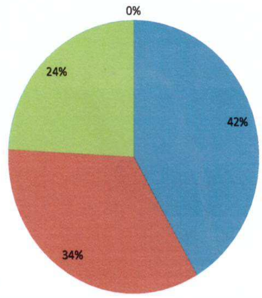


WEEKLY LOWER BODY SMVL (kg)

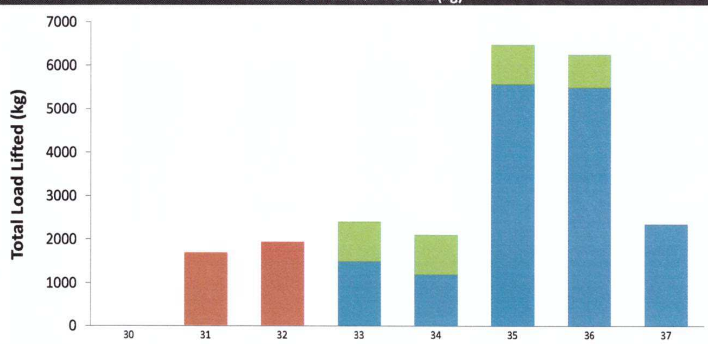


Week Number	30	31	32	33	34	35	36	37
Unloaded Power	0	0	0	0	0	0	0	0
Loaded Power	0	2313	7464	5076	7239	7569	10190	0
Strength Volume	0	10607	24874	0	7326	5605	5355	2810
Strength Intensity	0	0	0	5238	19527	15068	24394	4490

PROPORTION OF LB RESISTANCE TRAINING TYPE

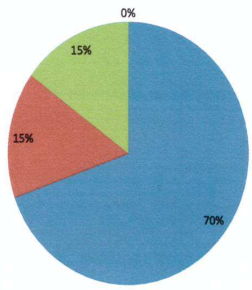


WEEKLY UPPER BODY SMVL (kg)



Week Number	30	31	32	33	34	35	36	37
Unloaded Power	0	0	0	0	0	0	0	0
Loaded Power	0	0	0	900	900	900	750	0
Strenghth Volume	0	1680	1920	0	0	0	0	0
Strength Intensity	0	0	0	1500	1200	5575	5500	2340

PROPORTION OF UB RESISTANCE TRAINING TYPE



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