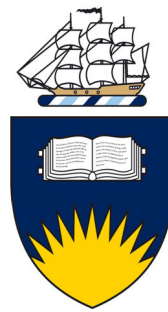


FIELD BASED TESTING PROTOCOLS TO MONITOR TRAINING ADAPTATIONS AND PERFORMANCE IN ELITE ROWERS

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THESIS CONTENTS

CHAPTER 1 - INTRODUCTION, BACKGROUND AND STATEMENT OF PROBLEM

1.1 INTRODUCTION	1
1.2 BACKGROUND	3
1.2.1 Competitive rowing	3
1.2.2 Descriptive characteristics of elite rowers.....	3
1.2.3 Physiological demands of competitive rowing	5
1.2.4 Physiological testing of elite rowers	7
1.3 STATEMENT OF PROBLEM	9
1.3.1 Aims	9
1.3.2 Limitations.....	11
1.3.3 Delimitations	12
1.4 DATA ANALYSIS CONSIDERATIONS.....	14

CHAPTER 2 - LITERATURE REVIEW: ROWING TESTING – LABORATORY AND FIELD PROTOCOLS

2.1 INTRODUCTION	16
2.2 ROWING ERGOMETRY	16
2.2.1 Metabolic cost of rowing.....	17
2.2.2 Aerobic and anaerobic energy contribution	19
2.2.3 Performance determinants and modelling	21
2.2.4 Fitness monitoring.....	23
2.3 LABORATORY BASED ROWING TESTING.....	24
2.3.1 Evaluation of training adaptations.....	24
2.3.2 Definition of lactate thresholds	26
2.3.3 Prescription of rowing training intensities	29
2.4 VALIDITY OF ERGOMETER ROWING	32
2.4.1 Movement patterns	32
2.4.2 Biomechanics	34
2.4.3 Rowing performance	36
2.4.4 Physiological responses.....	36
2.5 ON-WATER INCREMENTAL ROWING PROTOCOLS	38
2.5.1 Methodological limitations.....	39

2.5.2 Measurement of on-water rowing power output	40
2.5.3 Measurement of metabolic load during on-water rowing	41
2.5.4 Reliability	43
2.6 CONCLUSIONS	44

CHAPTER 3 - VALIDATION OF THE CONCEPT2 MODEL D ROWING ERGOMETER

3.1 INTRODUCTION	45
3.2 METHODS	48
3.2.1 Subjects	48
3.2.2 Experimental protocol	48
Incremental rowing protocol	48
3.2.3 Statistical analyses	50
3.3 RESULTS	51
3.3.1 Subjects	51
3.3.2 Comparison between ergometer models (C2C vs. C2D)	51
Submaximal performance	51
Maximal performance	51
Blood lactate thresholds	51
3.3.3 Reliability of test results using the C2D ergometer	53
Submaximal performance	53
Maximal performance	53
Blood lactate thresholds	53
3.4 DISCUSSION	60
3.4.1 Comparison between ergometer models (C2C vs. C2D)	60
3.4.2 Reliability of test results using the C2D ergometer	61
3.4.3 Practical applications	61
3.5 CONCLUSION	65

CHAPTER 4 - VALIDITY OF THE METAMAX3B PORTABLE METABOLIC SYSTEM

4.1 INTRODUCTION	66
4.2 METHODS	69
4.2.1 Subjects	69
4.2.2 Indirect calorimetry equipment	69
Portable metabolic system	69
Laboratory metabolic system	69
Calibration of the metabolic systems	72
Metabolic simulation system	74
4.2.3 Experimental protocol	74
Incremental rowing protocol	76
4.2.4 Statistical analyses	77
Reliability	77

Accuracy	78
4.3 RESULTS	79
4.3.1 Simulated metabolic outputs	79
4.3.2 Power output during biological trials	79
4.3.3 Biological trials	81
4.4 DISCUSSION.....	88
4.4.1 Reliability of repeated MM3B measurements.....	88
4.4.2 Accuracy of the MM3B compared with an automated Douglas bag system (MOUSE).....	89
4.5 CONCLUSIONS	93

CHAPTER 5 - COMPARISON OF ERGOMETER AND ON-WATER INCREMENTAL ROWING TESTS

5.1 INTRODUCTION	94
5.2 METHODS	98
5.2.1 Subjects	98
5.2.2 Experimental protocol	98
Laboratory test protocol	101
On-water test protocol.....	101
Blood lactate thresholds	102
5.2.3 Data treatment	103
5.2.4 Statistical analyses.....	107
5.3 RESULTS	109
5.3.1 Comparison between test modalities (laboratory vs. on water)	109
Power output measurements	109
Submaximal performance	109
Maximal performance	109
Blood lactate thresholds	112
5.3.2 Reliability of measures on water	112
Submaximal performance	112
Maximal performance	112
Typical error results	112
5.4 DISCUSSION.....	116
5.4.1 Comparison between test modalities (laboratory vs. on water)	117
5.4.2 Reliability of measures on water	121
5.5 CONCLUSION	125

CHAPTER 6 - MONITORING FITNESS AND PERFORMANCE WITH ERGOMETER AND ON-WATER INCREMENTAL ROWING TESTS

6.1 INTRODUCTION	126
6.2 METHODS	129
6.2.1 Subjects	129
6.2.2 Experimental protocol	129

2000-m ergometer time-trial	131
Laboratory test	131
On-water incremental test	132
Blood lactate thresholds	133
6.2.3 Data treatment	133
6.2.4 Statistical analyses.....	134
Classification of magnitude-based differences	134
Practically substantial differences based on the smallest worthwhile change	135
Prediction of rowing time-trial performance	135
6.3 RESULTS	138
6.3.1 Training logs.....	138
6.3.2 2000-m ergometer time-trial.....	138
6.3.3 Ergometer and on-water incremental rowing tests.....	138
Magnitude-based differences between baseline and post- training results.....	138
Practical interpretation of the baseline to post-training changes.....	139
Comparison of physiological responses to ergometer and on- water rowing	139
6.3.4 Relationship between incremental rowing test results and performance.....	145
6.4 DISCUSSION.....	147
6.4.1 Magnitude-based differences between baseline and post-training results	147
Practical interpretation of the baseline to post-training changes.....	149
6.4.2 Comparison of ergometer and on-water physiological responses.....	149
6.4.3 Relationship between incremental rowing test results and performance.....	150
6.5 CONCLUSIONS	152
 CHAPTER 7 - SUMMARY, CONCLUSIONS AND RECOMMENDATIONS	
7.1 SUMMARY.....	153
7.2 PRACTICAL APPLICATIONS.....	158
7.3 FUTURE DIRECTIONS	159
 REFERENCES	 161
 APPENDIX - PUBLICATIONS.....	 175

FIGURES

Figure 2-1: LT ₁ (aerobic threshold) and LT ₂ (AT) blood lactate thresholds determined by ADAPT software (AIS, Canberra, Australia) from the blood lactate-power output curve established during a 6-stage incremental rowing test.	28
Figure 2-2: Kinetic energy of the rower's body during a single rowing stroke performed on a stationary ergometer (ergo) and on-water (boat) and the kinetic energy of the boat (shell).	33
Figure 3-1: (A) Blood lactate concentration and (B) heart rate during the incremental rowing protocol performed on Concept2 Model C and Model D ergometers.	55
Figure 3-2: Oxygen economy during the incremental rowing protocol performed on Concept2 Model C and Model D ergometers.	57
Figure 3-3: (A) Blood lactate concentration, (B) heart rate and (C) oxygen consumption during both incremental rowing protocols performed on the Concept2 Model D ergometer.	58
Figure 4-1: Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER) and ventilation ($\dot{V}E$) as measured by the criterion MOUSE system during the incremental rowing test, and by the MM3B during Trial 1 and Trial 2 of duplicate rowing tests.	83
Figure 4-2: Bland-Altman plots of individual errors from duplicate MM3B trials (Trial 2 - Trial 1) during each workload of the incremental rowing test for oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER) and ventilation ($\dot{V}E$).	85
Figure 4-3: Bland-Altman plots of individual errors (MM3B - MOUSE) from each of the workloads during the incremental rowing test for oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER) and ventilation ($\dot{V}E$).	87
Figure 5-1: Mean power output during submaximal and maximal workloads for the ergometer (ERG) and on-water (OW) incremental tests.	104
Figure 5-2: Mean results for A) blood lactate (BLa), B) heart rate (HR) and C) oxygen consumption ($\dot{V}O_2$) using untreated data that does not account for the differences in submaximal workloads between ergometer (ERG) and on-water (OW) incremental rowing tests.	105
Figure 5-3: Mean submaximal results for A) heart rate (HR), B) blood lactate (BLa), C) oxygen consumption ($\dot{V}O_2$) and D) distance completed during ergometer (ERG) and on-water (OW) tests based on power normalised data using the standard power outputs.	110
Figure 5-4: Trial 1 (x axis) vs. Trial 2 (y axis) scatter plots and linear regression trendlines for A) heart rate (HR), B) blood lactate concentration (BLa), C) oxygen consumption ($\dot{V}O_2$) and D) distance completed during repeated on-water (OW) incremental rowing tests.	114

Figure 6-1: Mean results for heart rate (HR) using untreated data that does not account for the differences in submaximal workloads between A) the ergometer (ERG) and on-water (OW) incremental rowing tests, and B) the baseline and post-training tests using the OW protocol.	136
Figure 6-2: Average change in power output for individual athletes during the baseline and post-training 2000-m ergometer time-trials (TT).	142
Figure 6-3: Mean results using normalised submaximal data based on the standard power outputs for A) blood lactate (BLa), B) heart rate (HR) and C) oxygen consumption ($\dot{V}O_2$) during the baseline and post-training ergometer (ERG; left) and on-water (OW; right) incremental rowing tests.	143

TABLES

Table 1-1:	2000-m race times for finalists in World Cup, World Championship and Olympic regattas 2000-2004.	4
Table 1-2:	Summary of published literature relating to the physiological demands of competitive rowing for national level rowers.	6
Table 2-1:	Summary of literature on performance modelling of competitive rowing. Displayed values are correlation coefficients (R) between selected physiological and anthropometric variables and rowing time-trial performance.	22
Table 2-2:	Contemporary training intensity zones and traditional rowing classifications based on LT ₁ and LT ₂ blood lactate thresholds, and approximate heart rate and blood lactate concentration equivalents for a male heavyweight rower.	31
Table 3-1:	Subject description and performance characteristics during 4 min maximal ergometer rowing for males (<i>n</i> =6) and females (<i>n</i> =2).....	52
Table 3-2:	Power output, stroke rate and selected physiological variables during incremental rowing performed on Concept2 Model C and Model D ergometers.	56
Table 3-3:	LT ₁ and LT ₂ thresholds calculated from blood lactate-power output relationships during incremental rowing performed on Concept2 Model C and Model D ergometers.....	57
Table 3-4:	Reliability (% TE) of repeated measurements during the submaximal and maximal portions of the incremental rowing tests performed on the Concept2 Model D rowing ergometer.....	59
Table 4-1:	Physical characteristics of the subjects.	70
Table 4-2:	Simulated metabolic outputs for five different settings using the metabolic calibrator (<i>italicised</i>) and the corresponding mean results from either one trial (MM3B) or duplicate trials (MM3B2) with the MM3B portable metabolic system.	80
Table 4-3:	Differences between MM3B results during each stage of the duplicate incremental rowing tests (trial 2 - trial 1).....	84
Table 4-4:	Differences between metabolic measurements from the criterion MOUSE system and mean results from the two MM3B trials during each stage of the incremental rowing tests (MM3B - MOUSE).....	86
Table 5-1:	Physical characteristics of the subjects.	99
Table 5-2:	Regression analyses between measured variables and power output during ergometer (ERG) and on-water (OW) incremental rowing tests using pooled results from all subjects.	106
Table 5-3:	Mean (SD) performance characteristics during the maximal stage of the ergometer (ERG) and on-water (OW) tests.....	111
Table 5-4:	LT ₁ (aerobic) and LT ₂ (anaerobic) thresholds calculated from blood lactate-power output relationships using untreated data from the ergometer (ERG) and on-water (OW) tests.....	111

Table 5-5:	Reliability of repeated measurements during submaximal and maximal performance of on-water (OW) and ergometer (ERG) incremental rowing tests as indicated by relative typical error (%TE) and 90% confidence limits (90% CL).	115
Table 5-6:	Heart rate based training zones for two athletes displaying divergence between LT ₁ and LT ₂ heart rate results from the ergometer and on-water rowing tests.....	122
Table 6-1:	Physical characteristics of the 7 subjects.	130
Table 6-2:	Regression analyses between measured variables and power output during ergometer (ERG) and on-water (OW) incremental rowing tests using pooled results from all subjects.	137
Table 6-3:	Summary of the training completed during the 6-wk training period based on self-reported training logs.	141
Table 6-4:	Mean (SD) performance characteristics during the 2000-m ergometer time-trial (TT).....	142
Table 6-5:	Lactate threshold results and performance characteristics from the maximal stages of the ergometer (ERG) and on-water (OW) incremental rowing tests during baseline and post-training testing... ..	144
Table 6-6:	Linear regression analyses between selected results from the ergometer (ERG) and on-water (OW) incremental rowing tests and rowing performance (2000-m ergometer time-trial time and maximal power output from the on-water test) during the baseline and post-training test blocks.....	146

PLATES

- Plate 3-1:** The Concept2 Model C ergometer (C2C), including: A) PM2 work monitor unit; B) flywheel enclosure, and C) straight-design handle.47
- Plate 3-2:** The Concept2 Model D ergometer (C2D), including: A) PM3 work monitor unit; B) updated flywheel enclosure, and C) new 10° bent-handle.47
- Plate 4-1:** The MetaMax3B portable indirect calorimetry system, including: A) gas analysis-data telemetry module; B) telemetry receiver unit, and C) volume turbine assembly.71
- Plate 4-2:** The laboratory-based Maximum Oxygen Uptake System electronic (MOUSE) indirect calorimetry system, including: A) volume piston; B) AEI Technologies CD-3A CO₂ gas analyser; C) AEI Technologies S-3AI O₂ analyser; D) computer interface, and E) Mylar Douglas bags.73
- Plate 4-3:** The metabolic simulation system, including: A) computer interface; B) respiratory port, and C) internal mechanics.75
- Plate 5-1:** The WEBA Sport biomechanics system.97
- Plate 5-2:** A rower undertaking an on-water test on the Lake Burley Griffin rowing course.100

ABSTRACT

Laboratory-based rowing tests are the established standard for assessing fitness traits among elite rowers, and for prescribing individualised exercise intensities for training. But because tests occur on a rowing ergometer, the specificity of laboratory testing has been questioned compared with the criterion of on-water rowing. This project validated equipment required to replicate a laboratory-based rowing test in the field and evaluated the feasibility of on-water tests. Ergometer and on-water test results were compared to assess the validity of ergometer-derived training prescriptions and to establish the effectiveness of on-water tests for monitoring longitudinal fitness changes and for predicting rowing performance.

Concept2 rowing ergometers (Morrisville, USA) have frequently been used for rowing tests. Although subtle design variations exist between the different models of Concept2 ergometer, there were no substantial differences between the results from incremental rowing tests using Model C and Model D ergometers. The Concept2 Model D was therefore accepted as the standard ergometer for subsequent laboratory tests. Typical error (TE) results from duplicate Concept2 Model D tests conducted 2-4 d apart showed that laboratory tests were highly reliable (TE: maximal power = 2.8%, peak oxygen consumption = 2.5%).

As oxygen consumption ($\dot{V}O_2$) is measured routinely during laboratory rowing tests, it is necessary to obtain similar measurements during any on-water protocol. The MetaMax 3B portable indirect calorimetry system (Cortex, Leipzig, Germany) was therefore validated against a first-principles, laboratory-based indirect calorimetry system (MOUSE, Australian Institute of Sport, Canberra, Australia). $\dot{V}O_2$ from the MetaMax was significantly higher during submaximal exercise ($p=0.03$), although results were within $0.16 \text{ L}\cdot\text{min}^{-1}$ (4.1%) across all exercise intensities. There was good agreement between duplicate MetaMax trials separated by ~ 2 d; mean $\dot{V}O_2$ was within $0.11 \text{ L}\cdot\text{min}^{-1}$ (2.5%) and TE was $\leq 2.3\%$.

The specificity of rowing testing was improved using an On-water incremental test that replicated a laboratory-based Ergometer protocol. However, the individual variation in physiological responses between-tests meant that training intensity recommendations from the Ergometer test were not always applicable to on-water

training. Furthermore, measurements from the On-water protocol displayed similar or lesser reliability (TE=1.9-19.2%) compared with the Ergometer test (TE=0.1-11.0%).

As an effective fitness test must also be sensitive to longitudinal changes, the responses to 6 wks training were compared between the Ergometer and On-water methods. The magnitude of On-water training effects were usually greater (small Cohen's effect size) compared with the Ergometer test (trivial effect), although On-water and Ergometer tests both indicated that training responses were negligible because virtually all changes were less than one of their respective TEs. Correlations between test results and rowing performance were largest when rowing mode was matched between conditions, but Ergometer results provided the highest correlations (Ergometer vs. 2000-m ergometer time-trial: $R = -0.92$ to -0.97 compared with On-water vs. On-water maximal power output: $R = 0.52$ to 0.92).

Although On-water tests improved the specificity of on-water training prescriptions, these tests provided no obvious benefits for monitoring longitudinal fitness changes or performance compared with Ergometer tests. Given that On-water tests are also more time consuming and logistically challenging, their practical application is limited.

DECLARATION

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Andrew J. Vogler

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CHAPTER 1

INTRODUCTION, BACKGROUND AND STATEMENT OF PROBLEM

1.1 INTRODUCTION

This sport-based Doctorate of Philosophy (PhD) was underpinned by a collaboration between Flinders University and the Australian Institute of Sport (AIS). Given the core business of the AIS, the fundamental aims were to provide outcomes that would improve performance among elite Australian rowers and ultimately enhance the prospects of winning medals at international rowing competitions. The current PhD aimed to develop techniques to improve the specificity of physiological tests for rowing, with the anticipated downstream effects of a better understanding of training and ultimately an improved competitive performance. In essence, the aim was to provide the rowing coaches and scientists with more contextually relevant data about exercise prescriptions and the efficacy of training by conducting physiological tests in the field rather than in the laboratory. To achieve these aims, a series of studies were conducted to validate the equipment required to replicate a laboratory-based rowing test in the field and evaluate the feasibility of conducting on-water incremental rowing tests. Once the feasibility of on-water tests was established, subsequent studies compared results between ergometer and on-water tests to assess the validity of ergometer-derived training prescriptions and to establish the effectiveness of on-water tests for monitoring longitudinal fitness changes as well as for predicting rowing performance.

As the AIS is ultimately a training facility for elite athletes, the ability of the athletes and coaches to effectively coordinate training, competition and travel is clearly of paramount importance. Thus, applied sport science research conducted at the AIS must accommodate the extensive training and competition demands of the athletes and coaches. So, although the experimental data were collected with the support of the AIS Rowing program, it was not possible for AIS scholarship athletes to provide

the commitment necessary to participate in rigorously controlled scientific research. Other populations of high-calibre rowers were therefore recruited for this project, including rowers from the Australian Capital Territory Academy of Sport and from national and state-based talent identification squads.

1.2 BACKGROUND

1.2.1 Competitive rowing

Standard competitive rowing regattas are raced over 2000 m, with races grouped according to discipline (sculling or sweep-oared rowing), boat class (crew complement), weight category (heavyweight or lightweight) and gender. Sculling uses two oars (sculls), one on each side of the boat; while sweep rowing involves a single oar operated with both hands (Secher 1990). Sweep rowing involves crews of two, four or eight oarsmen and may also include a coxswain to steer the boat. While a coxswain is always present in the eights; pairs and fours are raced both with and without a coxswain. Sculling races are performed with single, double or quadruple boats, which again reflect the number of rowers involved - this form of rowing rarely involves a coxswain. Race times for 2000 m differ between rowing disciplines, sculling being generally faster than sweep rowing for boats with the same number of athletes. Table 1-1 displays median 2000-m race times for World Cup, World Championship and Olympic regattas during the 2000-2004 period. The variation in performance times within each of the rowing categories is largely the result of environmental influences. Wind and water conditions may fluctuate within and between races, meaning that rowing races must ideally be conducted head-to-head, and race times can not necessarily be used to compare rowing performances.

1.2.2 Descriptive characteristics of elite rowers

The physical characteristics of elite rowers have been summarised in numerous rowing reviews (Hagerman *et al.* 1979; Hahn 1990; Steinacker 1993; Shephard 1998; Mäestu and Jürimäe 2000). Typically, elite rowers are large individuals both in terms of height and body mass; this contributes to the long limb lengths, large muscle mass, high ventilatory capacity and maximal aerobic power associated with successful rowing performance. Indeed, normative anthropometric data for national level Australian rowers (Hahn 1990) reveal mean height and weight for heavyweight males as 191.9 cm and 90.2 kg, respectively; and for females 179.2 cm and 74.0 kg, respectively. Hahn (1990) also suggested that rowers exhibit longer arm and leg lengths as a proportion of total height compared with the general population. Due to the large body dimensions of elite heavyweight rowers, physiological characteristics such as minute ventilation ($\dot{V}E$) and maximum oxygen consumption ($\dot{V}O_{2\max}$) are

Table 1-1: 2000-m race times for finalists in World Cup, World Championship and Olympic regattas 2000-2004.

Rower category	Boat class	2000-m race time		
		Median	Fastest	Slowest
Men	1X	06:58.5	06:36.3	07:51.3
	2X	06:28.2	06:05.7	07:28.2
	4X	05:57.5	05:39.5	06:42.4
	2+	07:11.5	06:47.9	08:04.8
	2-	06:37.7	06:14.3	07:32.6
	4+	06:15.4	06:04.7	06:58.8
	4-	06:04.6	05:41.3	06:43.8
Women	8+	05:39.9	05:26.0	06:18.8
	1X	07:39.7	07:07.7	09:03.2
	2X	07:05.4	06:38.8	08:05.6
	4X	06:31.8	06:13.0	07:47.1
	2-	07:19.5	06:53.8	08:22.9
	4-	06:44.3	06:26.1	07:08.8
	8+	06:19.6	06:01.8	07:06.8
Lightweight men ^a	1X	07:13.9	06:49.4	08:27.6
	2X	06:28.6	06:10.8	07:27.7
	4X	06:05.4	05:50.8	06:55.5
	2-	06:47.2	06:30.0	08:20.6
	4-	06:03.8	05:47.2	06:52.5
	8+	05:45.7	05:35.0	06:28.0
Lightweight women ^b	1X	07:59.0	07:28.9	09:31.6
	2X	07:10.8	06:52.8	08:30.2
	4X	06:42.4	06:29.5	07:44.0
	2-	07:38.6	07:23.0	08:30.8

1X = single scull; 2X = double scull; 4X = quadruple scull; 2+ = coxed pairs; 2- = coxless pairs; 4+ = coxed four; 4- = coxless four; 8+ = eight; ^a weight restricted (72.5 kg maximum body weight, 70.0 kg crew average); ^b weight restricted (59.0 kg maximum body weight, 57.0 kg crew average).

among the largest observed in athletic populations. $\dot{V}E$ has commonly been reported to exceed 200 L.min⁻¹ (Hagerman *et al.* 1978; Hagerman *et al.* 1979; McKenzie and Rhodes 1982; Secher 1983) with values as high as 250-270 L.min⁻¹ (McKenzie and Rhodes 1982). Similarly, world-class male rowers exhibit large oxygen consumption ($\dot{V}O_2$) values of 6.0-6.6 L.min⁻¹ (Hagerman *et al.* 1978; Secher 1983; Steinacker 1993). Normative physiological data relating to Australian national heavyweight males show that $\dot{V}O_2$ values span 4.9-6.2 L.min⁻¹ during progressive ergometer tests, and that the equivalent data from female athletes ranges 3.5-4.6 L.min⁻¹ (Hahn *et al.* 2000).

1.2.3 Physiological demands of competitive rowing

The demands of competitive rowing have also been extensively considered (Hagerman *et al.* 1978; Hagerman and Staron 1983; Droghetti *et al.* 1991; Hartmann *et al.* 1993; Steinacker 1993; Jürimäe *et al.* 1999; Klusiewicz *et al.* 1999; Pripstein *et al.* 1999; Mäestu and Jürimäe 2000). For heavyweight males, peak force production during the drive phase is reported to span 1000-1500 N during maximal rowing (Hartmann *et al.* 1993; Steinacker 1993) and 500-700 N during the majority of a typical race (Steinacker 1993). Average power during ergometer rowing spans 358-412 W for male oarsmen during 2000-m or 6 min time-trials (Hagerman *et al.* 1978; Hagerman and Staron 1983; Droghetti *et al.* 1991; Jürimäe *et al.* 1999; Klusiewicz *et al.* 1999) and 266-277 W for experienced female rowers during 2000-m time-trials (Klusiewicz *et al.* 1999; Pripstein *et al.* 1999). The average (SD) power for heavyweight and lightweight males during a 2500-m ergometer time-trial are 351 (29) W and 286 (32) W, respectively (Mäestu and Jürimäe 2000). Furthermore, Steinacker (1993) suggests that the power sustained throughout the majority of a single scull race ranges 350-450 W. Table 1-2 reflects the variables most commonly reported in the literature but other physiological factors including hormonal responses (Steinacker *et al.* 1993b; Jürimäe and Jürimäe 2001), rate of perceived exertion (Gullstrand 1996; Bruce *et al.* 2000), muscle morphology (Roth *et al.* 1993), blood pressure (Clifford *et al.* 1994), energy system contribution (Hagerman *et al.* 1978; Pripstein *et al.* 1999; Romer *et al.* 1999) and seasonal fitness variations (Hagerman and Staron 1983; Vermulst *et al.* 1991; Womack *et al.* 1996; Petibois *et al.* 2003) have all been considered. The anaerobic threshold concept and its relationship to rowing performance has also been investigated comprehensively

Table 1-2: Summary of published literature relating to the physiological demands of competitive rowing for national level rowers. Values are mean (SD).

Author	Category	Mode	Physiological characteristic					
			Power (W)	$\dot{V}O_2$ (L.min ⁻¹)	$\dot{V}_{E\text{BTPS}}$ (L.min ⁻¹)	HR (bpm)	BLa (mmol.L ⁻¹)	
Jackson & Secher (1976)	HWM	2X & 2-		5.8-6.0				
Hagerman <i>et al.</i> (1978)	M	Lyons ergometer ^c	360 (13.8)	5.95 (0.33)	190 (11.3)	185 (6.9)	18.7 (1.7)	
Hagerman <i>et al.</i> (1979)	HWM	Rowing ergometer ^c	374 (13.2)	6.1 (1.6)	192 (10.8)	187 (2.5)	18.7 (1.7)	
	LWM	Rowing ergometer ^c	358 (7.6)	5.1 (0.7)	164 (4.6)	179 (2.2)	18.2 (1.5)	
	F	Rowing ergometer ^d	284 (21.0)	4.1 (0.4)	165 (15.6)	190 (1.8)	16.6 (1.6)	
Secher <i>et al.</i> (1982b)	M	Gjessing ergometer ^c	360 (8.2)	5.6 (0.1)	169 (5.2)	194 (1.5)		
	F	Gjessing ergometer ^e	277 (9.5)	3.92 (0.50)	112 (4.7)	199 (2.1)		
Hagerman & Staron (1983)	HWM	Stanford ergometer ^c	397.7 (14.9)	6.01 (0.45)	189.1 (14.4)	185 (4.4)		
Secher <i>et al.</i> (1983)	LWM	Gjessing ergometer ^c	331 (7.5)	5.13 (0.03)	164 (5.2)			
Mahler <i>et al.</i> (1984)	LWM	Concept II ergometer ^c	420 (43.0)	4.6 (0.2)	173 (18.0)	183 (6.0)		
Hahn <i>et al.</i> (1988)	F	Concept II ergometer ^f	255.5 (23.3)	3.50 (0.33)	127.1 (11.4)	185 (6.0)	14.9 (3.1)	
Secher (1990)	HWM	1X, 2X & 2-		6.6*				
Droghetti <i>et al.</i> (1991)	HWM	Gjessing ergometer ^c	409 (15.0)	5.58 (0.21)	197.5 (16.5)	193 (7.9)	16.1 (1.8)	
Klusiewicz <i>et al.</i> (1999)	M	Concept II ergometer ^a	412 (37.0)	5.55 (0.48)	177.2 (25.4)	186 (7.0)	14.7 (2.4)	
	F		266 (25.0)	4.00 (0.45)	132 (14.7)	191 (6.0)	12.8 (3.0)	
Hahn <i>et al.</i> (2000)	HWM	Concept II ergometer ^e		5.48 (0.32)				
	HWF			3.93 (0.32)				
Mäestu <i>et al.</i> (2000)	HWM	Concept II ergometer ^b	350.8 (29.3)			192.3 (4.4)	16.9 (1.6)	
	LWM		286.0 (31.5)			190.4 (8.0)	18.2 (3.6)	
Jürimäe <i>et al.</i> (2002a)	M	Concept II ergometer ^a	361.9 (28.5)	4.85 (0.7)		184.6 (7.5)	19.2 (2.9)	
Mikulic <i>et al.</i> (2007)	M	Rowing ergometer ^g		5.51 (0.4)				

HWM = heavyweight male; M = male (weight category not specified); F = female (weight category not specified); LWM = lightweight male; ^a = 2000-m time-trial; ^b = 2500-m time-trial; ^c = 6-min time-trial; ^d = 3-min time-trial; ^e = 4-min time-trial; ^f = 5-7 min time-trial; ^g = continuous progressive rowing test.

(Mickelson and Hagerman 1982; Beneke 1995; Forsyth and Reilly 2003); as have mechanical considerations such as stroke rate (Martin and Bernfield 1980), mechanical efficiency (Di Prampero *et al.* 1971; Celentano *et al.* 1974; Fukunaga *et al.* 1986; Droghetti *et al.* 1991; Affeld *et al.* 1993) and technique (Bompa 1980; Bompa *et al.* 1985; Sanderson and Martindale 1986; Dawson *et al.* 1998). However, the vast majority of the rowing literature is based on ergometer simulations of competitive rowing attempting to match either the duration or distance of the 2000-m race (1000 m for females until 1985).

1.2.4 Physiological testing of elite rowers

As the demands of competitive rowing have been extensively studied, and the physiological and anthropometric characteristics of successful rowers thoroughly described, the physiological traits that are known to contribute strongly to rowing performance can be assessed using specialised laboratory-based rowing tests. Rowing test results may then be used to identify talented athletes based on their physiological profiles (Hahn 1990), or to monitor longitudinal training adaptations (Hagerman and Staron 1983; Vermulst *et al.* 1991; Womack *et al.* 1996; Petibois *et al.* 2003) and provide training intensity prescriptions for individual athletes (Urhausen *et al.* 1993b). Given fitness results from laboratory rowing tests provide insights into rowing performance potential and fitness progression, results from these tests may even represent a component of the selection criteria for national representation (Koutedakis 1989).

During the initial stages of this PhD, the test protocol endorsed by Rowing Australia for the physiological assessment of elite Australian rowers was referred to as the “2-in-1 test”, which consisted of a 5-stage submaximal progressive incremental test followed by a simulated 2000-m time-trial (Bourdon *et al.* 2009). This laboratory test allowed the evaluation of submaximal exercise responses, rowing economy, $\dot{V}O_{2\max}$ and maximal accumulated oxygen deficit (MAOD). However, an abridged version using a 4-min maximal stage instead of the 2000-m time-trial was also commonly used in Australia. While this ‘4-min max’ variation did not incorporate an evaluation of MAOD, it had the advantage of being less taxing for the athlete and provided an effective and expedient alternative to the “2-in-1” test. The abridged “4-min max” protocol therefore formed the basis for the incremental rowing protocols used

throughout the majority of this project.

Laboratory-based physiological assessments at the AIS are performed at regular intervals throughout the domestic rowing season (October-March), usually at intervals of approximately 8-12 wk. This frequency provides an effective means for tracking the progression of fitness adaptations and providing insights into the effectiveness of the preceding training block. Test results are also used to adjust individualised training recommendations and to assist with the development of strategies for upcoming training cycles. Although the laboratory test is adequately sensitive to track changes in physiological status across testing sessions, actual on-water performance is observed to change considerably in this time (personal communication, Prof Allan Hahn). The 8-12 wk time frame between laboratory tests therefore not only leaves some uncertainty about the acute response to training micro-cycles within a training block, but also appears to lack the specificity to detect modulation of some factors that contribute to actual on-water performance. Furthermore, the literature suggests that the physiological response to exercise differs between rowing performed on an ergometer and on-water (Steinacker *et al.* 1987; Chènier and Leger 1991; Urhausen *et al.* 1993b; Payne *et al.* 1996; Ryan-Tanner *et al.* 1999b). Thus, the training intensity recommendations derived from a laboratory test do not necessarily translate to the on-water environment and are specific only to ergometer rowing. Issues such as these could potentially be circumvented by improving the specificity of physiological testing through the development of on-water testing protocols that mimic those undertaken in the laboratory.

1.3 STATEMENT OF PROBLEM

Laboratory-based ergometer tests have been used extensively by the rowing community to measure training related changes in fitness traits and to prescribe submaximal training thresholds that can be applied to training on and off the water. Specifically, sport scientists use blood lactate-power output and heart rate-blood lactate relationships obtained from laboratory testing to prescribe individualised on-water training intensities. In recent years, it appears that the intended transfer of data from laboratory-based tests to the field environment has not been used by many coaches because the relevance and specificity of the ergometer based testing has been challenged with regard to on-water rowing.

1.3.1 Aims

The major aim of this PhD was to evaluate whether a field-based rowing test that replicated established laboratory-testing practices could provide specific on-water training intensity prescriptions and better monitor fitness adaptations and performance readiness compared with laboratory tests. If laboratory testing techniques could be replicated in the field and if the results from on-water tests could be reproduced consistently, a sensitive and reliable on-water test could supplement routine laboratory tests by providing regular quantitative feedback from training scenarios and could generate specific recommendations for on-water training. It was hypothesised that on-water evaluation would enhance the specificity of rowing test results compared with current practices, as laboratory assessments are based on simulated rowing on an ergometer. Thus, on-water tests could potentially provide more accurate training prescriptions for on-water rowing and better feedback regarding the efficacy of the preceding training block. The results from on-water tests would therefore provide additional information that is directly applicable to on-water rowing and allow coaches to better refine the on-water aspect of their training programmes. Ultimately, if on-water testing proved to be a viable assessment method, the results would improve the quality of training and enhance rowing performance by maximising the time spent at an optimal training load.

While the overall aim of this PhD was to develop and evaluate an on-water incremental rowing test, intermediate issues relating to the validity of the equipment used during laboratory and on-water tests had to be addressed beforehand, in order

for on-water testing to proceed and to enable thorough comparisons between the laboratory and on-water methods. Thus, the following series of studies were used to systematically address aspects of the development of the on-water test and to compare the on-water method to the standard laboratory test. The aims of each of these studies were:

Study 1 – Validation of the Concept2 Model D rowing ergometer

- Establish the validity of the Concept2 Model D rowing ergometer compared with the Concept2 Model C.
- Determine the reliability of measurements obtained during laboratory-based rowing tests to establish the magnitude of physiological and performance variations between duplicate tests performed within 2-4 d.

Study 2 – Accuracy and reliability of the Cortex MetaMax3B portable metabolic system

- Validate the accuracy and reliability of the Cortex MetaMax3B portable metabolic system against the criterion of the automated Douglas bag system used by the AIS Department of Physiology.
- Evaluate the feasibility of using the portable system during on-water testing.

Study 3 – Physiological responses and training intensity recommendations from ergometer and on-water incremental rowing tests

- Evaluate the specificity of laboratory test results by comparing the physiological responses and training intensity prescriptions between matched laboratory and on-water incremental rowing tests.
- Determine the reliability of duplicate on-water tests separated by 1-3 d in comparison with the reliability results established for the laboratory test during Study 1.

Study 4 – Monitoring fitness and performance with ergometer and on-water incremental rowing tests

- Evaluate the effectiveness of the on-water test for monitoring longitudinal fitness changes compared with the current laboratory protocol.
- Determine the efficacy of the on-water test as a means of monitoring performance readiness.

1.3.2 Limitations

There are a number of possible limitations associated with the experimental protocols used during this project that have the potential to confound any conclusions, including:

- a) The recruited rowers were not elite open class athletes, so findings may not necessarily extend to the intended target population of international standard athletes.
- b) As senior AIS rowers were unable to participate in this project, there was limited access to rowers of an appropriate standard, thus sample sizes were limited to 6-8 athletes and statistical power to detect small effect sizes will be low (Hopkins *et al.* 2009).
- c) Time constraints imposed by the need to collect data during dedicated research camps, typically less than one week in duration, meant that there was limited time for subject familiarisation, as well as potential for fatigue to influence results when tests were performed on consecutive days.
- d) Subject compliance to the stipulated pre-experimental subject preparation protocols was not always confirmed.
- e) Injury and illness prevented some athletes from completing all aspects of some experimental protocols.
- f) Variable environmental conditions between field testing occasions may have impacted on the reproducibility of on-water testing results and confounded comparisons between laboratory and on-water tests and between duplicate on-water tests.
- g) The potential for non-steady-state conditions during on-water assessments of metabolic demand due to fluctuations in rowing intensity resulting from variable environmental conditions or uneven pacing.
- h) The potential for inflated measurement error due to alterations in the effort of performance or technique as a consequence of being observed, or due to potential movement-pattern restriction imposed by the equipment used for indirect calorimetry measurements.
- i) Error introduced from the linear regression models used to normalise physiological data and enable comparisons between laboratory and on-water tests at equivalent power outputs.
- j) Laboratory and on-water power output measurements were assumed to be

equivalent; physiological comparisons using power normalised data will be confounded if this assumption is violated.

1.3.3 Delimitations

To control for the above and other confounding factors, the following measures were undertaken:

- a) Participants were high calibre age group (under 23) athletes that had at least attained state-representation in national-level competition, although some of the rowers also achieved national (Australian) selection.
- b) Data collection was conducted during dedicated research camps to allow invited interstate athletes to participate, thereby increasing the available number subjects. Additionally, contemporary data analysis techniques (Hopkins *et al.* 2009) were used to limit the potential impact of small sample sizes on statistical tests.
- c) Subject familiarisation was addressed using shortened test protocols when time constraints prevented replication of the entire test protocol and where possible, tests were scheduled so that athletes avoided performance on consecutive days.
- d) The pre-experimental subject preparation protocols controlled for factors such as fatigue from prior exercise, recommendations regarding feeding in preparation for exercise tests and diurnal variation.
- e) In the instances where injury or illness prevented an athlete from completing an isolated aspect of the experimental protocol, but the remainder of their data were unaffected, only the missing data were removed from subsequent data analyses.
- f) Rowing power output was measured during the on-water tests to quantify exercise intensity and to permit comparisons between test results at equivalent power outputs.
- g) The likelihood of achieving steady-state conditions was maximised by allowing at least 2-3 min (of 4-min exercise bouts) for physiological responses to equilibrate with the exercise demands prior to metabolic data being recorded for subsequent analysis. Additionally, rowers were provided with visual feedback of their instantaneous stroke rate and were instructed to maintain a constant stroke rate throughout each workload.
- h) Indirect calorimetry equipment that was fitted to the subjects (respiratory valve and portable metabolic system) was adjusted to maximise subject comfort and minimise any potential movement-pattern restrictions - none of the rowers reported movement-pattern or rowing technique alterations due to the equipment.

All rowers were familiar with being supervised whilst rowing, as this was consistent with the athletes' normal experiences during rowing training.

- i) Very strong relationships (Pearson correlation coefficients) were obtained between physiological results and power outputs during the laboratory and on-water rowing tests, thereby ensuring that the errors from predictions using the linear regression models were minimised.
- j) It was not possible to use the same equipment to measure power output during the laboratory and on-water tests. However, diligent calibration procedures were always employed to ensure the accuracy and reliability of all measurements.

1.4 DATA ANALYSIS CONSIDERATIONS

Hypothesis testing with traditional inferential statistics calculates the probability (p value) that an observed effect (regardless of direction) is different to the null hypothesis based on a distribution corresponding to the degrees of freedom for the number of sample observations. An arbitrary value of $p < 0.05$ is usually used to reject the null hypothesis (no statistical difference or relationship) and report the observed effect as statistically significant. However, the p value alone does not account for the magnitude or direction of the actual effect, or the precision of the statistical estimate of the effect (Cohen 1990). A non-statistically significant result ($p > 0.05$) can therefore fail to elucidate important effects if data is derived from a small sample size and/or experimental techniques are subject to considerable measurement variability. However, new approaches to data analysis are emerging in the biomedical, clinical and sports sciences that are based on interpretations of the magnitude of effects (changes and differences) in relation to practically or clinically important thresholds (Hopkins *et al.* 2009). This analytical approach is especially relevant to elite athletic population as very small changes or differences can make substantial differences to performance outcomes (Hopkins *et al.* 1999).

Magnitude-based inferences (Batterham and Hopkins 2006) centre on the interpretation of experimental effects with regard to practically or clinically relevant thresholds, and may offer a more useful approach for interpreting the magnitude of experimental effects than traditional inferential statistics (Sterne and Davey Smith 2001). The magnitude of the effect is interpreted relative to the smallest worthwhile change (SWC), which is a reference value for the smallest important outcome for a given test or event. In applied sport science settings, the SWC has often be derived from reliability assessments (duplicate measures) of test protocols and measurement techniques (Driller *et al.* 2009), or where possible, modelling of athletic competition to determine the smallest performance improvement required to benefit race results (Batterham and Hopkins 2006; Robertson *et al.* 2009). Alternatively, the magnitude of the experimental effect can also be quantified using Cohen's effect size units to determine the likelihood that the effect is small, moderate, or large (Cohen 1988). Either way, the experimental effect (including the distribution for the confidence limits defining the precision of the statistical estimate) is compared to the SWC to determine the likelihood that the true effect conforms to one of three possible

outcomes: 1) substantially positive (greater than the SWC in a positive direction), 2) trivial (less than the SWC), or 3) substantially negative (greater than SWC in a negative direction). To make inferences about population effects, 90% confidence limits show an outcome is clear when estimates for the true value of the experimental effect are unlikely (<5% probability) to be simultaneously substantial in a positive and negative direction, and when the most likely outcome (either positive, trivial or negative) returns a probability $\geq 75\%$ (Hopkins 2007; Hopkins *et al.* 2009). When these criteria are not met, the effect is unclear, although the probability results still provide an indication of the possible magnitude and direction of the true effect. This analytical approach therefore permits rigorous but practically-based interpretations regarding the magnitude of the physiological differences resulting from the mode of rowing (i.e. ergometer or on-water), and between measurement devices (Concept2 ergometers and indirect calorimeters). Hypothesis testing as well as contemporary magnitude-based inferences have both been used to analyse each of the experimental sections and have generally shown good agreement in elucidating important differences between data comparisons. However, the magnitude-based approach did sometimes indicate substantial differences when statistical significance was not attained. In instances where hypothesis testing approached statistical significance and magnitude-based effects were substantial, the latter results were favoured given the potential for our small sample sizes to impact on the results from hypothesis tests.

CHAPTER 2

LITERATURE REVIEW: ROWING TESTING – LABORATORY AND FIELD PROTOCOLS

2.1 INTRODUCTION

Laboratory based ergometer testing has been used extensively to measure training related changes in fitness and prescribe sub-maximal training thresholds that can be applied to training on and off the water. Specifically, sport scientists have used average power output-blood lactate (BLa) and heart rate (HR)-BLa relationships obtained from laboratory testing to prescribe individualised on-water training intensities for incorporation into training programs (Urhausen *et al.* 1993b). In recent years, it appears that the intended transfer of data from laboratory based tests to the field environment has not been used by many Australian coaches (unpublished personal observation), as the relevance and specificity of ergometer based testing has been questioned. This review therefore considers the specificity of current rowing testing techniques by examining the role of laboratory-based ergometer testing and providing an overview of the validity of ergometer rowing with respect to the criterion of on-water performance.

2.2 ROWING ERGOMETRY

Rowing ergometers have become a standard feature of most sport science facilities. However, much of the early work investigating the physiological response to rowing was non sport-specific and relied on exercise tests using cycle ergometers or treadmills (Saltin and Astrand 1967; Secher *et al.* 1974; Larsson and Forsberg 1980). The specificity of research into the physiological demands of rowing was therefore greatly improved with the introduction of mechanically braked rowing ergometers to simulate sweep-oar rowing (Hagerman and Lee 1971; Bloomfield and Roberts 1972) and subsequent work using test protocols that simulated the distance or duration of the competitive 2000 m distance (Hagerman *et al.* 1972; Hagerman *et al.* 1978;

Secher *et al.* 1982a). Indeed, Hagerman *et al.* (1979) used simulated rowing on an ergometer to present one of the first thorough physiological profiles of elite rowers, including values for: power output, $\dot{V}O_{2\max}$, $\dot{V}E$, HR and serum lactate concentration. However, numerous other studies have also considered the competitive demands of rowing (Table 1-2; pg. 6). Indeed, rowing ergometry has allowed thorough evaluation of many facets of rowing physiology and performance including: the metabolic cost of rowing (Hagerman *et al.* 1979; Secher *et al.* 1983; Sanderson and Martindale 1986; Beneke 1995; Pripstein *et al.* 1999), the relationship between ergometry results and rowing performance (Bloomfield and Roberts 1972; Hagerman *et al.* 1972; Secher *et al.* 1982b; Cosgrove *et al.* 1999), and the magnitude and pattern of seasonal fitness changes (Bloomfield and Roberts 1972; Secher *et al.* 1982a; Hagerman and Staron 1983).

2.2.1 Metabolic cost of rowing

The metabolic cost of rowing is determined by the work performed to overcome the drag forces acting on the boat shell and ‘internal work’ due to movement of the rower’s body mass that does not contribute to propulsion. The major component of the drag force is from friction between the boat shell and water, although wave drag and air resistance also contribute. However, because the latter sources of drag are relatively small (~7% and 10%, respectively) in comparison to the drag of water, they are usually ignored (Sanderson and Martindale 1986). Therefore, drag force depends on boat velocity, the weight of oarsmen and technical proficiency (Secher and Vaage 1983; Sanderson and Martindale 1986). During rowing, drag is proportional to the square of boat velocity. Hence, an altered movement pattern during recovery has been proposed to reduce drag by minimising fluctuations in peak velocity relative to mean boat speed (Sanderson and Martindale 1986). Additionally, differing techniques between rowers may also contribute to differences in energy loss due to drag; for instance Sanderson & Martindale (1986) noted variations in boat speed efficiency between four single scullers according to gender and experience. The mechanical efficiency of rowing is reported to range 10-23% (Di Prampero *et al.* 1971; Droghetti *et al.* 1991), with the large range mainly due to the efficiency differences reported between simulated and actual rowing. During on-water rowing Di Prampero *et al.* (1971) reports an efficiency of 18% increasing to 23% at higher stroke rates, which is confirmed by other values reported in the literature of 20-22% (Secher 1983). The efficiency during simulated rowing is generally lower, with

minimum reported values of 10-14% (Di Prampero *et al.* 1971; Hagerman *et al.* 1978), but improving to 20-21% when stroke rate approximates racing cadence (Di Prampero *et al.* 1971; Droghetti *et al.* 1991).

When $\dot{V}O_2$ is measured during on-water rowing, the metabolic cost of the activity increases with boat speed to the power of 2.2-2.6 depending on rowing discipline (Secher 1983). Similarly, when on-water $\dot{V}O_2$ was estimated from the HR- $\dot{V}O_2$ relationship established during stationary sweep rowing in a tank, the metabolic cost was related to boat speed to the power of 3.2 (Di Prampero *et al.* 1971). However, movement of the rower's body mass during the stroke cycle also contributes to the metabolic cost of the activity regardless of whether or not force is applied to the oars (Secher 1983; Sanderson and Martindale 1986). Indeed, the oxygen cost of 'no-load' rowing on an ergometer increases with stroke rate from 0.75-1.25 L.min⁻¹ at 16 strokes.min⁻¹ to 1.75-2.8 L.min⁻¹ at 32 strokes.min⁻¹ depending on inter-individual efficiency (Droghetti *et al.* 1991) and approaches a value of 3.5 L.min⁻¹ at 40 strokes.min⁻¹ (Secher 1983). When the oxygen cost of this additional internal work is subtracted from the total oxygen requirement, the metabolic cost of rowing increases according to mean boat velocity to the power of 3.1 (Secher 1983). Thus confirming the theoretical relationship, that requires a cubic power function to overcome the energy dissipated due to drag (Di Prampero *et al.* 1971; Celentano *et al.* 1974; Secher 1983; Sanderson and Martindale 1986).

According to prediction equations by Secher (1983), the metabolic cost of rowing at racing velocity during FISA championships has increased from 5.1 L O₂.min⁻¹ in 1919 to 6.4 L O₂.min⁻¹ in 1979. Also, Di Prampero *et al.* (1971) estimated the total oxygen requirement of an individual during a 2000-m race in a pair-oared boat as 46 L, or 6.3 L O₂.min⁻¹. Using the equations of Secher (1983) to predict oxygen requirement from rowing velocity, the mean metabolic cost of rowing in the 2008 Beijing Olympics was ~7 L O₂.min⁻¹ for males competing in the single or double sculls and coxless pairs. However, the degree to which performance improvements can be attributed to improved athletic conditioning or technological advancements in rowing equipment is unknown. It is therefore unlikely that the prediction for Beijing is a true reflection of metabolic cost given the equation from which it is based is ~25 years old. However, several researchers have directly measured $\dot{V}O_2$ during on-

water rowing using Douglas bags (Jackson and Secher 1976; Chénier and Leger 1991) or a modern portable metabolic system (Kawakami *et al.* 1992). Of these, only Jackson and Secher (1976) is based on elite rowers, reporting $\dot{V}O_2$ values of 5.8-6.0 L.min⁻¹ at “ideal racing speeds”. However, none of these measurements were conducted over the full 2000-m race distance, and do not represent the total metabolic cost of the activity as they do not include the contribution from anaerobic energy sources.

It is also interesting to note the pattern of energy utilisation during a rowing race. Rather than accelerating to a pace that can be maintained for the entire duration of the race, rowers display an initial ‘spurt’ in which stroke rate, power output and boat velocity are considerably higher than those maintained for the majority of the race (Hagerman *et al.* 1978; Secher *et al.* 1982a; Steinacker 1993). This is reflected in the 500 m split times observed during a race. Typically, the first 500 m is the fastest, followed by a reasonably consistent middle 1000 m and slightly faster final 500 m as crews push for the finish (Hagerman *et al.* 1978; Secher *et al.* 1982a). The mean 500m split times for all crews competing in the final of the men’s coxless four at the 2008 Beijing Olympics provides an ideal example of this: 1:28.4, 1:35.2, 1:35.0 and 1:33.3 (min:s).

2.2.2 Aerobic and anaerobic energy contribution

Given the typical 5.5-8.0 min duration of a rowing race, the majority of the total metabolic requirement is met aerobically. However, BLa concentrations of 15-17 mmol.L⁻¹ following national and international regattas (Vaage 1977; Mäestu and Jürimäe 2000) and maximal values of 16-19 mmol.L⁻¹ (Jürimäe *et al.* 1999; Jürimäe *et al.* 2002a; Jürimäe *et al.* 2002b) after competition or ergometer-based race simulations indicate a significant anaerobic energy contribution. Given the pacing strategy adopted during racing, a considerable anaerobic effort is required during the initial 1.5-2 min, as indicated by the oxygen deficit (Hagerman *et al.* 1978; Pripstein *et al.* 1999) and peak BLa response (Hagerman *et al.* 1978). In fact, Secher *et al.* (1982a) suggest that the ‘spurt’ is performed to maximise $\dot{V}O_2$ kinetics which are faster for higher workloads. Following this rapid start, male rowers are able to sustain 96-98% of their $\dot{V}O_{2\max}$ (Hagerman *et al.* 1978), and female rowers 91% of $\dot{V}O_{2\max}$ (Pripstein *et al.* 1999), for the remainder of the race.

The contribution of aerobic energy to the total metabolic cost of rowing can be reliably assessed by measuring $\dot{V}O_2$ (Hagerman *et al.* 1978); however, the relative contribution of anaerobic metabolism is not so easily determined. In studies of rowing, anaerobic metabolism has generally been estimated from measurements of excess post exercise oxygen consumption (EPOC; Hagerman *et al.* 1978; Hagerman *et al.* 1979; Secher *et al.* 1982a) or oxygen deficit (Droghetti *et al.* 1991; Russell *et al.* 1998; Pripstein *et al.* 1999; Bourdon *et al.* 2009), for performances on a rowing ergometer. Both methods have limitations, processes that are not related to anaerobic metabolism during exercise also contribute to the EPOC - including elevated metabolic rate from increased body temperature and sympathetic nerve activity, and additional oxygen demand from the heart and respiratory muscles (Åstrand *et al.* 2003) - and may therefore cause the anaerobic energy contribution to be overestimated by this method (Hagerman 1984; Secher 1993). Conversely, the oxygen deficit method may underestimate the oxygen demand and therefore anaerobic contribution at supra-maximal workloads (Pripstein *et al.* 1999). Using EPOC, Hagerman *et al.* (1978) measured a 30 min post exercise oxygen consumption of 13.4 L; when combined with the 30.9 L of oxygen consumed during the 6-min row, the relative contribution of aerobic and anaerobic energy was 69.8% and 30.2%, respectively. Alternatively, anaerobic energy contribution determined from oxygen deficit during 6-min rowing revealed a value of 19.9% total energy expenditure (Droghetti *et al.* 1991). However, the 6 min duration adopted in the above studies is designed to replicate the competitive demands of the larger crewed boats (e.g. eights, fours and quads) and thus represents a shorter effort than what is required for the smaller classes of boat (Hagerman 1984). In the case of smaller boats, this leads to an overestimation of anaerobic contributions due to a lower total energy expenditure compared to a longer effort that better simulates the duration of a 2000-m race (Secher 1993). Thus, Pripstein *et al.* (1999) measured oxygen deficit during a 2000-m time-trial and reported a 12% anaerobic contribution for female rowers. Otherwise, much of the early research investigating anaerobic energy contribution in female rowers is based on rowing exercise of 3-4 min duration designed to simulate a 1000 m race distance (Hagerman *et al.* 1979; Secher *et al.* 1982a). Thus, for the reasons outlined above, these data are not comparable to those simulating the 2000 m race distance and have not been considered in this review.

2.2.3 Performance determinants and modelling

In the recent literature, rowing performance modelling has been widely considered (Klusiewicz *et al.* 1991; Kramer *et al.* 1994; Womack *et al.* 1996; Cosgrove *et al.* 1999; Jürimäe *et al.* 1999; Jürimäe *et al.* 2000; Mäestu *et al.* 2000; Ingham *et al.* 2002b; Jürimäe *et al.* 2002a; Yoshiga and Higuchi 2003; Bourdin *et al.* 2004). Physiological and anthropometric measures have been correlated with 2000-m and 2500-m ergometer time-trial performances and 2000-m on-water performances (Table 2-1). Many of the variables listed in Table 2-1 have been included in multiple regression analyses in an attempt to determine which parameters best predict 2000-m rowing performance. Performance models utilising between two and 10 independent variables display mixed results in accounting for performance variations in 2000-m rowing time or velocity on ergometers and single sculls. When the 2000-m ergometer time-trial is the performance criterion, the various models of ergometer performance generate R^2 ranging 0.50–0.99 with associated standard errors of estimate (SEE) spanning 10.6–1.42 s, respectively (Jürimäe *et al.* 2000; Yoshiga and Higuchi 2003). Similarly, when rowing velocity is the criterion, R^2 ranges 0.87 (Cosgrove *et al.* 1999) to 0.98 (Ingham *et al.* 2002b), and Ingham *et al.* (2002b) report limits of agreement between predicted and actual values of -0.006 to $0.098 \text{ m}\cdot\text{s}^{-1}$ (-1.52 to 6.89 s). Prediction of on-water performance accounts for less variation ($R^2=0.65\text{--}0.89$) and is associated with larger SEEs of 11.3 s using a two variable model of metabolic parameters (Jürimäe *et al.* 1999) and 6.3 s for a five variable model using metabolic and anthropometric predictors (Jürimäe *et al.* 1999). The effect of training has also been considered with performance models (Womack *et al.* 1996). Variables including peak ergometer velocity, peak oxygen consumption ($\dot{V}O_{2 \text{ peak}}$) and $\dot{V}O_2$ and velocity corresponding to $4.0 \text{ mmol}\cdot\text{L}^{-1}$ BLa are strongly correlated with 2000-m ergometer time-trial performance both before and after training, but training induced changes in peak velocity display the best relationship ($R^2=0.59$) with actual changes in time-trial performance (Womack *et al.* 1996). So although some of these models account for considerable variation in rowing performance, it has typically been the more complex models that utilise multiple variables that display the strongest relationships. Additionally, as all independent variables are derived from ergometer rowing, it is not surprising that stronger relationships occur when the ergometer time-trial is the performance criterion rather than the on-water condition. Furthermore, although some of these investigations considered the relationship between selected

Table 2-1: Summary of literature on performance modelling of competitive rowing. Displayed values are correlation coefficients (R) between selected physiological and anthropometric variables and rowing time-trial performance.

Author	Year	Variable										
		$\dot{V}O_2 \text{ max}$ L.min ⁻¹	$\dot{V}O_2 \text{ max}$ ml.kg ⁻¹ .min ⁻¹	P_{max} W	$P_{\dot{V}O_2 \text{ max}}$ W	W	BLa_4 L.min ⁻¹	$BL_{A_{350W}}$ mmol.L ⁻¹	Ht cm	BM kg	LBM kg	CSA_{Thigh} cm ²
<i>Male (HW & LW)</i>												
Bourdin et al.	2003 ^c	0.84	0.55 [†]	0.92					0.65			
Jurimae et al.	1999 ^d	0.75	0.11		0.97	0.95						
Jurimae et al.	2000 ^a	-0.64	-0.33		-0.70	-0.61		0.64	-0.36	-0.50	-0.51	-0.50
Jurimae et al.	2000 ^b	-0.76	-0.13		-0.97	-0.96		0.96	-0.77	-0.91	-0.91	-0.66
Jurimae et al.	2002 ^c	-0.85	-0.40	-0.88		-0.61 [#]		0.80	-0.63	-0.85	-0.88	-0.80
Yoshiga et al.	2000 ^b	-0.64	0.06						-0.35	-0.66	-0.68	
Cosgrove et al.	1999 ^c	0.85							0.21	0.70	0.85	
Ingham et al.	2002 ^c	0.82	0.19	0.88	0.93	0.92			0.66	0.76	0.84	
<i>Male (HW)</i>												
Bourdin et al.	2003 ^c	0.68	0.60 [†]	0.89								
Mäestu et al.	2000 ^c	-0.50	-0.06		-0.72	-0.54			-0.17	-0.65	-0.57	-0.65
Womack et al. Pre	1996 ^b	-0.84										
Womack et al. Post	1996 ^b	-0.87										
<i>Male (LW)</i>												
Bourdin et al.	2003 ^c	0.70	0.64 [†]	0.76								
Mäestu et al.	2000 ^b	-0.89	-0.68		-0.95	-0.83			-0.56	-0.65	-0.72	-0.43
<i>Female (HW & LW)</i>												
Kramer et al.	1994 ^e	-0.77										
Ingham et al.	2002 ^c	0.80	0.39	0.74	0.91	0.89			0.70	0.79	0.75	
<i>Junior</i>												
Klusiewicz et al.	1991 ^a	-0.30	-0.70			-0.53						

$\dot{V}O_2 \text{ max}$ = maximal oxygen consumption; P_{max} = maximal power output; $P_{\dot{V}O_2 \text{ max}}$ = power output corresponding to $\dot{V}O_2 \text{ max}$; BLa_4 = blood lactate concentration of 4 mmol.L⁻¹; $BL_{A_{350W}}$ = blood lactate concentration corresponding to 350 W power output; Ht = height; BM = mass; LBM = lean body mass; CSA_{Thigh} = thigh cross-sectional area; [#] = individual lactate threshold; [†] = scaled body mass (ml.kg^{-0.57}.min⁻¹); HW= heavyweight athlete; LW= lightweight athlete; ^a = 2000-m sculling time ^b = 2000-m ergo time; ^c = 2000-m ergo velocity; ^d = 2000-m ergo power; ^e = 2500-m ergo time.

variables and on-water time-trials, there appear to be no publications using independent variables measured during actual on-water rowing.

2.2.4 Fitness monitoring

Beyond using simulated rowing to describe the demands of the sport, to profile successful athletes, and to attempt to predict performance, it was recognised that ergometer tests could regularly assess fitness changes and provide training feedback. Incremental rowing protocols were therefore developed to determine the anaerobic threshold (AT) so that training intensities and fitness adaptations could be better prescribed (Mickelson and Hagerman 1982; Steinacker *et al.* 1982). Although it is unclear when rowing ergometers became standard equipment for routine physiological assessments of elite rowers, Steinacker *et al.* (1982) describe a formalised rowing ‘step-test’ protocol that is remarkably similar to those currently common in Australia (Hahn *et al.* 2000) and Britain (Godfrey and Whyte 2006). However, by the mid-1980s, rowing specific exercise tests on mechanically braked Gjessing ergometers or air-braked Concept2 ergometers were used regularly to evaluate training adaptations in US collegiate rowers (Mahler *et al.* 1985) and for routine testing of Australian rowers (Hahn *et al.* 1988). Furthermore, by the latter stages of the 1980s, it was accepted practice for the results of laboratory based rowing tests to contribute towards national team selection (Koutedakis 1989).

2.3 LABORATORY BASED ROWING TESTING

Incremental rowing tests are designed to assess physiological characteristics that are relevant to competitive rowing. As 2000-m ergometer time-trials require 70-88% aerobic energy contribution and 12-30% anaerobic contribution (Hagerman *et al.* 1978; Droghetti *et al.* 1991; Pripstein *et al.* 1999), the relationship between time-trial performance and various aerobic and anaerobic variables has therefore been considered. Of these, absolute $\dot{V}O_{2\max}$ (Secher *et al.* 1982b; Kramer *et al.* 1994; Womack *et al.* 1996; Jürimäe *et al.* 2000; Jürimäe *et al.* 2002a; Yoshiga and Higuchi 2003; Bourdin *et al.* 2004), power output at $\dot{V}O_{2\max}$ (Jürimäe *et al.* 2000; Mäestu *et al.* 2000; Ingham *et al.* 2002a; Jürimäe *et al.* 2002a) and power output at 4 mmol.L⁻¹ BLa concentration (Jürimäe *et al.* 1999; Jürimäe *et al.* 2000; Ingham *et al.* 2002a) or individual anaerobic threshold (IAT; Jürimäe *et al.* 2002a) have shown the strongest single variable associations. Progressive incremental rowing tests to exhaustion have consequently been used to establish relationships between power output and BLa, HR and $\dot{V}O_2$, thereby permitting determination of lactate thresholds, $\dot{V}O_{2\max}$ and associated power outputs. These tests typically comprise 5-7 workloads, with the initial stages set according to predetermined sub-maximal workloads, so exercise intensity ranges from relatively low levels during the early stages to maximal performance during the final stage. Work-stage duration is sufficient to achieve steady-state conditions and is therefore usually about 4 min or slightly longer, and stages are separated by 30 s to 1 min to allow for BLa sampling (Hahn *et al.* 2000; Vogler *et al.* 2007). Physiological variables measured during these tests include: HR, $\dot{V}O_2$, BLa and rating of perceived exertion (RPE). Data may be continuously monitored during the test, or recorded during the latter parts of the sub-maximal workloads to reflect the steady-state nature of the task, and peak values recorded during maximal exercise. Additionally, power output, stroke rate and total distance completed are also recorded for each of the stages, either from the ergometer display unit or directly measured using specialised instrumentation (Lormes *et al.* 1993; Boyas *et al.* 2006). Overviews of laboratory testing procedures are supplied by Hahn *et al.* (2000) and Godfrey & Whyte (2006).

2.3.1 Evaluation of training adaptations

A major role of laboratory based rowing testing has been to monitor the progress of

fitness adaptations and provide insights into the effectiveness of preceding training blocks (Mahler *et al.* 1985). Responses to the previous training block can be assessed from changes in calculated physiological parameters and direct comparisons between data from equivalent workloads during consecutive tests. Thus, standard fitness adaptations include lowered HR and BLa responses during sub-maximal workloads, improved power output at calculated BLa thresholds, and higher $\dot{V}O_{2\max}$. Steinacker (1993) provides a comprehensive review of the biochemical and morphological basis of physiological adaptations in response to rowing training.

Previous investigations using rowing ergometry to assess seasonal variations in physiological parameters and rowing performance generally report large improvements of 10-18% for $\dot{V}O_{2\max}$ (Hagerman and Staron 1983; Mahler *et al.* 1984; Mahler *et al.* 1985) and 14-18% for maximal power output (Hagerman and Staron 1983; Mahler *et al.* 1985). While these are representative of changes across an entire rowing season (early preparation to pre-competition), Secher *et al.* (1982a) reported a modest 4% increase in $\dot{V}O_{2\max}$ following 6 months early season training. Adding further detail, Mahler *et al.* (1984; 1985) present results from an intermediate test performed mid-way through the season and show that improvements in $\dot{V}O_{2\max}$ and maximal power may occur steadily throughout the season (Mahler *et al.* 1985), or develop more rapidly during the early stages of preparation (Mahler *et al.* 1984). However, Vermulst *et al.* (1991) suggests that power output at a fixed BLa of 4 mmol.L⁻¹ is a more sensitive indicator of endurance ability than either $\dot{V}O_{2\max}$ or maximal power and that this variable increases by 8-10% in parallel with training loads. Results from serial testing also show improvements in AT; $\dot{V}O_2$ at AT increased by 23% across a whole season, but displayed the largest gain (17%) during the second half of seasonal preparations when there was an increased emphasis on anaerobic training (Mahler *et al.* 1984). Furthermore, the $\dot{V}O_2$ at AT may represent a greater proportion of $\dot{V}O_{2\max}$ (79% vs. 89%) as the season progresses, even though $\dot{V}O_{2\max}$ has also increased (Mahler *et al.* 1984). Similar patterns of adaptation have been observed among elite rowers tested at our laboratory in the lead-up to the 2007 Australian National Championships. During this four-month period, $\dot{V}O_{2\max}$ and maximal power output improved 5.9% and 6.1% for males and 5.8% and 6.7% for females, respectively. Similarly, power output at AT improved by 7.9% for males

and 3.6% for females. $\dot{V}O_2$ at AT also increased as a proportion of $\dot{V}O_{2\max}$ (from 86% to 90%), but only for male rowers. These comparatively modest gains may be due to the shorter assessment period (4 months vs. 6-9 months), as further gains are likely to occur as preparation continues for international competition. Alternatively, improved off-season training practices may curtail detraining between rowing seasons, thereby limiting seasonal fitness variations for current athletes compared to the reported assessments from the 1980s (Secher *et al.* 1982a; Hagerman and Staron 1983; Mahler *et al.* 1984; Mahler *et al.* 1985).

While ergometer testing reveals large pre-season to race-season changes in physiological conditioning and is adequately sensitive to track changes in physiological status across testing sessions (Hagerman and Staron 1983; Mahler *et al.* 1984; Mahler *et al.* 1985; Vermulst *et al.* 1991; Petibois *et al.* 2003), the improvement in on-water performance over this time may be far greater (unpublished personal observation about Australian international rowers). Additionally, comparisons between ergometer time-trials and competitive on-water scenarios display only moderate to strong shared variation as indicated by coefficients of determination of 0.52–0.81 (Jürimäe *et al.* 1999; Ryan-Tanner *et al.* 1999a; Jürimäe *et al.* 2000; Barrett and Manning 2004). So although there is an association between factors contributing to competitive and ergometer performances, laboratory based ergometer testing may lack the specificity to detect important factors that contribute to actual on-water performance.

2.3.2 Definition of lactate thresholds

The anaerobic threshold concept has generated much discussion surrounding BL_a and ventilatory responses to graded exercise and the transition from primarily aerobic metabolism to a state where anaerobic energy contribution becomes increasingly important (Skinner and McLellan 1980; Brooks 1985; Davis 1985; Meyer *et al.* 2005b). Criticism of the concept has mainly focused on the mechanism and description presented by Wasserman and McIlroy (1964), whereby increases in BL_a are the direct result of muscle hypoxia and anaerobic processes (Davis 1985). However, the validity of this original hypothesis has been questioned by evidence that: lactate production is not intrinsically linked to muscle hypoxia (Green *et al.* 1983; Chirtel *et al.* 1984; Connett *et al.* 1984); BL_a may not be indicative of muscle lactate concentration as BL_a is the net result of lactate production and removal

(Donovan and Brooks 1983; Green *et al.* 1983), and decoupling between BLA and ventilatory thresholds (Hagberg *et al.* 1982; Hughes *et al.* 1982; Hagberg 1984). Review articles by Brooks (1985) and Davis (1985) provide a thorough discussion of the controversy surrounding the validity of this concept. Furthermore, the complexity of this issue is also compounded by inconsistent terminology and alternative descriptions of BLA and ventilatory responses that use one or two critical points. The initial increase in BLA above resting levels (AT according Wasserman and McIlroy 1964) has therefore also been termed lactate threshold (LT; Coyle *et al.* 1983; Hagberg and Coyle 1983) or 'aerobic threshold' (Kindermann *et al.* 1979; Skinner and McLellan 1980). Similarly, the point beyond which BLA rapidly accumulates has also been called the AT (Skinner and McLellan 1980); or alternatively, the IAT (Stegmann and Kindermann 1982; McLellan and Jacobs 1993; Urhausen *et al.* 1993a; Beneke 1995; Coen *et al.* 2003), or maximal lactate steady-state (MLSS) (Stegmann and Kindermann 1982; Urhausen *et al.* 1993a; Beneke 1995). Similarly, ventilatory breakpoints (Wasserman and McIlroy 1964; Mickelson and Hagerman 1982; Davis 1985) and fixed BLA concentrations of $\sim 2 \text{ mmol.L}^{-1}$ (LaFontaine *et al.* 1981; Payne *et al.* 1996) and 4 mmol.L^{-1} (onset of blood lactate accumulation, OBLA; Kindermann *et al.* 1979; Sjodin *et al.* 1982; Heck *et al.* 1985; Payne *et al.* 1996) have also been used to indicate these metabolic transitions. But caution should be used when interpreting thresholds based on fixed BLA values, as these do not account for individual variation in these parameters (Bourdon 2000; Buckley *et al.* 2003). Alternatively, an individualised two threshold model that results in a three phase transition from rest to maximal exercise, designates the two reference points as the aerobic and anaerobic thresholds, respectively (Skinner and McLellan 1980). For the purpose of this review, these thresholds will be termed LT_1 (aerobic threshold) and LT_2 (AT) in accordance with Australian Sport Science practices, although when discussing the literature, AT will be used as a generic term for the various lactate and ventilatory thresholds. Figure 2-1 shows a BLA-power output curve from an incremental rowing test that displays LT_1 and LT_2 .

Despite on-going controversy surrounding the AT threshold concept, a large volume of research across a variety of sports has considered the effectiveness of AT determinations in monitoring fitness status (Mickelson and Hagerman 1982; Bunc *et al.* 1989; Vermulst *et al.* 1991; Lucía *et al.* 1998; Lucía *et al.* 2000) and defining

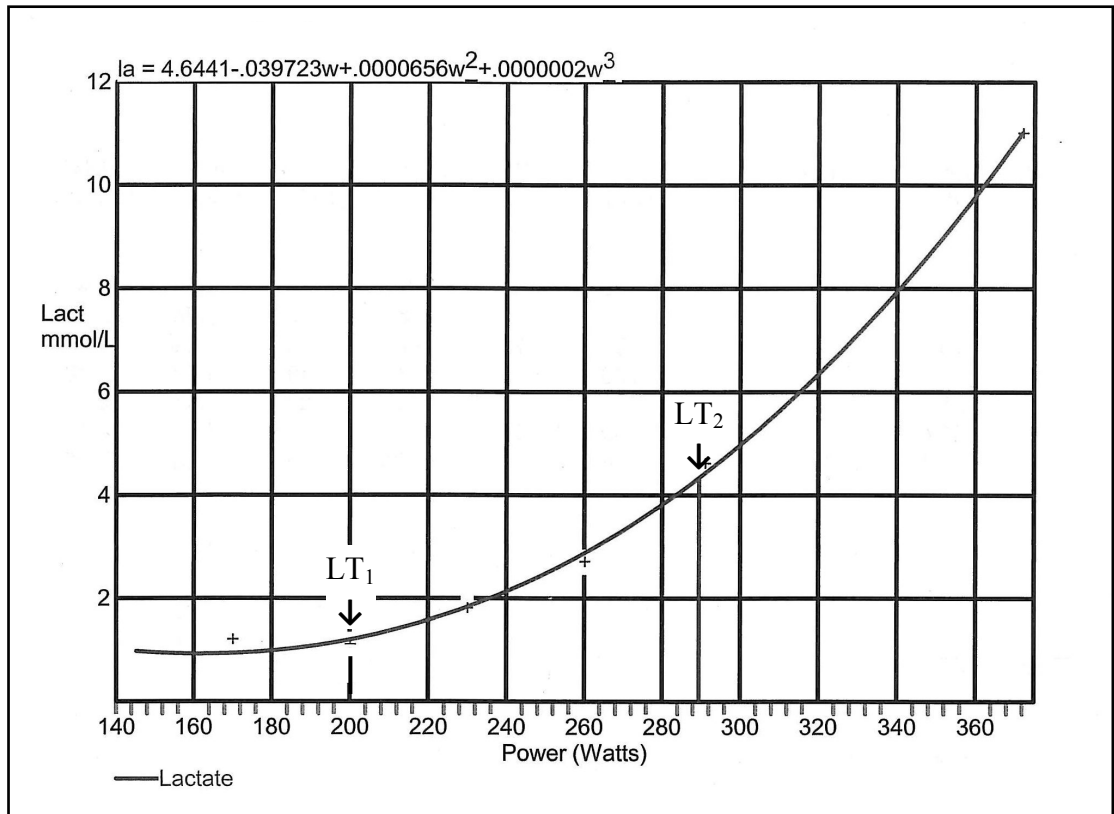


Figure 2-1: LT_1 (aerobic threshold) and LT_2 (AT) blood lactate thresholds determined by ADAPT software (AIS, Canberra, Australia) from the blood lactate-power output curve established during a 6-stage incremental rowing test.

training intensities (Mickelson and Hagerman 1982; Mahler *et al.* 1985; Urhausen *et al.* 1993a; Lucía *et al.* 1999; Meyer *et al.* 1999). Table 2-1 (pg. 23) shows that estimates of AT are strongly related to rowing performance despite the wide range of methodologies used to determine AT. Similarly, AT has been shown to differentiate between professional cyclists and elite amateurs (Lucía *et al.* 1998), and is indicative of endurance fitness changes for rowers (Mickelson and Hagerman 1982; Mahler *et al.* 1984; Mahler *et al.* 1985; Vermulst *et al.* 1991), cyclists (Lucía *et al.* 2000) and runners (Bunc *et al.* 1989). Furthermore, AT provides a better indication of endurance ability than $\dot{V}O_{2\max}$ because AT may continue to improve disproportionately more than $\dot{V}O_{2\max}$ once $\dot{V}O_{2\max}$ approaches a plateau (Davis 1985; Mahler *et al.* 1985; Jacobs 1986), thereby limiting the effectiveness of $\dot{V}O_{2\max}$ as a means of differentiating endurance capacities' between highly trained athletes (Lucía *et al.* 1998; Lucía *et al.* 2000). Additionally, given that exercise prescriptions based on percentages of $\dot{V}O_{2\max}$ or maximal heart rate (HR_{\max}) do not allow for between-individual variations in BLa response, a workload corresponding to 75% $\dot{V}O_{2\max}$ has been shown to result in exercise intensities between 86-118% of an individual athletes AT (Meyer *et al.* 1999). Based on similar findings, the AT has been recommended as a more appropriate means of prescribing exercise intensities for endurance training than the 'fixed percentage' method (Katch *et al.* 1978; McLellan and Skinner 1981; Meyer *et al.* 1999). Thus, AT determinations have frequently been used to calculate exercise intensity zones for application to athletic training (Urhausen *et al.* 1993a; Lucía *et al.* 1999; Hagerman 2000; Hahn *et al.* 2000; Meyer *et al.* 2005b). BLa thresholds therefore continue to be routinely calculated from incremental rowing tests to evaluate training adaptations and as a basis for individualised training intensity recommendations.

2.3.3 Prescription of rowing training intensities

Another function of laboratory based rowing tests has been to provide individualised exercise intensity guidelines for on-water and land-based rowing training. Rowing training has traditionally been divided into a continuum of 6-7 training zones according to intensity and targeted training outcome (Hagerman 2000; Hahn *et al.* 2000), although more recently, a standardised 5 tier classification system has been adopted in Australia (Table 2-2). Each of these divisions are calculated from an athlete's BLa-workload curve (3rd order polynomial relationship; Figure 2-1) and are

based on identification of LT_1 (aerobic) and LT_2 (anaerobic) thresholds (Hahn *et al.* 2000). Intensities below LT_1 are termed T1 (Light aerobic), while work between LT_1 and LT_2 is divided into two zones, such that T2 (Moderate aerobic) represents the lower half and T3 (Heavy aerobic) the upper end (Hahn *et al.* 2000). LT_2 is assigned a separate training zone (T4; Threshold) and is regarded as the highest sustainable steady-state workload (Heck *et al.* 1985; Beneke 1995). Beyond this, the T5 zone (Maximal aerobic) has an increased reliance on anaerobic energy pathways, whereby the development of metabolic acidosis limits the duration and interval training is favoured. However, traditional rowing training classifications also assign an Anaerobic zone that is not directly based on the BLa-workload curve, but instead involves intensities equivalent to, or beyond race pace (Hahn *et al.* 2000) and may be subdivided into two zones depending on the duration of efforts, and the lactic or alactic training focus (Hagerman 2000). The International Rowing Federation (FISA) have also provided guidelines for rowing fitness training that include training zone recommendations, these are described by Altenburg (1992). Furthermore, HR-workload data from the laboratory test can be used to align HR values with the training zones established from the BLa-workload curve, thereby providing a guideline by which the calculated training zones can be applied during on-water sessions. However, as some evidence suggests, biomechanical (Martindale and Robertson 1984; Lamb 1989; Smith *et al.* 1993; Dawson *et al.* 1998; Kleshnev 2005) and physiological differences (Clausen 1976; Steinacker *et al.* 1987; Urhausen *et al.* 1993b; Payne *et al.* 1996; Ryan-Tanner *et al.* 1999b) exist between ergometer and on-water rowing conditions. Consequently, the specificity of ergometer testing has been questioned by rowing coaches because the training recommendations from laboratory tests are not readily applied to on-water training.

Table 2-2: Contemporary training intensity zones and traditional rowing classifications based on LT_1 and LT_2 blood lactate thresholds, and approximate heart rate and blood lactate concentration equivalents for a male heavyweight rower.

Training zone	Traditional rowing classifications	Lactate threshold	BLa (mmol.L ⁻¹)	HR _{max} (%)
	Anaerobic 1		Maximal	100
	Anaerobic 2		10.0 – 14.0	95 – 100
T5: Maximal aerobic	Transport	> LT_2	5.0 – 10.0	90 – 95
T4: Threshold	Anaerobic threshold	LT_2 (assuming 4.0 mmol.L ⁻¹)	4.0 – 5.0	85 – 90
T3: Heavy aerobic	Utilisation 1	Upper 50% (LT_2 - LT_1)	2.8 – 4.0	75 – 85
T2: Moderate aerobic	Utilisation 2	Lower 50% (LT_2 - LT_1)	1.5 – 2.8	65 – 75
T1: Light aerobic	Recovery	< LT_1 (assuming 1.5 mmol.L ⁻¹)	< 1.5	< 65

BLa = blood lactate concentration; HR_{max} = maximal heart rate.

Assumes blood lactate concentrations of 1.5 mmol.L⁻¹ and 4.0 mmol.L⁻¹ for the LT_1 and LT_2 thresholds, respectively, although actual LT_1 and LT_2 blood lactate concentrations will vary on an individual basis.

2.4 VALIDITY OF ERGOMETER ROWING

A variety of methods have been used to validate simulated rowing on an ergometer against the criterion of on-water rowing. Research has focussed on kinematic analyses (Martindale and Robertson 1984; Lamb 1989; Dawson *et al.* 1998; Elliott *et al.* 2002), mathematical relationships between time-trial performances (Ryan-Tanner *et al.* 1999a) and assessments of physiological responses (Clausen 1976; Steinacker *et al.* 1987; Chènier and Leger 1991; Urhausen *et al.* 1993b; Payne *et al.* 1996; Ryan-Tanner *et al.* 1999b) to compare rowing under laboratory and field conditions.

2.4.1 Movement patterns

Digitised footage of ergometer and on-water rowing has been employed to compare movement patterns and stroke characteristics between the two environments (Martindale and Robertson 1984; Lamb 1989). Gjessing (Martindale and Robertson 1984), Stanford (Lamb 1989) and RowPerfect (Elliott *et al.* 2002) ergometer designs have all been used to compare sculling (Martindale and Robertson 1984) or sweep-oar rowing (Lamb 1989). Martindale and Robertson (1984) compared ergometer and on-water rowing using a kinematic film analysis to calculate total body and segmental mechanical energy characteristics throughout one complete stroke cycle. When linear handle displacement was compared between rowing modes, sculling resulted in handle movements ~10-30 cm shorter than ergometer rowing, although the difference would be reduced if total handle movement was used instead of linear displacement as the handles actually travel through an arc (Martindale and Robertson 1984). However, work-time relationships also differed between the ergometer and rowing shell due to different interactions between the rower's body mass and the boat or ergometer (Martindale and Robertson 1984). Hence, the boat was able to move both with, and independently of the rower, in response to movement of their body mass, whereas the ergometer was stationary and motion therefore limited to movement of the rower's body mass forward and back along the slide (Figure 2-2). Given the additional kinetic energy from movement of the rower-boat system during the on-water condition, it was not possible to directly compare the rowing devices using total work calculations derived only from the video footage. Instead, Martindale and Robertson (1989) addressed differences according to calculations of energy saved via exchange between body segments and interconversion between potential and kinetic energy. Energy exchange as a proportion of total work was

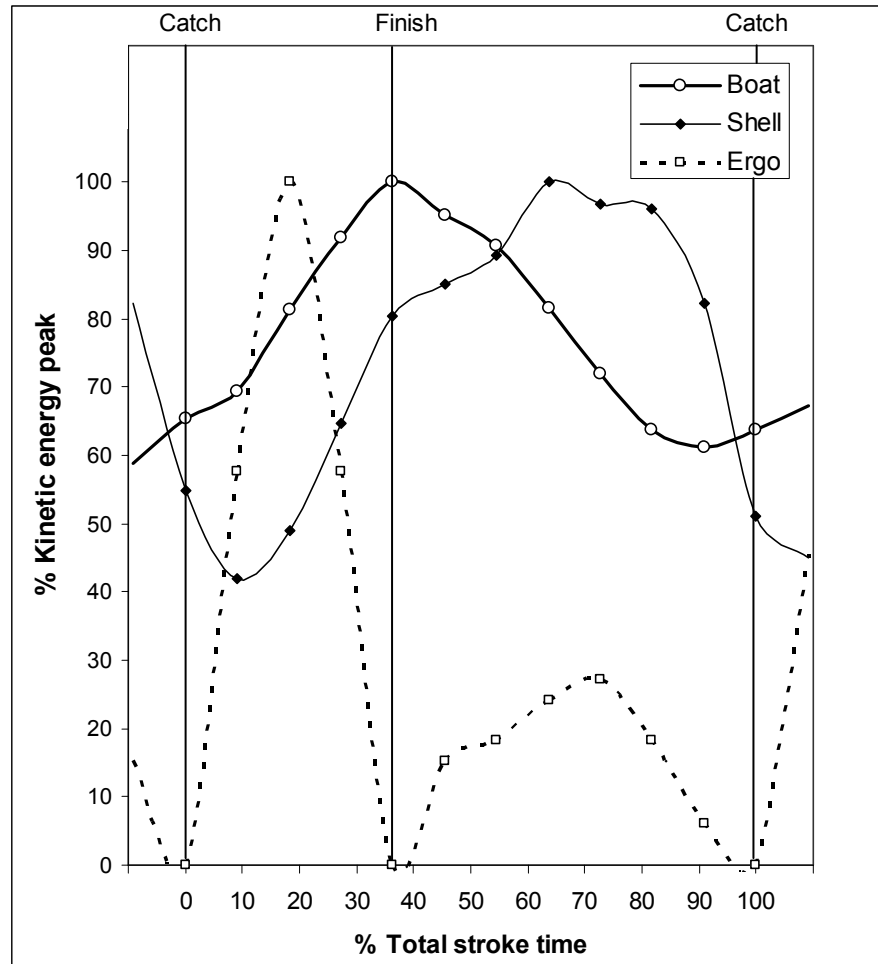


Figure 2-2: Kinetic energy of the rower's body during a single rowing stroke performed on a stationary ergometer (ergo) and on-water (boat) and the kinetic energy of the boat (shell). *Adapted from Martindale and Robertson (1984).*

therefore greater during on-water rowing as a consequence of the energy transferred from body to boat during sculling. Martindale and Robertson (1984) therefore concluded that there were substantial differences between the movements of on-water sculling and rowing performed on Gjessing ergometers.

Similarly, Lamb (1989) used a 'vector loop model' that separated the rower into body segments (e.g. trunk, upper arm, lower leg) and upper and lower body 'loops' to permit between rowing mode comparisons of each body segment's contribution to total linear velocity at intervals representing 10% of the drive time. Differences in movement pattern were again apparent between ergometer and boat, most notably during the early and late stages of the drive. The author explained that these differences may be due to water 'slippage' around the blade during sculling thereby reducing the arms' contribution to oar velocity compared to the ergometer and that ergometer rowing did not require the rower to 'feather' in preparation for recovery (Lamb 1989). Nevertheless, Lamb (1989) concludes that these differences are trivial given the arms contribute relatively little to overall linear velocity during the drive phase compared to the trunk and leg segments.

Kinematic analyses have also been employed to investigate the relative timing of the drive and recovery phases across increasing stroke rates during ergometer and on-water conditions (Dawson *et al.* 1998). Although strong linear relationships ($R^2=0.94-0.97$) were reported between changes in drive to recovery ratio and stroke rate, when the coefficient of variation for phase proportion was plotted against stroke rate, it was apparent that the recovery was associated with the greatest variability, particularly during on-water rowing. Dawson *et al.* (1998) therefore suggest the recovery phase is the most difficult portion of the rowing stroke and that variations in stroke timing during on-water rowing are more difficult to overcome compared to ergometer performance. Findings such as these fundamentally challenge the conclusion of Lamb (1989), that there is no appreciable difference in rowing technique between ergometer and on-water conditions, given that the recovery phase was not included in the analysis.

2.4.2 Biomechanics

Further research investigating biomechanical differences between ergometer rowing and sculling is provided by Elliott *et al.* (2002) in their comparison of the

RowPerfect ergometer and on-water sculling. Owing to the floating foot stretcher design of the RowPerfect, Elliott *et al.* (2002) propose that this style of ergometer will better simulate the inertial forces experienced in the boat thereby enhancing the degree to which the sculling motion is replicated. Using an instrumented boat, blade force and oar angle were measured during on-water rowing; similarly, force and power measures, derived from the work monitor unit, were recorded for the ergometer and stroke length was determined from flywheel rotations. The pattern and consistency of force application was then compared between conditions using force-angle (on-water) and force-length (ergometer) curves that were normalised using a scale of 0-100, where 100 represented peak values for force production and angle/length. Average RowPerfect stroke length (1.36-1.40 m) and on-water stroke angle (106-113°) did not alter significantly across the investigated stroke rates of 24-28 strokes.min⁻¹. However, average force production on the ergometer (390-401 N) was considerably higher than that measured for the combined left and right hands on-water (273-288 N). Nevertheless, when force-angle and force-length curves were assessed for consistency across five sequential strokes, mean coefficients of multiple determination were similar between the ergometer ($R^2=0.99$) and on-water conditions ($R^2=0.98$), despite the environmental variations in the latter situation. Additionally, anatomical markers placed on the rowers during each of the trials allowed comparisons of joint angles between conditions using digitised video footage. Analysis revealed that average body angles (trunk, thigh, knee and leg) were not statistically different between the ergometer and on-water performance. Given the apparent similarities between force curve patterns and body angles, Elliott *et al.* (2002) concludes that the RowPerfect ergometer has a similar “rowing structure to on-water sculling and is therefore suitable for rowing specific training and team selection”. The RowPerfect ergometer may therefore provide a better simulation of on-water rowing compared to the Gjessing (Martindale and Robertson 1984) and Stanford (Lamb 1989) ergometers previously evaluated. However, based on handle forces that were again 30-40% higher during ergometer rowing and significant differences between handle velocities and acceleration profiles between the ergometers and single sculling, Kleshnev (2005) suggests that the Rowperfect and Concept2 ergometers are cross-training devices only. Additionally, standard error of measurement (% SEM) results for mean power from repeated 2000-m time-trials are reported to be more variable on the on the Rowperfect ergometer (3.3%) than the Concept2 (1.3%; Soper and Hume 2004). So although the RowPerfect ergometer

may better simulate on-water rowing compared to the Concept2, performance reliability appears to limit its potential as a laboratory testing device. Concept2 have also attempted to better simulate the inertial forces experienced during on-water rowing by introducing 'sliders' that allow the entire ergometer to 'float' in a similar manner to the RowPerfect footstretcher assembly. While there appears to be no published literature comparing on-water rowing with the sliding Concept2, it is likely that this apparatus may be subject to the same limitations as the RowPerfect ergometer.

2.4.3 Rowing performance

While the above studies have investigated isolated aspects of rowing that contribute to overall rowing performance, ergometer and on-water rowing have also been compared according to performance outcomes. As a Spearman rank order correlation between 2000-m rowing performance during repeated ergometer time-trials and pair-oared rowing was strong ($R=0.74$), it suggests an association between factors contributing to time-trial performance under either condition (Ryan-Tanner *et al.* 1999a). Similar comparisons have also been reported for single sculling with Pearson correlation coefficients spanning $R=0.72-0.90$ (Jürimäe *et al.* 1999; Jürimäe *et al.* 2000; Barrett and Manning 2004).

2.4.4 Physiological responses

The conclusions from biomechanical studies have been somewhat equivocal, either finding substantial differences between rowing modes (Martindale and Robertson 1984; Dawson *et al.* 1998; Kleshnev 2005), or supporting that ergometer rowing provides a reasonable simulation of the on-water condition (Lamb 1989; Elliott *et al.* 2002); however, even one of the latter studies has noted some differences between conditions (Lamb 1989). Also, given the variety of ergometer designs used, comparisons between studies are difficult. Equipment has included the air-braked RowPerfect (Elliott *et al.* 2002; Kleshnev 2005) and Concept2 (Kleshnev 2005) designs, the mechanically braked Gjessing machine (Martindale and Robertson 1984) and sweep style Stanford ergometer (Lamb 1989). Furthermore, none of these comparisons have included any physiological data.

Differences are also apparent when the physiological responses to rowing are compared between ergometer and on-water environments. Payne *et al.* (1996)

conclude that the two conditions elicit different physiological responses which may be the result of biomechanical variations between conditions. Of the variables considered in the literature, HR and BLA have been most commonly addressed. HR is generally reported to be higher during the on-water situation (Urhausen *et al.* 1993b; Ryan-Tanner *et al.* 1999b), although Steinacker *et al.* (1987) suggest that ergometer performance elicits a higher HR. Conversely, BLA is higher during ergometer rowing (Urhausen *et al.* 1993b; Ryan-Tanner *et al.* 1999b), possibly by as much as 35% (Ryan-Tanner *et al.* 1999b). Other measured variables include catecholamines (Urhausen *et al.* 1993b), which are higher during ergometer performance, and $\dot{V}O_{2\text{ peak}}$ (Chènier and Leger 1991), which differs by -0.5% to +2.7% depending on the design of the reference ergometer. Given the potential for biomechanical differences between the two performance scenarios and the resulting variations in physiological response, an element of on-water testing would be worthwhile to ‘fine-tune’ training intensity recommendations from ergometer tests.

2.5 ON-WATER INCREMENTAL ROWING PROTOCOLS

Very few scientific publications relate to formalised incremental exercise protocols performed in the on-water environment. Those who have attempted field-based tests of this nature have all developed different protocols for the mode of rowing, number of stages, stage duration, workload to recovery ratio and method of progression. Typically, assessments have been limited to pair-oared boats (Steinacker *et al.* 1987; Payne *et al.* 1996; Coen *et al.* 2003), although Steinacker *et al.* (1987) also considers single sculls. The number of stages performed and stage duration varies from 4 x 6-min exercise bouts (Coen *et al.* 2003) to 8 x 3-min stages (Payne *et al.* 1996). Both constant duration stages (Payne *et al.* 1996; Coen *et al.* 2003) and fixed distance stages (Steinacker *et al.* 1987) have been used. The recovery between stages has also varied and this is largely influenced by the time required to collect data and prepare for the subsequent stage. Recovery intervals have therefore ranged from 1.5 min (Payne *et al.* 1996) to ~9 min (Steinacker *et al.* 1987) depending on the time required to realign the boat. Intensity and stage progression have been controlled by either boat velocity (Coen *et al.* 2003) or stroke rate (Steinacker *et al.* 1987; Payne *et al.* 1996).

While all investigations have compared the results of an on-water protocol with an ergometer-based incremental test and adopted an ergometer protocol that used predetermined target power outputs and increments, only Payne *et al.* (1996) matched the on-water version for stage duration, recovery and stroke rate. Steinacker *et al.* (1987) and Coen *et al.* (2003) instead adopt what appears to be a standard laboratory incremental test, although they did not attempt to match this with their on-water protocol. These studies have generally found good agreement between ergometer and on-water tests when comparing mean HR values at fixed BLa concentrations of 4 mmol.L⁻¹ (Steinacker *et al.* 1987; Payne *et al.* 1996) or IAT (Coen *et al.* 2003), with mean HR values ranging 167-172 and 167-171 beats.min⁻¹ for ergometer and on-water tests, respectively. However, when individual HR values equivalent to 2 mmol.L⁻¹ and 4 mmol.L⁻¹ are compared between test modes (Payne *et al.* 1996), linear regression displays moderate-strong correlations of R=0.72 and R=0.66, but corresponds to SEE of 5 beats.min⁻¹ (3.3 %) and 8 beats.min⁻¹ (5.0 %), respectively. Payne *et al.* (1996) then explains that this degree of imprecision in the estimation of the on-water HR threshold would result in on-water BLa concentrations

ranging 1.4-3.2 mmol.L⁻¹ and 2.8-5.9 mmol.L⁻¹. Similarly, Steinacker *et al.* (1987) also calculates HR values corresponding to 4 mmol.L⁻¹ and reports a correlation of R=0.84 between results from ergometer and on-water incremental tests. Although when the prescribed HR intensity was applied to a 4 km steady-state rowing session, half the rowers produced BLA concentrations below the 4 mmol.L⁻¹ target (1.5-2.9 mmol.L⁻¹), while the remaining rowers were above the predicted concentration (4.5-5.2 mmol.L⁻¹). Thus, on-water training intensities may not be adequately established from ergometer testing (Steinacker *et al.* 1987; Payne *et al.* 1995, 1996). Payne *et al.* (1995, 1996) therefore suggest that this might be better achieved from on-water incremental tests controlled by stroke rate and perceived effort, or at least supplement ergometer testing as a method for determining specific training intensity guidelines (Steinacker *et al.* 1987; 1993b). Indeed, when Coen *et al.* (2003) compared the BLA, HR and rowing velocity corresponding to the IAT derived from an on-water incremental test, values were reflective of those observed during on-water endurance training. Although, as the exercise intensity prescribed by the coach during the reference training session was below IAT, a direct comparison was not possible. However, the observed BLA, HR and velocity values were 70%, 91% and 95%, respectively, of those determined during the on-water test (Coen *et al.* 2003).

2.5.1 Methodological limitations

While stage progressions based on prescribed stroke rates or boat velocities will ensure the desired progressive increase in intensity, they are susceptible to the influence of environmental factors. Wind speed and direction relative to the boat, as well as water conditions, have a profound effect on boat velocity and relative intensity at a given stroke rate. This means that any field-based protocol relying on these independent variables for the control of workload can only be reliably performed in near perfect environmental conditions.

The dynamic, unpredictable nature of environmental conditions means that accurate and reliable testing on-water is difficult, especially when attempting to standardise testing within and between sessions (Steinacker *et al.* 1987; Coen *et al.* 2003). Steinacker *et al.* (1987) caution that on-water step tests are practically demanding and require fair weather conditions for optimal results. Factors such as wind speed and direction can potentially change during an effort and have a significant impact on boat velocity. So, although boat velocity is a key determinant of on-water

performance in a regatta situation, it is unsuitable as an independent variable to monitor the responses to a given training workload. Also, substantial variation in stroke rate (Smith *et al.* 1993) and HR (Urhausen *et al.* 1993b) between field and laboratory environments means that these parameters are unreliable as independent variables for controlling changes in intensity during on-water work. The only true and independent measure of work is therefore the power output exerted by the rower to propel the boat.

2.5.2 Measurement of on-water rowing power output

Ideally, an on-water test would use prescribed target power outputs to control workload in the same manner as an ergometer test. However, as power output measurements during on-water rowing require boats to be instrumented with specialised biomechanics equipment to measure propulsive forces and the angular velocity of the oars, there are very little data concerning direct measurements of rowing power output in the field. One of the earliest investigations (Di Prampero *et al.* 1971) instrumented the oarlock with strain gauges to measure force application, although the angular velocity of the oar was not directly measured, but estimated based on an assumed constant for handle displacement and the duration of the force application. More recently, Smith *et al.* (1993, 1994) described a custom-designed rowing biomechanics system where the strain on the oar was measured with a linear proximity transducer that was calibrated by hanging a known mass (47.1 kg) from the oar handle, and oar angle was measured with a potentiometer attached to the oar pivot, which was calibrated at known points throughout the expected range of a rowing stroke. Using the same system as Smith *et al.* (1994), Payne *et al.* (1996) measured on-water power outputs during an on-water incremental rowing test, although on-water workloads could not be prescribed using target power outputs as the rowing biomechanics system did not provide instantaneous feedback. Instead, workloads were controlled by a combination of target stroke rates and the rower attempting to match blade (oar) force applications between the on-water test and an earlier ergometer test. Average power outputs during each 3-min stage of the on-water test ranged 132-304 W, although these were lower compared to directly measured power outputs from the corresponding ergometer test by ~9-27 W during submaximal exercise and ~64-94 W during maximal efforts. The discrepancy between ergometer and on-water results was likely due to the additional force applied to the footstretcher that was not included in the power output calculations,

which were based on force measurements from only the oar (Payne *et al.* 1996). Similar power measurement systems have also been described for rowing evaluations using rowing tanks (Di Prampero *et al.* 1971; Henry *et al.* 1995), with mean power output from 30 s maximal tank rowing reported as 739 W, compared with 667 W during a similar test on a Concept2 ergometer (Henry *et al.* 1995). While Henry *et al.* (1995) validated power outputs during tank rowing against those from equivalent performances on Concept2 ($R=0.77$) and Stanford ($R=0.70$) rowing ergometers, Di Prampero *et al.* (1971) cautions that tank rowing is mechanically and physiologically different compared to actual rowing. More recently, Kleshnev (2000) and Smith and Loschner (2002) have described more advanced rowing biomechanics systems that also include footstretcher forces, and have reported that power output is ~17% higher when the additional force recorded by the footstretcher is included in the calculation of power output. So although these systems provide a more complete indication of the propulsive power output during rowing, it is unclear whether these devices would allow instantaneous power output feedback during on-water rowing, or show similar work-to-metabolic cost relationships to those measured on the ergometer.

While all publications detailing on-water power output measurements with rowing biomechanics systems have used custom-designed devices, Aitchison and Grey (2002) have described a instrumented rowing gate system that integrates load cells and a potentiometer within the body of the rowing gate. Given the system's compact and portable design, Aitchison and Grey (2002) have suggested that this style of system could be readily commercialised. Indeed, WEBA Sport (Wien, Austria) now offers a commercially available rowing biomechanics system that uses an instrumented rowing gate design, although power output measurements would likely be underestimated as the system does not include propulsive forces from the footstretcher (Kleshnev 2000). Despite some limitations regarding measurement of all the forces contributing to boat propulsion and non-instantaneous power output feedback, rowing biomechanics systems could feasibly be used to quantify power output (or at least a proportion of the true power output) during on-water incremental rowing tests. However, as the rowing biomechanics systems used to measure on-water power output are expensive, the cost may limit their widespread use.

2.5.3 Measurement of metabolic load during on-water rowing

Another limitation of the previous studies that compared the physiological

differences between on-water rowing and ergometer performance is that none of the comparisons have included $\dot{V}O_2$ data as an indication of metabolic load. In fact, very few researchers have attempted to directly measure the oxygen cost of rowing in the field environment. Jackson and Secher (1976) and Chènier and Leger (1991) have used the Douglas bag method to measure $\dot{V}O_2$ during single and double sculling and paired sweep rowing, although measurements were limited to maximal intensities only (Chènier and Leger 1991) or used very short sample durations (45-60 s; Jackson and Secher 1976). Alternatively, Kawakami *et al.* (1992) used a Cosmed K2 portable indirect calorimetry system to continuously measure $\dot{V}O_2$ for a single sculler during four incremental workloads. Interestingly, the resulting $\dot{V}O_2$ -boat velocity relationship was very similar to that reported by Di Prampero *et al.* (1971), who calculated the oxygen cost of on-water rowing based on the HR- $\dot{V}O_2$ relationship established during tank rowing. Provided measurements from portable metabolic systems are accurate and reliable compared to criterion indirect calorimetry systems, this technology seems ideally suited for on-water assessments of metabolic demand during rowing.

The accuracy of gas exchange measurements from portable metabolic devices has typically been evaluated by comparing results with Douglas bag measurements (McLaughlin *et al.* 2001; Larsson *et al.* 2004; Crouter *et al.* 2006) or other laboratory-based metabolic systems (Eisenmann *et al.* 2003; Duffield *et al.* 2004; Crouter *et al.* 2006). Accuracy and reliability data have been previously reported for a variety of portable models, including: Cosmed (Rome, Italy) K4b² (McLaughlin *et al.* 2001; Eisenmann *et al.* 2003; Duffield *et al.* 2004), K4 (Hauswirth *et al.* 1997) and K2 (Kawakami *et al.* 1992) models; the Medical Graphics (St. Paul, USA) VO2000 (Kautza *et al.* 2004; Crouter *et al.* 2006), and the Cortex (Leipzig, Germany) MetaMax I (Meyer *et al.* 2001) and II (Larsson *et al.* 2004). Accuracy comparisons show that mean values for $\dot{V}E$ (Crouter *et al.* 2006), $\dot{V}O_2$ (Duffield *et al.* 2004; Larsson *et al.* 2004; Crouter *et al.* 2006), carbon dioxide production (VCO_2 ; Duffield *et al.* 2004; Larsson *et al.* 2004; Crouter *et al.* 2006) and respiratory exchange ratio (RER; McLaughlin *et al.* 2001) sometimes differ between systems. However, because these differences have been isolated to only some of the measured variables, and limited to a few of the evaluated workloads, most studies have concluded that portable systems display adequate accuracy. While the accuracy of

portable systems has been widely addressed, the reproducibility of repeated measurements is equally important (Atkinson *et al.* 2005) and has not been extensively reported. Reliability assessments have been published for the Cosmed K4b² (Duffield *et al.* 2004) and K2 (Kawakami *et al.* 1992), the Medical Graphics VO2000 (Crouter *et al.* 2006) and the Cortex MetMax I (Meyer *et al.* 2001). Of these, the Cosmed and Cortex evaluations both concluded that reliability results were satisfactory (Meyer *et al.* 2001; Duffield *et al.* 2004). Provided results from laboratory-based validity studies directly translate to the field environment, it appears that some designs of portable metabolic system meet the requirements to achieve their intended purpose as field-based devices for the measurement of metabolic load.

2.5.4 Reliability

Although the reliability of rowing tests performed on rowing ergometers has been reported for 500-m and 2000-m time-trials (Schabort *et al.* 1999; Soper and Hume 2004), the reproducibility of results from incremental tests has not been widely reported. Similarly, only Payne *et al.* (1996) has considered the reproducibility of results from repeated on-water tests. Pearson correlation coefficients for HR and power output data corresponding to 4 mmol.L⁻¹ BL_a from repeated on-water and laboratory tests were statistically significant ($p < 0.05$) for both modes of rowing. HR results from the on-water test displayed a between-test correlation of $R = 0.46$, which compared to $R = 0.85$ for the ergometer method. However, the SEE for the on-water result (8 beats.min⁻¹) was much higher compared with the ergometer test (3 beats.min⁻¹; Payne *et al.* 1996). However, for the power output at 4 mmol.L⁻¹ BL_a, stronger correlations (on-water: $R = 0.89$; ergometer: $R = 0.93$) and lower SEEs (on-water: 12 W; ergometer: 7 W) were obtained. Payne *et al.* (1996) also considered the reliability of power outputs for each workload of the on-water and ergometer tests, reporting statistically significant correlations ($p < 0.001$) for the ergometer and on-water conditions. However, as instantaneous power output feedback was only available under ergometer conditions, a stronger correlation was observed for repeated ergometer trials ($R = 0.84$) compared with the on-water test ($R = 0.72$). This limitation means that results from on-water tests may be less reliable compared to ergometer assessments.

2.6 CONCLUSIONS

Ergometer-based simulations of rowing have enabled thorough evaluations of the demands of competitive rowing in a controlled environment, and have greatly improved the specificity of test results compared to early investigations using non-rowing exercise. Consequently, laboratory-based incremental tests performed on rowing ergometers have become the standard method for assessing athletes' physiological profiles, monitoring longitudinal fitness changes, and prescribing individualised exercise intensities for rowing training. However, as kinematic, biomechanical, and physiological differences exist between ergometer simulations and on-water rowing, it appears that the external validity of ergometer rowing is limited compared with the criterion of on-water performance. Given this limitation, incremental rowing tests have been successfully replicated in the on-water environment to improve the specificity of training intensity recommendations compared with those from laboratory-based tests. While field-based rowing tests are susceptible to the influence of unpredictable environmental conditions, on-water workloads can be quantified by power output measurements from rowing biomechanics systems, which should therefore offer greater control for environmental influences. Ideally, on-water tests should also incorporate indirect calorimetry measurements from a portable system to quantify the metabolic demands of on-water rowing, and to provide a more complete comparison between the physiological responses to ergometer and on-water rowing, which have previously been based on BLa and HR data only. Beyond further comparisons between laboratory and field tests to evaluate the validity of ergometer based simulations, further research is required to quantify the reliability of on-water measurements. It is also relevant to evaluate whether the results from on-water tests could be used to monitor fitness changes, and if competitive performance can be better predicted compared with ergometer tests.

CHAPTER 3

VALIDATION OF THE CONCEPT2 MODEL D ROWING ERGOMETER

3.1 INTRODUCTION

Rowing ergometers are essential tools for physiological monitoring, training prescription and scientific research. Comparisons have previously been made between the physiological responses to exercise performed on different designs of rowing ergometer. The friction-resisted Gjessing ergometer has been compared to the fixed foot stretcher air-braked Concept2 Model C ergometer (Hahn *et al.* 1988; Lormes *et al.* 1993) and the floating foot stretcher Rowperfect ergometer (Mahony *et al.* 1999). Recently, Soper and Hume (2004) also compared the Concept2 Model C and Rowperfect ergometers and found that performance in short and long distance time-trials was more reliable on the Concept2; however, they measured no physiological variables. To date, no investigation has determined if physiological differences exist between different models of Concept2 ergometer: Model C (C2C; Plate 3-1) and Model D (C2D; Plate 3-2).

The Concept2 air-braked rowing ergometer has been popular among researchers and competitive rowers as a sport-specific testing device and indoor trainer. Results from progressive incremental tests performed on Concept2 ergometers are commonly used to interpret physiological adaptations to rowing training and to provide specific training intensity recommendations (Hahn *et al.* 2000). The Australian Institute of Sport (AIS) Physiology laboratory has conducted laboratory tests with the C2C ergometer for approximately a decade. Indeed, many sport science laboratories and training centres have data from physiological tests using the C2C ergometer. However, the introduction of the C2D model means that test results will have to be compared between ergometers where laboratories have upgraded to the C2D ergometer or when rowers are tested at multiple locations using different Concept2 ergometers. The C2D rowing ergometer was introduced in 2003 to update and

replace the C2C model. New features of the C2D ergometer are an updated work monitor unit, altered flywheel enclosure and redesigned ergonomic handle. While the latter changes reduce operational noise and improve the ‘feel’ of the ergometer, flywheel enclosure modifications may alter damping characteristics and therefore resistance, even though other resistance determinants such as flywheel moment of inertia and chain gearing have remained the same. Although any variations in resistance should be accounted for by the drag factor setting, physiological differences may be apparent if the drag factors of the C2C and C2D ergometers are different, or the new handle design alters rowing technique. Any such difference would affect test results and confound comparisons between physiological data obtained on the different Concept2 ergometer models. The aims of this study were therefore to: a) determine whether the results from both ergometers are equivalent by comparing the physiological responses to incremental rowing to exhaustion on the C2C and C2D ergometers, and b) establish the reliability of rowing tests using the C2D ergometer.

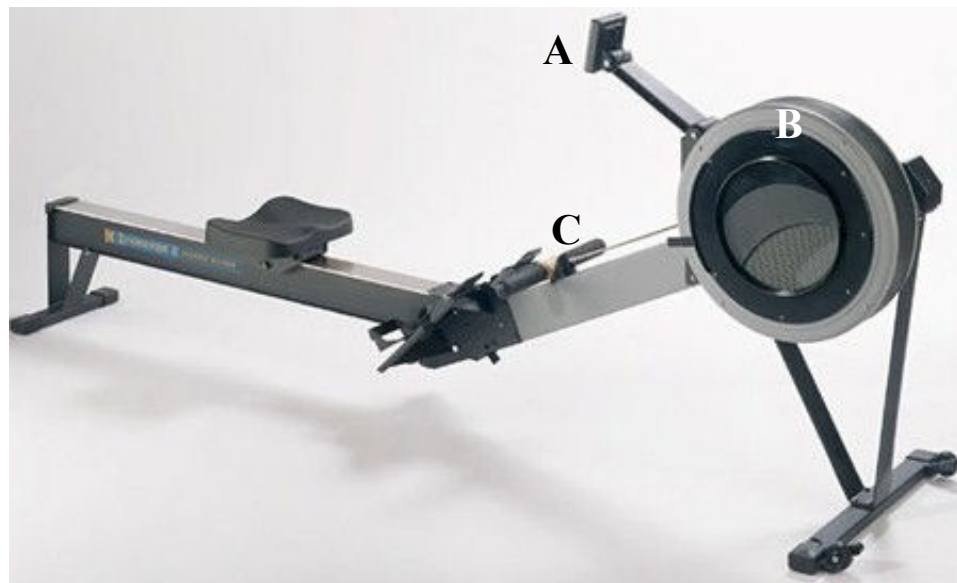


Plate 3-1: The Concept2 Model C ergometer (C2C), including: A) PM2 work monitor unit; B) flywheel enclosure, and C) straight-design handle.

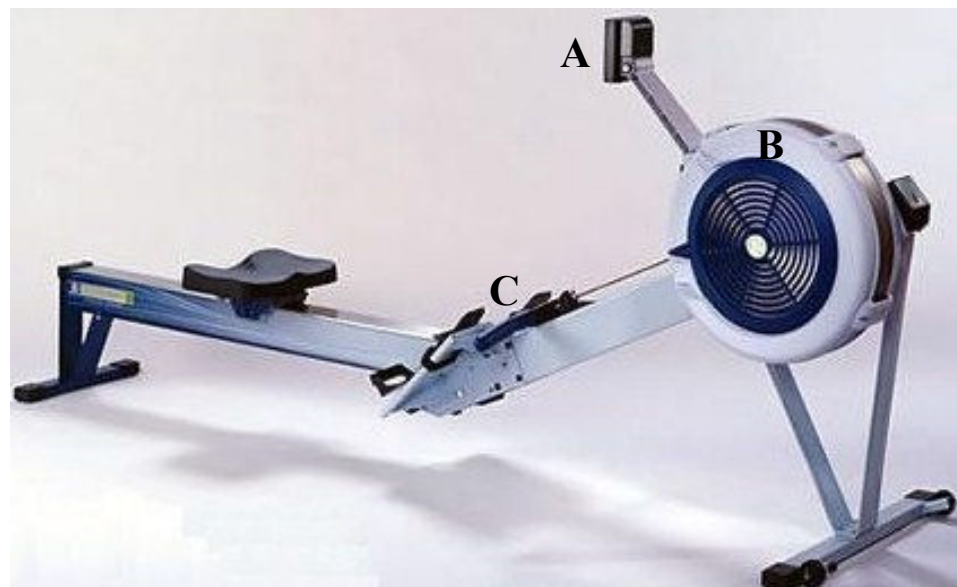


Plate 3-2: The Concept2 Model D ergometer (C2D), including: A) PM3 work monitor unit; B) updated flywheel enclosure, and C) new 10° bent-handle.

3.2 METHODS

3.2.1 Subjects

Eight experienced rowers (males: $n=6$; females: $n=2$) participated in the study. All had >5 yr training experience and were members of a national level training squad; four had been members of the Australian National team. Each rower provided informed consent to participate and the experimental protocol had previously been approved by the AIS Ethics Committee.

3.2.2 Experimental protocol

Each participant completed three matching trials over 5-8 days; two trials using the C2D and a single trial with the C2C. Trial 1 familiarised each rower with the C2D ergometer and test protocol; results from this trial were also compared with the subsequent C2D trial to assess the reproducibility of rowing tests using this ergometer. While this clearly increased the potential for variation between the C2D tests due to habituation effects, we decided that this approach would better approximate normal routine testing practices where familiarisation trials are not performed. However, familiarisation was not required for the C2C ergometer as all rowers had considerable experience with this model from prior indoor training and testing. A randomised cross-over design then ensured that half the rowers performed Trial 2 on the C2D ergometer and half on the C2C ergometer, before swapping ergometers for Trial 3. All sessions were separated by 48-72 h to allow complete recovery between tests, which were scheduled for the same time of day to control for diurnal variation. Subjects were instructed to eat similar meals and limit training to light workloads during the 24 h prior to testing.

Incremental rowing protocol

The progressive incremental test protocol of Hahn et al. (2000) was modified to comprise 5 x 4-min submaximal stages and a single 4-min maximal stage. The initial workload and progression of intensity were prescribed according to rower category (i.e. male or female, lightweight or heavyweight). Males started with an initial workload of 150 W with stage progressions of 40 W and 30 W for heavyweights and lightweights, respectively. Heavyweight women started at 125 W and progressed in 25 W increments. No lightweight women participated in this study. The submaximal stages were separated by 1-min recovery periods, with a 5-min rest before the

maximal stage. Subjects were then instructed to row as far as possible during the 4-min maximal time-trial. Blood lactate concentration (BLa; Lactate Pro, Arkray Inc, Shiga, Japan) was determined by analysis of capillary blood samples collected from the ear lobe: prior to the test, during each recovery period, immediately post maximal exercise and 4 min post maximal exercise. Submaximal BLa was used to ensure all subjects presented to the maximal stage in a 'similar' physiological condition. If BLa exceeded 4 mmol.L⁻¹ before the fifth submaximal stage, then the remaining submaximal stages were omitted and the 5-min recovery period prior to the maximal stage began immediately. As a result of this condition, three of the eight subjects completed only 4 x 4-min submaximal stages and the single 4-min maximal stage during each of the trials.

Upon arrival at the laboratory, subjects were weighed in minimal clothing on a calibrated digital scale (Teraoka Seiko Co, Tokyo, Japan). Once comfortably seated on the ergometer, the drag factor was set to 130 for heavyweight men and 120 for heavyweight women and lightweight men. During exercise, mixed expired air passed through a Hans Rudolph R2700 valve (Kansas City, USA) into aluminised 200 L Mylar® collection bags which were connected to a fully automated indirect calorimetry system (AIS, Belconnen, ACT, Australia). This system has been described elsewhere (Russell *et al.* 2002). The Ametek (Applied Electrochemistry, Pittsburgh, PA, USA) O₂ and CO₂ analysers were calibrated before each test using three precision grade gases (BOC Gases Australia Ltd, Sydney, Australia) that spanned the physiological range of measurement. Both gas analysers were also checked for drift after each test. Oxygen consumption ($\dot{V}O_2$) and carbon dioxide production ($\dot{V}CO_2$) were calculated at 30 s intervals throughout each stage. The $\dot{V}O_2$ for each workload was defined as the highest O₂ consumption attained during two consecutive 30 s sampling periods. Average power output, stroke rate (SR), heart rate (HR) and rating of perceived exertion (RPE) were recorded upon completion of each workload. HR during each test was monitored using short-range telemetry (S610i, Polar Electro OY, Kempele, Finland) while RPE was ascertained using the 15-point Borg scale (Borg 1973). Rowing economy was also calculated for each stage by dividing mean $\dot{V}O_2$ by the average power output.

Automated software (ADAPT Software, AIS, Belconnen, ACT, Australia)

determined lactate thresholds from the power output-BLa relationship established from each of the submaximal stages and the maximal stage using 3rd order polynomial regression. Lactate threshold 1 (LT₁; aerobic threshold) was defined as the point at which BLa began to increase ($\geq 0.4 \text{ mmol.L}^{-1}$) above resting levels. Lactate threshold 2 (LT₂; anaerobic threshold, AT) was defined as the point on the polynomial regression curve that yielded the maximum perpendicular distance to the straight line formed by joining LT₁ and peak BLa (modified D-max; Bishop *et al.* 1998). HR, power output and $\dot{V}O_2$ at LT₁ and LT₂ were subsequently determined using the ADAPT software.

3.2.3 Statistical analyses

Three subjects did not complete the required 5 x 4-min submaximal workloads before displaying a BLa of $\geq 4 \text{ mmol.L}^{-1}$ during all three trials. Consequently, data from the first four submaximal stages were used for subsequent statistical analyses for all subjects. Physiological responses and lactate threshold results were compared between ergometer models (C2C vs. C2D) to validate the new model of Concept2 ergometer against the established laboratory-testing device. Additionally, the repeated C2D trials were also examined to establish the reproducibility of repeated measures using this ergometer. For both comparisons, submaximal data were analysed using 2 (test) x 4 (stage) factorial ANOVAs with repeated measures on both dimensions (STATISTICA for Windows, Tulsa, USA); maximal data and lactate threshold results were compared using dependent *t*-tests. Statistical significance was established at $p < 0.05$ for all analyses. Furthermore, the effects of ergometer model and repeated C2D trials were also analysed to determine the likelihood that the true value of the observed Cohen effect statistic was trivial (< 0.2), or at least small (0.2), moderate (0.6) or large (1.2; Hopkins 2002; Hopkins *et al.* 2009). Briefly, a clear effect size (ES) was established when the likelihood $\geq 75\%$ that the true value of the effect statistic was greater than one of the above thresholds (e.g. small or moderate). As the analysis also considers the likely direction of an effect (either positive or negative), an ES was unclear when the likelihood was $< 75\%$ for a positive ES and $> 5\%$ for a negative ES (Hopkins 2007; Hopkins *et al.* 2009), or vice-versa. Magnitude-based differences are reported as the largest likely effect size and associated percent probability (e.g. small, 85%). The reliability of measurements from repeated C2D trials was also determined using typical error (TE; Hopkins 2000a).

3.3 RESULTS

3.3.1 Subjects

The peak performance characteristics for the subjects are in Table 3-1. Peak power ranged from 358 W to 479 W for males and 254 W to 318 W for females. The inclusion of heavyweight and lightweight rowers among the male group contributed to the broad range in peak power outputs.

3.3.2 Comparison between ergometer models (C2C vs. C2D)

Submaximal performance

Figure 3-1 and Table 3-2 present data for both ergometer models during the 4 x 4-min submaximal workloads and the 1 x 4-min maximal performance trial. Despite the trend for BLa and rowing economy (Figure 3-2) to be higher on the C2D ergometer during submaximal exercise, there were no statistically significant differences for either of these variables. Only $\dot{V}CO_2$ ($p < 0.001$) and RER ($p = 0.03$) displayed statistically significant main effects for ergometer model, with both being higher on the C2D than the C2C. Despite these, the actual differences across all submaximal stages were only 0.08-0.12 L.min⁻¹ for $\dot{V}CO_2$ (trivial effect, 99% probability) and 0.01-0.03 for RER (small, 95%). Otherwise, magnitude-based effects were trivial for BLa (100% probability), HR (100%), $\dot{V}O_2$ (100%) and \dot{V}_E (100%), although the magnitude of the effect for economy was unclear (trivial, 61%).

Maximal performance

There were no significant differences between results from the 4-min maximal performance trials on the C2C and C2D ergometers. Effects for peak HR, $\dot{V}O_2$ and \dot{V}_E were all trivial ($\geq 79\%$ probability), although BLa was 0.9 mmol.L⁻¹ higher during the C2D trial (small, 74%). But the effects for $\dot{V}CO_2$ (trivial, 65%) and RER (small, 49%) were unclear. Performance between ergometers was very reproducible with a mean difference of 1.7 W (trivial, 100%).

Blood lactate thresholds

Table 3-3 contains the LT₁ and LT₂ BLa thresholds calculated from the 3rd order

Table 3-1: Subject description and performance characteristics during 4 min maximal ergometer rowing for males ($n=6$) and females ($n=2$). Data are presented as mean (SD) for males and mean (range) for females.

	Mass (kg)	$\dot{V}O_{2 \text{ peak}} (\text{L}\cdot\text{min}^{-1})$	$\dot{V}O_{2 \text{ peak}} (\text{mL}\cdot\text{kg}^{-1}\cdot\text{min}^{-1})$	P_{peak} (W)
Male	82.3 (11.3)	5.06 (0.29)	62.3 (6.6)	407 (43)
Female	80.8 (75.7-86.1)	4.17 (3.70-4.62)	51.5 (48.9-54.3)	287 (254-318)

$\dot{V}O_{2 \text{ peak}}$ = peak oxygen consumption; P_{peak} = average power during the 4 min maximal performance trial

polynomial of the BLa-power output relationship and the value of selected physiological variables equivalent to LT_1 and LT_2 . Apart from LT_1 BLa ($p=0.02$; small, 92%), there were no differences between results from the two ergometer models. LT_1 occurred at 65% of peak $\dot{V}O_2$ ($\dot{V}O_{2\text{ peak}}$) and 79% of peak HR during the maximal stage (HR_{peak}), whereas LT_2 occurred at 86% of $\dot{V}O_{2\text{ peak}}$ and 92% of HR_{peak} .

3.3.3 Reliability of test results using the C2D ergometer

Submaximal performance

Figure 3-3 shows results from the two trials using the C2D ergometer. There were no significant differences between submaximal power outputs or $\dot{V}O_2$, $\dot{V}CO_2$, RER and \dot{V}_E results, although HR ($p=0.049$) and BLa ($p=0.04$) showed statistically significant main effects with both tending higher on Trial 1. The mean between-trial differences for each of the workloads were 3-5 $\text{beats}\cdot\text{min}^{-1}$ for HR and 0.1-0.5 $\text{mmol}\cdot\text{L}^{-1}$ for BLa, although the magnitude of these effects were small (83% probability) and unclear (trivial, 43%), respectively. Magnitude-based effects were trivial for $\dot{V}O_2$ (100% probability), $\dot{V}CO_2$ (100%), and \dot{V}_E (100%), although RER was unclear (trivial, 68%). TE results for submaximal intensities are displayed in Table 3-4.

Maximal performance

Mean power outputs were within 7 W during the two C2D trials ($p=0.10$; trivial, 90%). However, $\dot{V}O_2$ ($p=0.04$; unclear small, 71%), $\dot{V}CO_2$ ($p=0.03$; unclear small, 52%) and \dot{V}_E ($p=0.02$; small, 80%) were all higher during the second of the repeated trials. BLa also displayed a small between-trial effect (78% probability), although the 1.5 $\text{mmol}\cdot\text{L}^{-1}$ increase during Trial 2 was not statistically significant ($p=0.13$). Despite these differences, relative TE results were generally within 3% (Table 3-4), except for BLa measures and associated calculated thresholds, as well as for SR.

Blood lactate thresholds

There were no statistically significant differences between LT_1 and LT_2 threshold results, and magnitude-based effects were no greater than small (LT_2 BLa: small

effect, 81%). TEs for LT_1 and LT_2 BLa and power output results are displayed in Table 3-4 and range from 10.1-15.6% (0.2 and 0.4 mmol.L⁻¹, respectively).

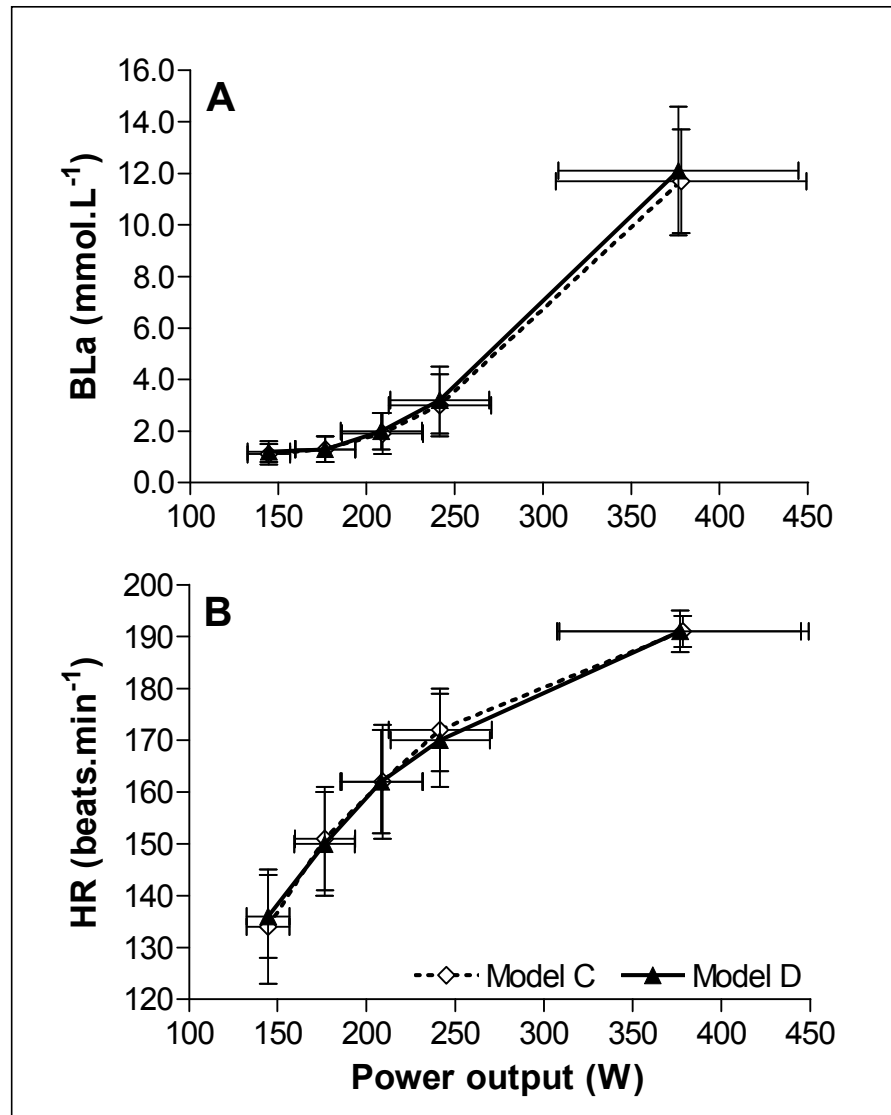


Figure 3-1: (A) Blood lactate concentration and (B) heart rate during the incremental rowing protocol performed on Concept2 Model C and Model D ergometers. *Error bars denote ± 1 SD.*

Table 3-2: Power output, stroke rate and selected physiological variables during incremental rowing performed on Concept2 Model C and Model D ergometers. Data are presented as mean (SD).

Workload	Power (W)		SR (strokes·min ⁻¹)		RPE (6-20)		$\dot{V}O_2$ (L·min ⁻¹)		$\dot{V}CO_2$ (L·min ⁻¹)		RER	
	C2C	C2D	C2C	C2D	C2C	C2D	C2C	C2D	C2C	C2D	C2C	C2D
1	145 (12)	145 (12)	17 (2)	17 (2)	7 (2)	7 (2)	2.65 (0.22)	2.65 (0.31)	2.20 (0.21)	2.28 (0.30)	0.83 (0.06)	0.86 (0.05)
2	177 (17)	176 (17)	18 (1)	18 (2)	10 (3)	9 (2)	3.08 (0.30)	3.14 (0.31)	2.74 (0.32)	2.86 (0.30)	0.89 (0.05)	0.91 (0.05)
3	209 (23)	208 (23)	19 (2)	19 (1)	12 (2)	12 (1)	3.54 (0.35)	3.57 (0.37)	3.29 (0.41)	3.37 (0.40)	0.93 (0.06)	0.94 (0.05)
4	241 (29)	242 (28)	21 (2)	21 (2)	14 (2)	14 (1)	3.94 (0.40)	3.97 (0.43)	3.78 (0.52)	3.87 (0.45)	0.96 (0.06)	0.98 (0.06)
MAX	378 (71)	377 (68)	35 (4)	36 (2)	20 (0)	20 (0)	4.81 (0.51)	4.87 (0.57)	5.47 (0.92)	5.58 (0.78)	1.13 (0.09)	1.15 (0.08)

SR = stroke rate; RPE = rating of perceived exertion; $\dot{V}O_2$ = oxygen consumption; $\dot{V}CO_2$ = carbon dioxide production; RER = respiratory exchange ratio; C2C = Concept2 Model C ergometer; C2D = Concept2 Model D ergometer.

Table 3-3: LT₁ and LT₂ thresholds calculated from blood lactate-power output relationships during incremental rowing performed on Concept2 Model C and Model D ergometers.

Threshold	Variable	C2C	C2D	p
		Mean (SD)	Mean (SD)	
LT ₁	Power (W)	176 (27)	180 (25)	0.32
	BLa (mmol.L ⁻¹)	1.2 (0.4)	1.4 (0.4)	0.02
	HR (beats.min ⁻¹)	151 (7)	151 (4)	0.65
	$\dot{V}O_2$ (L.min ⁻¹)	3.10 (0.43)	3.22 (0.42)	0.12
LT ₂	Power (W)	273 (46)	268 (50)	0.41
	BLa (mmol.L ⁻¹)	4.2 (0.7)	4.2 (0.9)	0.91
	HR (beats.min ⁻¹)	176 (3)	174 (4)	0.17
	$\dot{V}O_2$ (L.min ⁻¹)	4.14 (0.46)	4.13 (0.48)	0.75

C2C = Concept2 Model C ergometer; C2D = Concept2 Model D ergometer; SD = standard deviation; HR = heart rate; BLa = blood lactate concentration; $\dot{V}O_2$ = oxygen consumption; p = probability resulting from a paired *t*-test between C2C and C2D data.

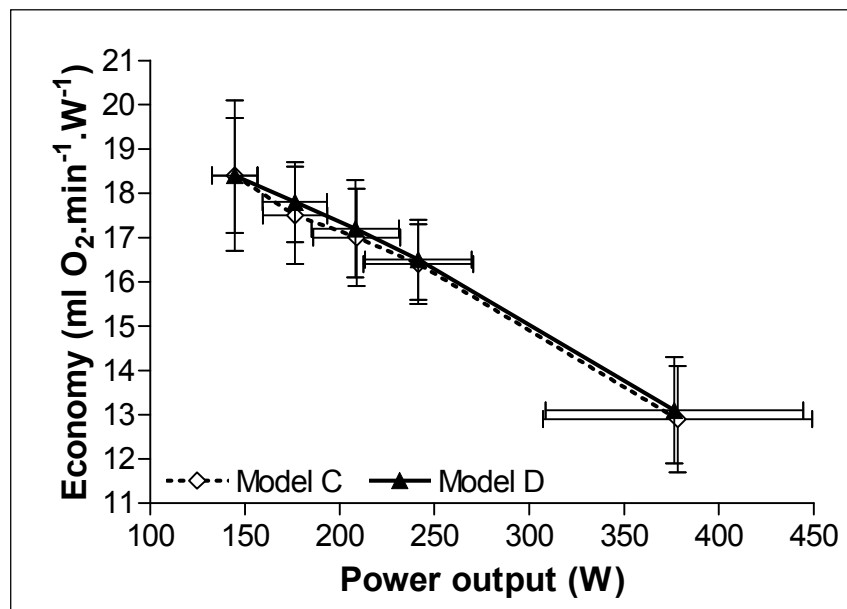


Figure 3-2: Oxygen economy during the incremental rowing protocol performed on Concept2 Model C and Model D ergometers. *Error bars denote ± 1 SD.*

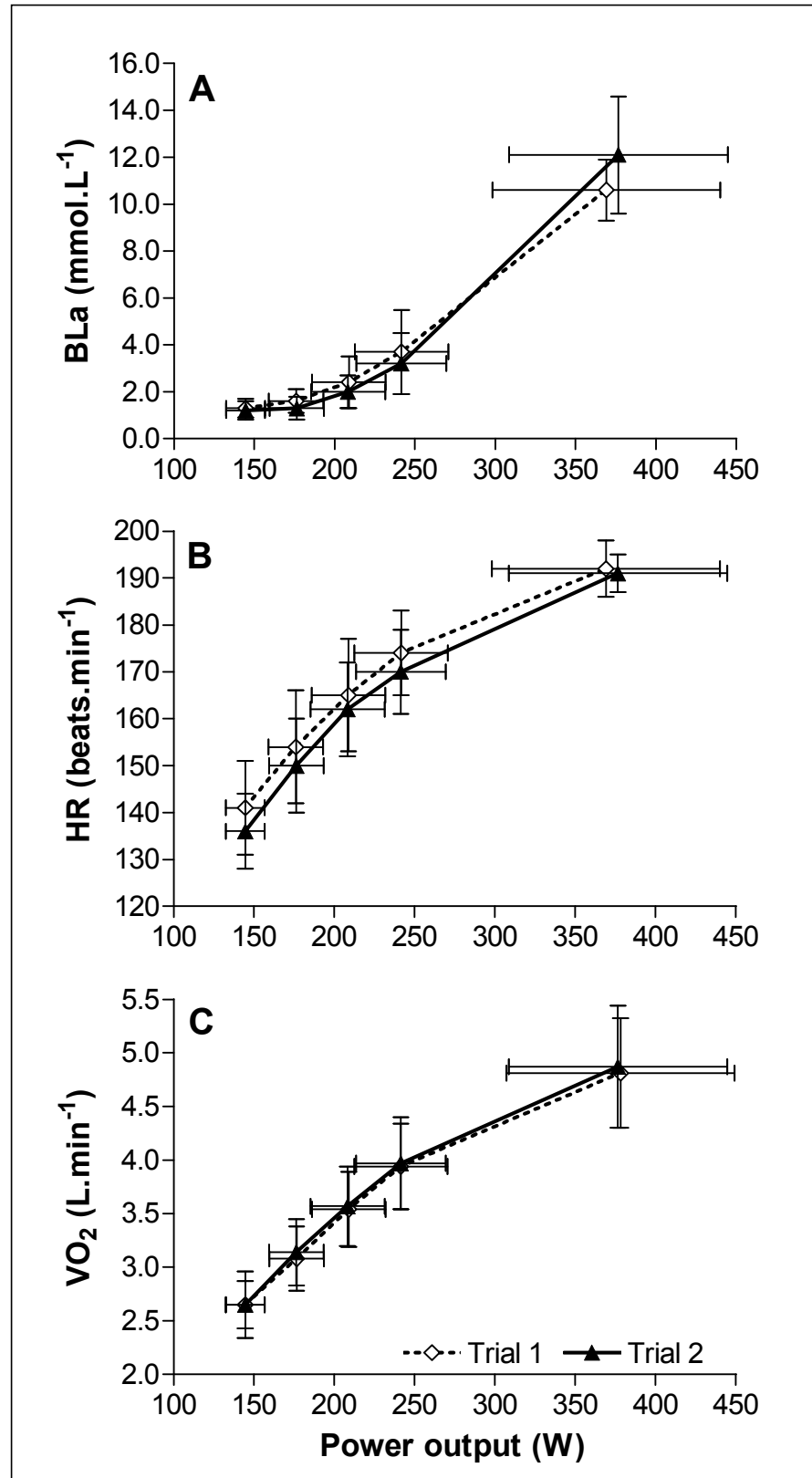


Figure 3-3: (A) Blood lactate concentration, (B) heart rate and (C) oxygen consumption during both incremental rowing protocols performed on the Concept2 Model D ergometer. Error bars denote ± 1 SD.

Table 3-4: Reliability (% TE) of repeated measurements during the submaximal and maximal portions of the incremental rowing tests performed on the Concept2 Model D rowing ergometer.

Variable	% TE (95% CL)	
	Submaximal	Maximal
Power output (W)	0.5 (0.4-0.7)	2.8 (1.9-5.2)
HR (beats.min ⁻¹)	2.4 (1.9-3.1)	1.6 (1.1-2.9)
BLa (mmol.L ⁻¹)	14.3 (12.3-20.4)	15.6 (11.3-32.9)
$\dot{V}O_2$ (L.min ⁻¹)	2.6 (2.1-3.4)	2.5 (1.8-4.7)
RPE (Borg 15-point scale)	8.4 (7.1-11.5)	1.3 (0.9-2.5)
SR (strokes.min ⁻¹)	4.6 (3.8-6.2)	9.8 (7.0-19.6)
Distance (m)	0.2 (0.2-0.3)	0.8 (0.5-1.5)
LT ₁ BLa (mmol.L ⁻¹)	15.6 (10.8-37.3)	
LT ₁ power output (W)	4.5 (3.0-9.6)	
LT ₂ BLa (mmol.L ⁻¹)	10.1 (6.9-22.7)	
LT ₂ power output (W)	5.0 (3.4-10.7)	

% TE = relative typical error (%); 95% CL = 95% confidence limits; HR = heart rate; BLa = blood lactate concentration; $\dot{V}O_2$ = oxygen consumption; RPE = Borg's rating of perceived exertion; SR = stroke rate; Distance = distance covered during each stage.

3.4 DISCUSSION

Our study is the first to show that the physiological responses to progressive exercise on the C2C and C2D models of Concept2 rowing ergometer are essentially identical despite the updated design of the C2D model. The current study evaluated the physiological responses to an incremental submaximal rowing test and maximal performance trial on C2C and C2D ergometers. The results indicate that there are only minor differences between the models with greatest variation seen during maximal performance, which is effort dependent. Test results also displayed a high degree of reproducibility between repeated trials on the C2D ergometer. These findings therefore provide reassurance that direct comparisons between the results from the two ergometer models are valid.

3.4.1 Comparison between ergometer models (C2C vs. C2D)

Differences between C2C and C2D ergometers were less than or similar to those reported in the literature between other ergometer designs. Comparisons between Gjessing and early model Concept2 ergometers report mean power differences of 21.8 W (Hahn *et al.* 1988) and 39.0 W (Lormes *et al.* 1993) during simulated racing and incremental tests, respectively. These compare with the 1.7 W difference (Table 3-2) during the maximal stage in the current investigation. Despite our small discrepancy in average power, $\dot{V}O_{2\text{ peak}}$ differed by 0.06 L·min⁻¹ between the Concept2 models compared with 0.04 L·min⁻¹ between ergometer designs (Hahn *et al.* 1988). Response variables such as \dot{V}_E , HR and BLa have also been compared across Concept2, Gjessing and Rowperfect designs. Differences between these designs span 3.1-5.0 L·min⁻¹ for \dot{V}_E , 0.1-0.6 mmol·L⁻¹ for BLa and 0-4 bpm for HR (Hahn *et al.* 1988; Lormes *et al.* 1993; Mahony *et al.* 1999). Furthermore, maximal SR is reported to be one point higher on the Gjessing than the Concept2 (Hahn *et al.* 1988). Thus, with the exception of $\dot{V}O_2$, all variables in the current study displayed greater agreement between the two Concept ergometer models (C2C and C2D) than that between different ergometer designs. Despite our greater variation in $\dot{V}O_2$ between the two ergometer models than previously reported (Hahn *et al.* 1988), this value was well within the TE established for this measurement using the repeated C2D trials (0.13 L·min⁻¹) and was therefore considered to be within the typical between-test variation.

3.4.2 Reliability of test results using the C2D ergometer

As fitness tests are usually conducted on a regular basis to monitor fitness changes across the rowing season (Vermulst *et al.* 1991; Petibois *et al.* 2003), between-test reliability is an important consideration as it determines a test's sensitivity to detecting change. While performance variations between repeated rowing ergometer time-trials have previously been quantified (Schabort *et al.* 1999; Soper and Hume 2004), the reliability of physiological responses during repeated incremental rowing tests has not been considered. Our findings showed that rowing tests using the C2D ergometer generally provided results that were highly reproducible. TE for $\dot{V}O_2$ (2.5%) was less than that reported for previous evaluations of between-day biological variation in $\dot{V}O_2$ of 3-4% (Stuart *et al.* 1981; Armstrong and Costill 1985). BLa showed larger variations between the repeated trials as reflected by the 10-16% TE for the individual lactate thresholds (Table 3-4), although absolute TE was 0.2 and 0.4 mmol.L⁻¹ for LT₁ and LT₂, respectively. However, the power output corresponding to the LT₁ and LT₂ thresholds displayed TE results of ~5% and should therefore be better suited to monitoring submaximal fitness changes. Otherwise, relative TE results were generally within 3%, except for submaximal SR (4.6%) and RPE (8.4%), although based on typical submaximal values, these TE results equate to errors of approximately 1 stroke.min⁻¹ or 1 RPE unit, respectively. While the inclusion of data from the C2D familiarisation trial had the potential to negatively affect our reliability results compared to a scenario where a separate familiarisation was performed, the current approach was used to better approximate between-test variation during routine testing, where familiarisation trials are not performed.

3.4.3 Practical applications

The present study attempted to replicate the conditions under which athletes present for routine testing. They were therefore asked to refrain from strenuous exercise in the preceding 24 h and consume a similar meal, high in carbohydrate, prior to each test. In addition, all tests were undertaken at the same time of day and the order effect for the final two ergometer trials was controlled by counterbalancing. Despite these intended controls, some subjects may have presented to the laboratory in a physiological state that was not consistent with previous trials. This may have impacted on the integrity of our HR and BLa measurements. However, this is the 'real world' situation and we should therefore be prepared to expect this extent of

variation for test-retest scenarios. Thus, the reliability estimates from this investigation were designed to quantify the typical between-test variation from routine rowing testing in our laboratory.

Other potential limitations to the investigation include the small sample size, and that power output was recorded directly from the ergometer display units and not by independent measurement of handle force and displacement. Directly measured power outputs of C2C and C2D rowing ergometers demonstrate that their display units underestimate power by 5.1% (Lormes *et al.* 1993) and 6.6% (Boyas *et al.* 2006), respectively. Although power output was not directly measured in our investigation, both Concept2 ergometer models are reported to use the same algorithm for calculating power (Boyas *et al.* 2006). Nevertheless, despite potential inaccuracy in calculated power, there appeared to be very little between-trial variation in the displayed power outputs during submaximal exercise and only slightly greater variation in peak power outputs during the maximal performance trial. Indeed, the variation between ergometer models during the maximal performance trial was well within the TE of 2.8% for this equipment in our laboratory and is therefore consistent with normal between-day variation in performance. Additionally, as our investigation compared a C2C model with previous operational experience to a brand new C2D model, chain tension and the elasticity of the chain return mechanism may have differed between ergometers, neither of which are accounted for in power output or drag factor calculations (Boyas *et al.* 2006). While there was no way to directly compare or control for these potential differences, both ergometers used throughout this investigation were well maintained and the C2C model had experienced minimal operation because it had only been used for laboratory testing. Furthermore, the reproducibility of the measured physiological variables suggests that mechanical differences between ergometers were negligible. Ideally, dynamic calibration of the Concept2 ergometer would account for differences between true power and that displayed by the work monitor unit, but such a calibration procedure would be exceedingly difficult for this style of ergometer. Indeed, there does not appear to be reported anywhere in the literature a first-principles calibration rig that can simulate the rowing stroke.

As the C2D ergometer incorporates an altered flywheel enclosure and modified handle grip, resistance characteristics and rowing technique could potentially be

changed. For example, as the leg drive along the slide and ultimate finish position are limited by leg length and practical limits to hip/trunk extension, many rowers (particularly heavyweight men) attempt to maximise stroke length at the front of the slide by allowing the handle to retract within several centimetres of the ergometer's frame. As the C2D handle design positions the hands further from the chain-handle interface, the same hand position at the catch results in less handle displacement and therefore shorter stroke length compared to the C2C model. As such, close inspection of the C2D model reveals that handle displacement would differ by a maximum of 4 cm when the handle was allowed to touch the ergometer frame. Rowers would therefore be required to apply greater force at the same stroke rate, or a higher stroke rate at the same handle force, to achieve the same power output on the C2D as on the C2C model. We therefore anticipated that the design of the C2D ergometer may have altered rowing stroke mechanics and economy ($\text{mL O}_2 \cdot \text{min}^{-1} \cdot \text{W}^{-1}$) thereby resulting in an increased O_2 cost. When rowing economy was calculated, there were subtle differences between the two ergometer models in the anticipated direction (Figure 3-2) but none of them was large enough to be statistically significant. Except for the first submaximal stage, mean economy throughout all exercise intensities was better on the C2C model with O_2 costs during maximal exercise of $12.9 \text{ mL O}_2 \cdot \text{min}^{-1} \cdot \text{W}^{-1}$ on the C2C and $13.1 \text{ mL O}_2 \cdot \text{min}^{-1} \cdot \text{W}^{-1}$ on the C2D. SRs during the corresponding submaximal and maximal workloads were also very similar (Table 3-2) thereby reinforcing the reproducibility of physiological responses when completing exercise on either ergometer model, and rejecting our assertion that the different handle designs would alter stroke mechanics and O_2 cost. The observed discrepancy in rowing economy may therefore be the result of slight differences in intra-stroke work output resulting from subtle between trial deviations in stroke rate.

Differences between ergometer models were greatest during the maximal stage of the incremental test. This was largely due to the within-subject standardisation of average power during the submaximal stages. However, unlike exercise tests performed on a treadmill or cycle ergometer, fixed-constant power output cannot be pre-determined on rowing ergometers; control of power output is therefore somewhat dependent on the skill of the rower. Between ergometer differences at submaximal workloads are therefore mainly due to the rower's ability to hold a given pace. All subjects were skilled rowers with previous testing experience, but the most experienced athletes were better able to reproduce the target submaximal workloads.

Rowers were not provided with target workloads during the maximal stage but were instructed to complete as much work as possible during the 4-min stage. While most rowers adopted a pacing strategy during the first half of the maximal trial, to ensure they were able to complete the entire stage, the potential for differences due to poor self-pacing was increased compared to the submaximal stages. So, although the response to maximal exercise was more variable than during submaximal workloads, it is likely that performance was more dependent on subject presentation and pacing than the model of Concept2 ergometer.

3.5 CONCLUSION

Incremental exercise performed on the C2D ergometer elicits a physiological response that is equivalent to that on the C2C model. Direct comparisons between test results obtained on either model of Concept2 rowing ergometer are therefore possible. As results from rowing tests using the C2D ergometer are also very reproducible, the C2D rowing ergometer is valid laboratory testing device.

CHAPTER 4

VALIDITY OF THE METAMAX3B PORTABLE METABOLIC SYSTEM

4.1 INTRODUCTION

Metabolic variables including oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), ventilation ($\dot{V}E$) and respiratory exchange ration (RER) are commonly measured during exercise tests to assess athletes' physiological profiles and to monitor their training status. While indirect calorimetry techniques once relied solely on the Douglas bag method (Douglas 1911) of collecting and measuring expired gas fractions and $\dot{V}E$, automated electronic gas analysis systems have almost entirely replaced the gold standard Douglas bag method. Although modern electronic metabolic systems are compact relative to the equipment required for measurements using Douglas bags, most are still designed for laboratory use only. However, the development of portable metabolic devices has allowed gas exchange measurements to be performed in a variety of field-based settings including running (Kawakami *et al.* 1992; Crouter *et al.* 2001), cycling (MacRae *et al.* 2000; Millet *et al.* 2002) and rowing (Kawakami *et al.* 1992). Given on-going interest in ways to improve the specificity of physiological testing for elite athletes, portable metabolic systems provide a means of assessing the metabolic demands of exercise in a sport-specific field environment. However, for this to be a realistic outcome, it is essential to validate the accuracy and reliability of measurements from portable metabolic systems compared with the standard laboratory equipment.

The accuracy of gas exchange measurements from portable metabolic devices has typically been evaluated by comparing results to those obtained from either Douglas bag measurements (McLaughlin *et al.* 2001; Larsson *et al.* 2004; Crouter *et al.* 2006) or other laboratory-based metabolic systems (Hauswirth *et al.* 1997; Schulz *et al.* 1997; Pinnington *et al.* 2001; Eisenmann *et al.* 2003; Duffield *et al.* 2004; Crouter *et*

al. 2006), although mechanical gas exchange simulators have also been described (Gore *et al.* 1997; Prieur *et al.* 2003). Accuracy and reliability data have been previously reported for a variety of portable models from several manufacturers, including: Cosmed (Rome, Italy) K4b² (McLaughlin *et al.* 2001; Pinnington *et al.* 2001; Eisenmann *et al.* 2003; Duffield *et al.* 2004), K4 (Hauswirth *et al.* 1997) and K2 (Kawakami *et al.* 1992) models; the Medical Graphics (St. Paul, USA) VO2000 (Kautza *et al.* 2004; Crouter *et al.* 2006) and Cortex (Leipzig, Germany) MetaMax II (Larsson *et al.* 2004), MetaMax I (Meyer *et al.* 2001) and X1 (Schulz *et al.* 1997) designs. Comparisons between these portable devices and criterion systems have usually involved duplicate tests on separate days (Hauswirth *et al.* 1997; McLaughlin *et al.* 2001; Duffield *et al.* 2004; Larsson *et al.* 2004; Crouter *et al.* 2006), although several studies have attempted to remove between-test biological variation by performing simultaneous measurements with both machines (Pinnington *et al.* 2001; Duffield *et al.* 2004; Larsson *et al.* 2004; Crouter *et al.* 2006); however, interference between the systems has been reported when using this approach (Duffield *et al.* 2004; Crouter *et al.* 2006). Regardless of these variations in protocol, accuracy comparisons show that mean values for $\dot{V}E$ (Pinnington *et al.* 2001; Crouter *et al.* 2006), $\dot{V}O_2$ (McLaughlin *et al.* 2001; Eisenmann *et al.* 2003; Duffield *et al.* 2004; Larsson *et al.* 2004; Crouter *et al.* 2006), $\dot{V}CO_2$ (McLaughlin *et al.* 2001; Duffield *et al.* 2004; Larsson *et al.* 2004; Crouter *et al.* 2006) and RER (McLaughlin *et al.* 2001) sometimes differ between measurement systems. Because these differences have been isolated to only some of the measured variables, and limited to a few of the evaluated workloads, most studies have concluded that portable systems display adequate accuracy. Indeed, Meyer *et al.* (2005a) provides a detailed review of validation studies and concludes that results from portable systems do not greatly differ from laboratory metabolic carts; although they do acknowledge the potential for publication of only favourable results, and criticise some publications for inadequate methods of analyses. While the accuracy of portable systems has been widely addressed, the reproducibility of repeated measurements is equally important (Atkinson *et al.* 2005) and has not been as extensively reported. Reliability assessments from duplicate tests performed on separate days have only been published for the Cosmed K4b² (Duffield *et al.* 2004) and K2 (Kawakami *et al.* 1992), the Medical Graphics VO2000 (Crouter *et al.* 2006) and the Cortex MetMax I (Meyer *et al.* 2001). Of these, the studies evaluating the Cosmed and Cortex systems both concluded that reliability results were satisfactory (Meyer *et al.* 2001; Duffield

et al. 2004). Provided results from laboratory-based validity studies directly translate to the field environment, it appears that some designs of portable metabolic system meet the requirements to achieve their intended purpose as field-based measurement devices. Thus, once the accuracy and reliability of a portable metabolic device has been thoroughly characterised, sport-specific evaluations of metabolic demand can be performed in the field and the results interpreted with some confidence. Despite extensive publication of studies considering the validity of portable metabolic systems, no evaluation has been reported for the current Cortex breath-by-breath model, the MetaMax 3B (MM3B). The purpose of the current investigation was therefore to: 1) evaluate the accuracy of the MM3B compared with an automated Douglas bag system during submaximal and maximal exercise; 2) establish the reproducibility of MM3B measurements during duplicate trials; and 3) determine whether the MM3B is a viable tool for assessing metabolic demands during on-water rowing.

4.2 METHODS

4.2.1 Subjects

Eight rowers (6 males and 2 females) provided written informed consent to participate in this investigation; all but one athlete were competing at a national level in Under 23 rowing competition. The male and female groups both consisted of heavyweight and lightweight rowers whose physical characteristics are described in Table 4-1. All biological testing procedures were approved by the AIS Human Ethics Committee.

4.2.2 Indirect calorimetry equipment

Portable metabolic system

The MM3B is a breath-by-breath indirect calorimetry system (total weight <850 g, including battery) consisting of a face mask-volume turbine assembly and gas analysis-data telemetry module (Plate 4-1), which is designed to permit field-based cardiopulmonary exercise assessments. During exercise testing, the base module (gas analysis and data telemetry) is fastened to the subject's chest using a neoprene harness, and attached to the facemask-volume turbine assembly via the gas-analysis sample line and volume turbine cord. However, during the current study, the harness was reversed so that the system was worn on the back, thereby preventing the connections between the base module and volume turbine assembly from interfering with the rowers' hands at the finish position of the rowing stroke. According to the manufacturer's specifications, the volume turbine permits flow-transduced volume measurements ranging 0.05-20.0 L.sec⁻¹, while electro-chemical O₂ and infra-red CO₂ analysers allow gas concentration measurements ranging 0-35% O₂ and 0-13% CO₂ with a 90% response time of ≤100 ms. Expired gas is sampled from a face mask (VmaskTM, Hans Rudolf Inc, Shawnee, USA; deadspace 40-49 ml) and 'dried' by a 60 cm length of Nafion[®] tubing on-route to the analysers. Metabolic data can then be displayed in real-time via radio telemetry or logged by the on-board memory for subsequent download and analysis. Rechargeable lithium ion batteries provide approximately 2 h of continuous data collection.

Laboratory metabolic system

Criterion measurements were acquired with a customised laboratory-based system

Table 4-1: Physical characteristics of the subjects.

Measure	Males (n=6)		Females (n=2)	
	Mean (SD)	Range	Mean	Range
Age (yr)	23.0 (5.3)	20.3–33.7	21.7	20.6-22.8
Height (m)	1.89 (0.06)	1.81-1.97	1.75	1.74-1.75
Mass (kg)	82.1 (5.2)	75.5-88.0	67.6	59.0-76.2
$\dot{V}O_{2\text{ peak}}$ (L.min ⁻¹)	4.79 (0.52)	4.34-5.58	3.63	3.30-3.95
P _{max} (W)	367 (34)	337-420	263	245-280

$\dot{V}O_{2\text{ peak}}$ = peak oxygen consumption during the 4-min maximum performance trial; P_{max} (W) = average power output during the 4-min maximum performance trial.



Plate 4-1: The MetaMax3B portable indirect calorimetry system, including: A) gas analysis-data telemetry module; B) telemetry receiver unit, and C) volume turbine assembly.

that used an automated Douglas bag design (MOUSE, AIS, Canberra, Australia; where the acronym MOUSE is short for Maximum Oxygen Uptake System electronic). This system uses first principles assessment of volume combined with AEI Technologies (Naperville, USA) O₂ (model S-3AI) and CO₂ (model CD-3A) gas analysis, and has been described elsewhere (Russell *et al.* 2002). The system is shown in Plate 4-2. Based on previous reliability assessments of rowing tests using the MOUSE system (Chapter 3), submaximal and maximal typical errors (TE) for each of the metabolic variables are: $\dot{V}O_2 = 2.6$ and 2.5%; $\dot{V}CO_2 = 4.4$ and 4.2%; $\dot{V}E = 5.5$ and 5.2%; and RER = 3.2 and 4.1%, respectively.

Calibration of the metabolic systems

The MM3B and MOUSE systems were both calibrated according to normal operational procedures. Prior to calibration and testing, the MM3B was switched-on for at least 45 min before gas analysis commenced. The MM3B operational software includes calibration routines for the gas analysers, volume turbine and pressure sensor. Gas analyser calibration consisted of a semi-automated two-point procedure whereby the MM3B sampled atmospheric air (assumed to be 20.93% O₂ and 0.03% CO₂) until the calibration routine determined a stable measurement (typically 60-150 s), and this process was replicated using a precision grade ($\pm 0.03\%$) gas (16.05% O₂ and 4.99% CO₂; BOC Gases Australia Ltd, Sydney, Australia). Additionally, the MM3B also performs an automatic atmospheric-air check prior to operation. The volume turbine was calibrated using five strokes of a Hans Rudolph 3 L syringe at a flow rate of ~ 60 L.min⁻¹, the generated calibration factor was checked by a further three strokes of the 3 L syringe at each of ~ 30 , 60 and 180 L.min⁻¹ to ensure that the measured volumes were within 3% of the criterion across a wide range of flows. The AEI O₂ and CO₂ analysers used by the MOUSE system were calibrated before each test using a three-point procedure; precision gases ($\pm 0.03\%$, BOC Gases Australia Ltd.) spanned the physiological range of measurement (14.48-17.98% O₂ and 2.50-5.94% CO₂) and included a mid-range reference (16.62% O₂ and 4.00% CO₂) to verify analyser linearity. Pre-test calibration of MOUSE volume measurements was not necessary as these were obtained from the displacement of a fixed-diameter piston, although volume measurements (50-240 L.min⁻¹) were regularly checked with a metabolic calibrator (details below). However, a pre-test volume initialisation routine was performed to ensure that both Douglas bags had been evacuated of all air



Plate 4-2: The laboratory-based Maximum Oxygen Uptake System electronic (MOUSE) indirect calorimetry system, including: A) volume piston; B) AEI Technologies CD-3A CO₂ gas analyser; C) AEI Technologies S-3AI O₂ analyser; D) computer interface, and E) Mylar Douglas bags.

and that the volume piston was functioning correctly. The gas analysers from both systems were also checked for drift after each test.

Metabolic simulation system

Additionally, a metabolic calibrator (AIS, Canberra, Australia; Plate 4-3) was also used to evaluate the accuracy and reliability of MM3B measurements by providing mechanically generated ‘tidal volumes’ that consisted of known concentrations for dry ‘expired’ gas fractions. The simulator comprises two fixed-diameter pistons; a small piston delivers precise volumes of CO₂ into a larger piston that regulates the volume of air expelled each stroke and allows mixing with a known volume of atmospheric air. Reference gas fractions were then calculated by the metabolic calibrator based on the dilution of precise volumes of alpha gas (21.00% CO₂; BOC Gases Australia Ltd.) within known volumes of atmospheric air. By controlling the stroke length of the small and large pistons, a range of expired gas fractions can be generated to span the physiological range. Similarly, by controlling the speed of the pistons, flow rates can also be varied to span the physiological range, thereby allowing $\dot{V}E$ and $\dot{V}O_2$ simulations beyond 240 L.min⁻¹ (BTPS) and 7.0 L.min⁻¹ (STPD), respectively. As the gas fractions calculated by the metabolic calibrator are accurate to within 0.10% (absolute) and $\dot{V}E$ is accurate to within 1%, the values predicted for $\dot{V}O_2$ and $\dot{V}CO_2$ are accurate to ~4%, assuming both errors act cumulatively (Withers *et al.* 2000). Further details about the principles of the metabolic calibrator are described by Gore *et al.* (1997).

4.2.3 Experimental protocol

The accuracy and reliability of the MM3B was evaluated using two methods: 1) simulation of gas exchange parameters using the metabolic calibrator, and 2) comparing MM3B and MOUSE results during biological trials with athlete subjects.

During testing with the metabolic calibrator, piston configurations were adjusted to provide five simulated metabolic outputs that varied between 50-240 L.min⁻¹ $\dot{V}E$ (BTPS) and 1.92-5.75 L.min⁻¹ $\dot{V}O_2$ (STPD); Table 4-2 shows the reference values for $\dot{V}E$, $\dot{V}O_2$, $\dot{V}CO_2$ and RER for each of the settings. The MM3B was attached to the calibrator by connecting the volume turbine assembly to the respiratory port of the metabolic calibrator using an air tight rubber adaptor; barometric pressure and

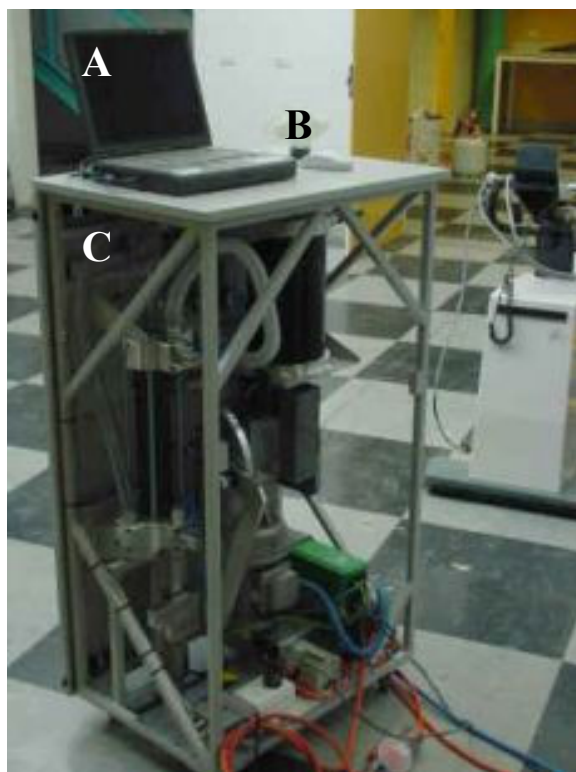


Plate 4-3: The metabolic simulation system, including: A) computer interface; B) respiratory port, and C) internal mechanics.

temperature readings were then matched between both devices to ensure that conversions between gas volumes (ATP to STPD or BTPS) were consistent. Steady-state measurements were performed for each of the five settings that were maintained for 4 min, with mean results recorded from the final 60 s of each period. Additionally, the reproducibility of MM3B measurements was evaluated by recalibrating the MM3B gas analysers and repeating the protocol for three of the metabolic calibrator settings (Table 4-2). However, despite being able to address measurement accuracy and reproducibility by this method, the metabolic calibrator does not simulate the saturated expirate of human subjects, or evaluate the system under ambulatory conditions. Thus, any evaluation of a portable metabolic system must also include biological testing.

Biological testing required athletes to complete three matched rowing trials on the same ergometer (Concept2 Model D, Morrisville, USA). Metabolic variables: $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$ and RER were measured continuously during all 3 trials with either the MM3B or MOUSE. Gas exchange measurements were conducted with the MM3B during two trials to establish the reproducibility of results obtained from the portable device, while a single trial was completed using the MOUSE system, thereby providing a criterion against which the accuracy of the MM3B could be compared. All trials were completed in 3-10 d and the order of trials was counterbalanced so that half the subjects completed their first trial with the MM3B and half with the MOUSE. Subjects were instructed to eat similar meals and limit training to light workloads during the 24 h prior to testing.

Incremental rowing protocol

The progressive incremental test comprised 4 x 4-min submaximal workloads using fixed target power outputs, and a single 4-min maximal performance trial. The initial workload and progression of intensity were prescribed on an individual basis according to rower category (i.e. male or female, lightweight or heavyweight) and recent 2000-m ergometer time-trial results. Thus, workloads were designed to elicit a similar physiological intensity between subjects of approximately 60, 70, 80 and 90% of maximum 2000-m rowing power output. Submaximal stages were separated by 1 min recovery periods, with a 5 min rest before the maximal stage. Subjects were then instructed to complete as much distance as possible during the 4-min maximal performance trial.

Prior to each test, flywheel resistance was standardised using the Concept2 ergometer drag factor, which was set to 130 for heavyweight men, 120 for heavyweight women and lightweight men, and 110 for lightweight women. During exercise, each of the metabolic variables was calculated at 30 s intervals throughout each stage. As this was the default sample rate for the MOUSe system, breath-by-breath measurements from the MM3B were averaged over the same 30 s duration using the mean-time average function available in the MetaMax analysis software. Thus, regardless of metabolic device, $\dot{V}O_2$, $\dot{V}CO_2$, $\dot{V}E$ and RER for each workload was defined as the mean of the two 30 s samples obtained from the final minute of each submaximal stage, and the highest two consecutive 30 s samples during the maximal performance trial. Heart rate (HR; Polar Electro, Kempele, Finland) was also measured continuously during each stage, with the steady-state HR recorded during the final 30 s of each workload. Additionally, blood lactate concentration (BLa; Lactate Pro, Arkray Inc, Shiga, Japan) was determined by analysis of capillary blood samples collected from the ear lobe immediately following each stage and 4 min after completion of the maximal workload. Average power output, stroke rate (SR) and rating of perceived exertion (RPE, Borg 15-point scale; Borg 1973) were also recorded upon completion of each workload.

4.2.4 Statistical analyses

Reliability

As the metabolic calibrator evaluation consisted of single measurements for each of the simulated outputs, agreement between duplicate MM3B trials (Trial 1 vs. 2) was described by percent differences between the respective means and Pearson correlation coefficients from linear regression; standard error of the estimate (SEE) from the linear regression provided an average estimate of the error.

Results from the matched MM3B trials during biological testing were examined using 2 (trial) x 4 (stage) factorial ANOVAs with repeated measures on both dimensions (SPSS 15.0 for Windows; SPSS, Chicago, Illinois, USA). Maximal data were compared using dependent *t*-tests. Statistical significance was established at $p < 0.05$ for all analyses, with pairwise comparisons using Holm-Bonferroni adjusted alpha levels (Holm 1979) in the event of significant ANOVA results. The magnitude of the differences between MM3B trials was also analysed to determine the probability that the true value of the effect (using 90% confidence intervals) was

greater than the threshold for smallest worthwhile change (SWC), which was based on reliability data from the criterion MOUSe system (Hopkins 2002; Hopkins *et al.* 2009). These values (reported p. 72) were therefore set as the smallest worthwhile effects for each of the metabolic variables. Between-trial effects that displayed a likelihood $\geq 75\%$ of being larger than the SWC (in either a positive or negative direction) were defined as practically substantial, while effects that displayed $\geq 75\%$ likelihood for being within the range of the SWC were defined as trivial. An effect was unclear when the likelihood was $< 75\%$ for a practically substantial difference in the positive direction and $> 5\%$ for a substantial negative difference (Hopkins 2007; Hopkins *et al.* 2009), or vice-versa. Magnitude-based differences are reported as the most likely effect and associated percent probability (e.g. positive, 85%). The reliability of repeated MM3B measurements was also established using TE (Hopkins 2000a).

Accuracy

The accuracy of the MM3B compared to the metabolic calibrator (MM3B vs. metabolic calibrator) and the automated Douglas-bag system (MM3B vs. MOUSe) was quantified using the same data analysis methods as described for Reliability. Additionally, modified Bland-Altman plots (Bland and Altman 1986; Crouter *et al.* 2006) with 95 % limits of agreement were also used to permit comparisons between our results and those from other validity studies.

4.3 RESULTS

4.3.1 Simulated metabolic outputs

Accuracy and reproducibility results from the evaluation with the metabolic calibration system are shown in Table 4-2. Compared to the metabolic outputs predicted by the calibration system, MM3B results were within 2.1-7.8% ($\dot{V}O_2$), 0.8-10.2% ($\dot{V}CO_2$) and 2.5-4.0% ($\dot{V}E$). Absolute differences between measured and target gas fractions were 0.21-1.03% (O_2) and 0.36-1.08% (CO_2); RER results were within 0.01-0.06. While the magnitude of measured differences were sometimes greater than that attributable to the precision of the metabolic simulations (approximately 1%, 0.10% and 3-5% for $\dot{V}E$, gas fractions and $\dot{V}O_2/\dot{V}CO_2$, respectively), correlations between MM3B and metabolic calibrator results were greater than $R=0.996$ ($p<0.001$) for all measured variables. SEE results for these linear regressions were 0.15, 0.10 and 0.27 $L\cdot min^{-1}$ for $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$, respectively. Differences between repeated MM3B trials using duplicate metabolic calibrator settings ranged 1.7-4.2% ($\dot{V}O_2$), 0.3-2.0% ($\dot{V}CO_2$) and 0.2-0.7% ($\dot{V}E$). Absolute differences in F_{EO_2} and F_{ECO_2} were 0.11-0.56% and 0.16-0.50%, respectively, while variation in RER was 0.01-0.02. Correlations between Trial 1 and Trial 2 results of the MM3B were very strong for all variables ($R>0.997$; $p=0.002-0.05$) and SEE results for $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ were 0.10, 0.03 and 0.31 $L\cdot min^{-1}$, respectively.

4.3.2 Power output during biological trials

Power output and HR results displayed good agreement between all trials. During the two MM3B trials, mean power outputs differed by no more than 0.4 W for each of the submaximal workloads ($F_{1,7}=1.58$, $p=0.25$) and 1.4 W ($p=0.71$) during maximal exercise; mean HRs differed by less than 4 $beats\cdot min^{-1}$ ($F_{1,7}=1.62$, $p=0.24$) and 1 $beat\cdot min^{-1}$ ($p=0.71$) during submaximal and maximal intensities, respectively. Similarly, mean power outputs and HRs during comparisons between MM3B and MOUSE trials were within 0.5 W ($F_{1,7}=3.59$, $p=0.10$) and 2 $beats\cdot min^{-1}$ ($F_{1,7}=0.59$, $p=0.47$) for the submaximal component of the test and 3.9 W (higher during the MOUSE trial; $p=0.30$) and 2 $beats\cdot min^{-1}$ ($p=0.25$) during maximal performance.

Table 4-2: Simulated metabolic outputs for five different settings using the metabolic calibrator (*italicised*) and the corresponding mean results from either one trial (MM3B) or duplicate trials (MM3B2) with the MM3B portable metabolic system. Differences between MM3B results and the metabolic calibrator, and between duplicate MM3B trials, are displayed as % error[†].

Setting	System	Metabolic output results					
		$\dot{V}E_{\text{BTPS}}$ (L.min ⁻¹)	$F_{E\text{O}_2}$ %	$F_{E\text{CO}_2}$ %	$\dot{V}O_2$ STPD (L.min ⁻¹)	$\dot{V}CO_2$ STPD (L.min ⁻¹)	RER
1	<i>Calibrator</i>	50.00	15.96	5.01	1.92	1.92	1.00
	MM3B	51.99	14.93	6.09	2.07	2.12	1.02
	MM3B 2	51.82	15.49	5.48	1.99	2.07	1.04
	% error _{acc}	4.0	-1.03	1.08	7.8	10.2	2.0
	% error _{rel}	-0.3	0.56	-0.61	-4.2	-2.0	2.1
2	<i>Calibrator</i>	100.00	18.44	2.53	1.93	1.93	1.00
	MM3B	103.42	18.11	3.05	1.97	2.09	1.06
	% error _{acc}	3.4	-0.33	0.52	2.1	8.3	6.0
3	<i>Calibrator</i>	100.00	15.97	4.99	3.83	3.83	1.00
	MM3B	103.25	15.10	5.84	4.03	4.08	1.01
	MM3B 2	103.09	15.47	5.57	3.92	4.07	1.04
	% error _{acc}	3.3	-0.87	0.85	5.1	6.5	1.0
	% error _{rel}	-0.2	0.37	-0.27	-2.8	-0.3	2.6
4	<i>Calibrator</i>	180.00	18.52	2.45	3.36	3.36	1.00
	MM3B	184.47	18.31	2.81	3.27	3.43	1.05
	% error _{acc}	2.5	-0.21	0.36	-2.8	1.9	5.0
5	<i>Calibrator</i>	240.00	17.83	3.14	5.75	5.75	1.00
	MM3B	246.15	17.57	3.58	5.58	5.71	1.03
	MM3B 2	244.52	17.46	3.73	5.67	5.78	1.02
	% error _{acc}	2.6	-0.26	0.44	-3.0	-0.8	3.0
	% error _{rel}	-0.7	-0.11	0.15	1.7	1.4	-0.4

[†] Errors for $\dot{V}E$, $\dot{V}O_2$, $\dot{V}CO_2$ and RER are relative errors, whereas errors for $F_{E\text{O}_2}$ and $F_{E\text{CO}_2}$ are absolute errors since the units of the latter two are percent.

$\dot{V}E$ = ventilation; $F_{E\text{O}_2}$ = fractional concentration of oxygen in expired air; $F_{E\text{CO}_2}$ = fractional concentration of carbon dioxide in expired air; $\dot{V}O_2$ = oxygen consumption; $\dot{V}CO_2$ = carbon dioxide production; RER = respiratory exchange ratio; % error_{acc} = percent difference between MM3B and metabolic calibrator results (MM3B-metabolic calibrator); % error_{rel} = percent difference between repeated MM3B trials (MM3B 2-MM3B) for the three metabolic outputs that were simulated on two separate occasions.

4.3.3 Biological trials

The physiological responses measured during repeated MM3B trials are displayed in Figure 4-1. Mean differences between each of the workloads were no more than 0.11 L.min⁻¹ (2.5%) for $\dot{V}O_2$ and $\dot{V}CO_2$, 0.01 (0.9%) for RER and 3.39 L.min⁻¹ (2.7%) for $\dot{V}E$; there were no statistically significant differences during the submaximal or maximal stages (Table 4-3). Additionally, the magnitude of between-trial differences was nearly always trivial based on probabilities of practically substantial effects. The probability of a trivial difference between the two trials ranged 62-92% for $\dot{V}O_2$ during each of the submaximal workloads, although the difference was unclear (trivial effect, 53% probability) during the maximal workload. Probability results for $\dot{V}CO_2$ (range: 85-99%), RER (93-96%) and $\dot{V}E$ (94-98%) indicated trivial effects across all test stages. Table 4-3 displays reliability results from the repeated MM3B trials and shows that TE ranged 2.3% ($\dot{V}O_2$) to 3.6% ($\dot{V}E$) during submaximal workloads and 2.0% ($\dot{V}O_2$) to 2.6% ($\dot{V}CO_2$, RER and $\dot{V}E$) during maximal exercise. Additionally, individual between-trial errors are displayed by Bland-Altman plots (Figure 4-2) and show that mean bias and 95% limits of agreement for each variable were: 0.07 ± 0.23 L.min⁻¹ ($\dot{V}O_2$); 0.03 ± 0.30 L.min⁻¹ ($\dot{V}CO_2$); 0.01 ± 0.07 (RER) and 0.74 ± 8.12 L.min⁻¹ ($\dot{V}E$).

Figure 4-1 shows the metabolic responses measured by the MM3B and MOUSE during matched rowing tests. As the TE results from the reliability assessment indicated that MM3B measurements were highly reproducible, and there were no statistically significant or practically substantial differences between the repeated MM3B trials, results from the two MM3B trials were averaged for subsequent comparisons with the criterion MOUSE system. Differences between the results from the MM3B and MOUSE are displayed in Table 4-4. $\dot{V}O_2$ (Stage 2, p=0.005), RER (Stage 3, p=0.012) and $\dot{V}CO_2$ (Stages 1-4, p=0.008 to p<0.001) all displayed statistically significant differences during submaximal workloads; however, only $\dot{V}CO_2$ (p=0.01) and RER (p=0.02) displayed significant differences during the maximal stage (Table 4-4). Furthermore, probabilities of practically substantial differences for each of the submaximal workloads ranged: 58-85% positive ($\dot{V}O_2$); 91-100% positive ($\dot{V}CO_2$) and 58-70% (unclear) positive (RER), but 54-85% trivial

for $\dot{V}E$. During the maximal stage, $\dot{V}CO_2$ results again displayed strong likelihoods for substantial positive effects (94%), while the effect for $\dot{V}E$ was very likely trivial (91%); $\dot{V}O_2$ and RER were unclear (51% positive and 73% positive, respectively). Bland-Altman plots (Figure 4-3) show that individual $\dot{V}O_2$, $\dot{V}CO_2$, RER and $\dot{V}E$ measurements were nearly always over-estimated by the MM3B. Mean bias and 95% limits of agreement for each variable were: 0.12 ± 0.32 L.min⁻¹ ($\dot{V}O_2$); 0.27 ± 0.39 L.min⁻¹ ($\dot{V}CO_2$); 0.04 ± 0.08 (RER) and 2.63 ± 10.95 L.min⁻¹ ($\dot{V}E$).

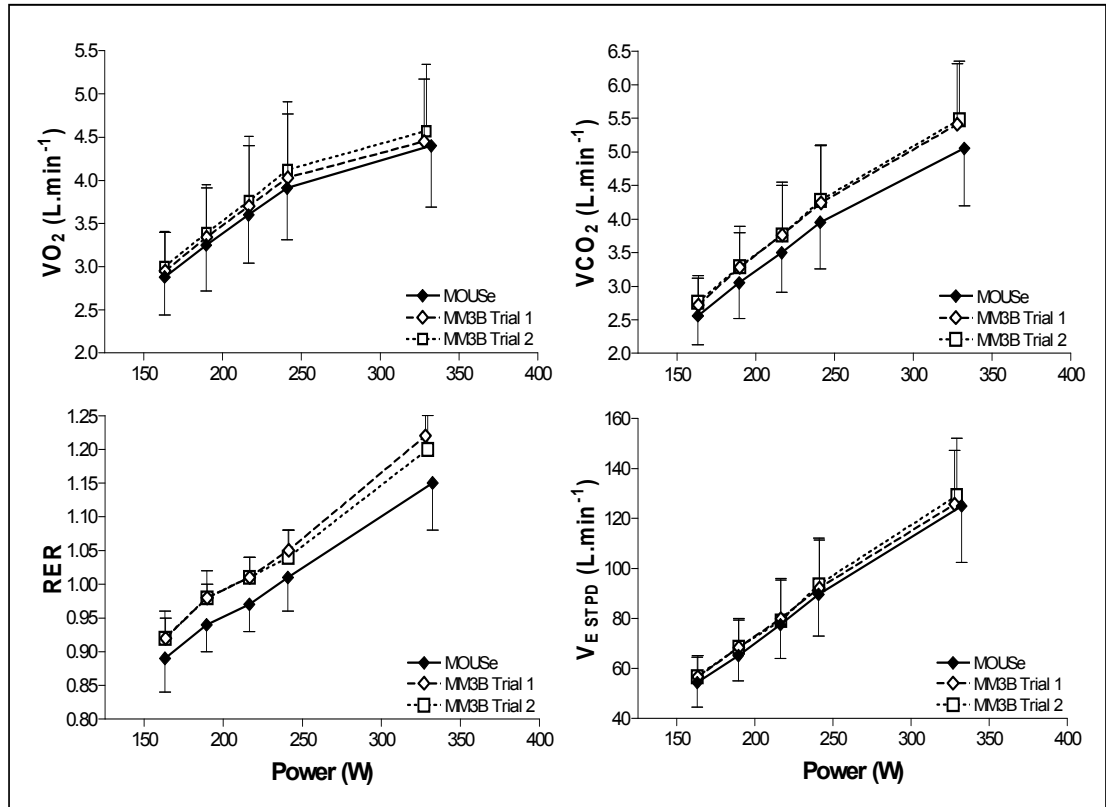


Figure 4-1: Oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER) and ventilation ($\dot{V}E$) as measured by the criterion MOUSE system during the incremental rowing test, and by the MM3B during Trial 1 and Trial 2 of duplicate rowing tests. Values are means and standard deviations.

Table 4-3: Differences between MM3B results during each stage of the duplicate incremental rowing tests (trial 2 - trial 1).

Measure	Δ	Mean (90% CI)				
		Stage 1	Stage 2	Stage 3	Stage 4	Maximum
$\dot{V}O_2$ (L.min ⁻¹)	Absolute	0.05 (-0.04-0.14)	0.05 (0.01-0.09)	0.06 (-0.01-0.12)	0.09 (-0.01-0.19)	0.11 (0.02-0.21)
	%	1.6 (-1.3-4.6)	1.4 (0.2-2.6)	1.5 (-0.3-3.2)	2.2 (-0.3-4.7)	2.5 (0.4-4.6)
		Main effect: F _{1,7} = 4.28, p = 0.08 ^a				p = 0.06 ^b
	TE (%)	2.3 (1.9-3.0)				2.0 (1.4-3.9)
$\dot{V}CO_2$ (L.min ⁻¹)	Absolute	0.04 (-0.07-0.15)	0.01 (-0.09-0.11)	0.00 (-0.09-0.09)	0.04 (-0.06-0.14)	0.08 (-0.06-0.21)
	%	1.6 (-2.5-5.6)	0.3 (-2.7-3.2)	0.0 (-2.5-2.5)	1.0 (-1.4-3.4)	1.4 (-1.1-3.8)
		Main effect: F _{1,7} = 0.31, p = 0.60 ^a				p = 0.31 ^b
	TE (%)	3.0 (2.5-3.8)				2.6 (1.8-5.0)
RER	Absolute	0.00 (-0.02-0.02)	-0.01 (-0.03-0.01)	-0.01 (-0.03-0.01)	-0.01 (-0.03-0.01)	-0.01 (-0.04-0.02)
	%	0.0 (-2.4-2.4)	-0.6 (-3.2-1.9)	-0.9 (-3.2-1.4)	-0.8 (-3.1-1.4)	-0.9 (-3.6-1.7)
		Main effect: F _{1,7} = 0.23, p = 0.65 ^a				p = 0.51 ^b
	TE (%)	2.4 (2.0-3.1)				2.6 (1.8-5.0)
$\dot{V}E$ (L.min ⁻¹)	Absolute	0.12 (-1.79-2.04)	0.05 (-2.24-2.34)	-0.83 (-3.44-1.75)	1.28 (-1.75-4.30)	3.39 (-0.23-7.00)
	%	0.2 (-3.2-3.6)	0.1 (3.3-3.4)	-1.0 (-4.3-2.2)	1.4 (-1.9-4.6)	2.7 (-0.2-5.5)
		Main effect: F _{1,7} = 0.03, p = 0.88 ^a				p = 0.12 ^b
	TE (%)	3.6 (3.0-4.6)				2.6 (1.8-5.1)

$\dot{V}O_2$ = oxygen consumption; $\dot{V}CO_2$ = carbon dioxide production; RER = respiratory exchange ratio; $\dot{V}E$ = ventilation; Absolute = between-trial error in raw units (trial 2-trial 1); % = between-trial error expressed as a percentage of the mean (trial 2-trial 1); TE (%) = percent typical error for the submaximal and maximal components of the rowing test as determined from repeated trials; ^a = result of repeated measure 2 x 4 factorial ANOVA for submaximal data; ^b = result of dependent *t*-test for maximal data.

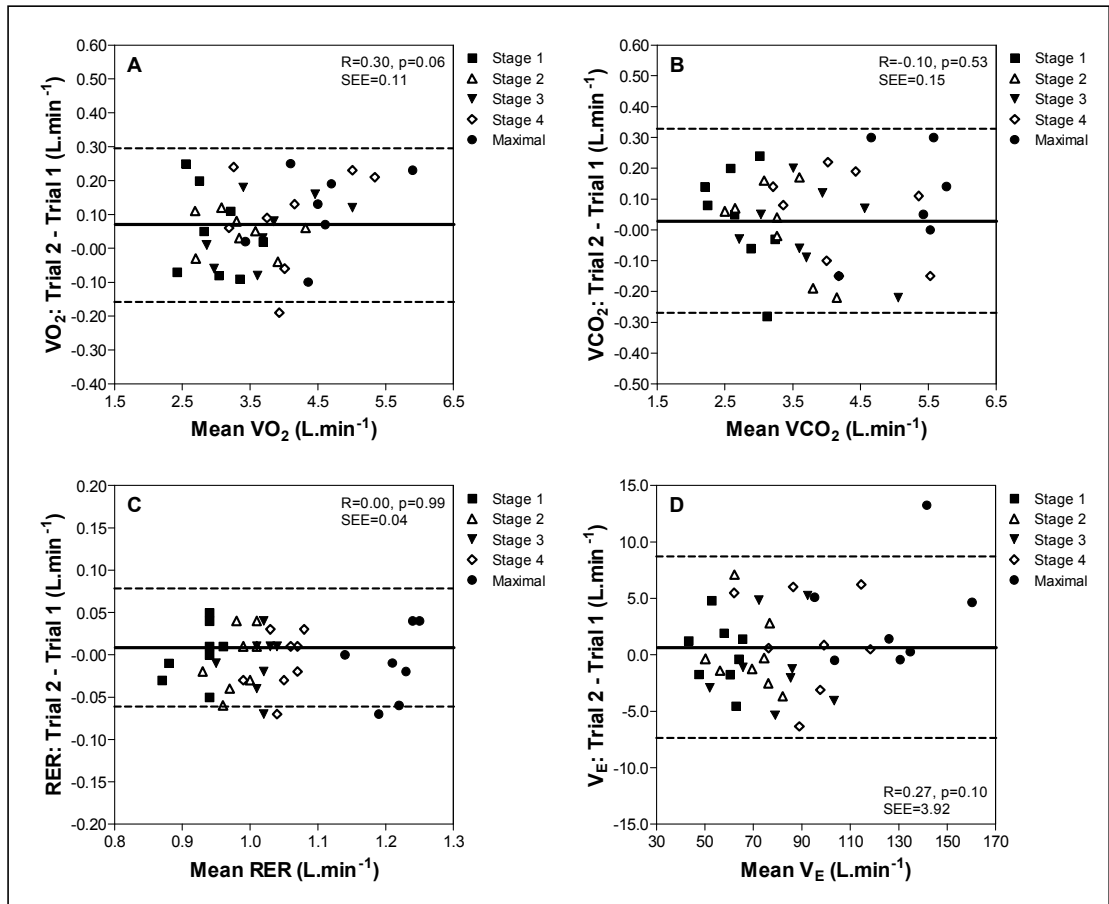


Figure 4-2: Bland-Altman plots of individual errors from duplicate MM3B trials (Trial 2 - Trial 1) during each workload of the incremental rowing test for oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER) and ventilation ($\dot{V}E$). *Solid lines* represent mean bias (pooled across all workloads); *dashed lines* represent 95% limits of agreement.

Table 4-4: Differences between metabolic measurements from the criterion MOUSE system and mean results from the two MM3B trials during each stage of the incremental rowing tests (MM3B - MOUSE).

Measure	Δ	Mean (90% CI)				
		Stage 1	Stage 2	Stage 3	Stage 4	Maximum
$\dot{V}O_2$ (L.min ⁻¹)	Absolute	0.10 (0.02-0.18)	0.12* (0.06-0.18)	0.13 (-0.01-0.27)	0.16 (0.02-0.30)	0.13 (0.02-0.24)
	%	3.5 (0.7-6.3)	3.7 (1.8-5.6)	3.6 (-0.3-7.5)	4.1 (0.5-7.7)	2.8 (0.5-5.1)
Main effect: $F_{1,7} = 7.44, p = 0.03^a$					$p = 0.12^b$	
$\dot{V}CO_2$ (L.min ⁻¹)	Absolute	0.18* (0.09-0.27)	0.24† (0.19-0.28)	0.26* (0.12-0.39)	0.31* (0.19-0.43)	0.32 (0.09-0.55)
	%	7.1 (3.7-10.5)	7.7 (6.3-9.1)	7.4 (3.6-11.2)	7.7 (4.7-10.7)	6.1 (1.7-10.5)
Main effect: $F_{1,7} = 55.6, p < 0.001^a$					$p = 0.01^b$	
RER	Absolute	0.03 (0.00-0.06)	0.04 (0.01-0.07)	0.04* (0.02-0.06)	0.03 (0.01-0.05)	0.04 (-0.01-0.09)
	%	3.7 (0.0-7.4)	3.9 (1.5-6.3)	3.7 (1.6-5.8)	3.4 (1.1-5.7)	3.5 (-0.6-7.6)
Main effect: $F_{1,7} = 10.70, p = 0.01^a$					$p = 0.02^b$	
$\dot{V}E$ (L.min ⁻¹)	Absolute	2.34 (-1.90-5.68)	3.22 (-0.18-6.62)	1.95 (-1.49-5.39)	3.22 (-0.30-6.74)	0.59 (-4.77-5.95)
	%	4.3 (-3.5-12.1)	4.9 (-0.3-10.1)	2.5 (-1.9-6.9)	3.6 (-0.3-7.5)	0.5 (-3.7-4.7)
Main effect: $F_{1,7} = 2.29, p = 0.17^a$					$p = 0.37^b$	

$\dot{V}O_2$ = oxygen consumption; $\dot{V}CO_2$ = carbon dioxide production; RER = respiratory exchange ratio; $\dot{V}E$ = ventilation; Absolute = error of MM3B measurements in raw units (MM3B-MOUSE); % = error of MM3B measurements expressed as a percentage of the MOUSE result (MM3B-MOUSE); ^a = result of repeated measure 2 x 4 factorial ANOVA for submaximal data; ^b = result of dependent *t*-test for maximal data; * = post-hoc statistically significant difference (Holm-Bonferoni adjusted alpha level; $p \leq 0.01$); † = post-hoc statistically significant difference (Holm-Bonferoni adjusted alpha level; $p \leq 0.001$).

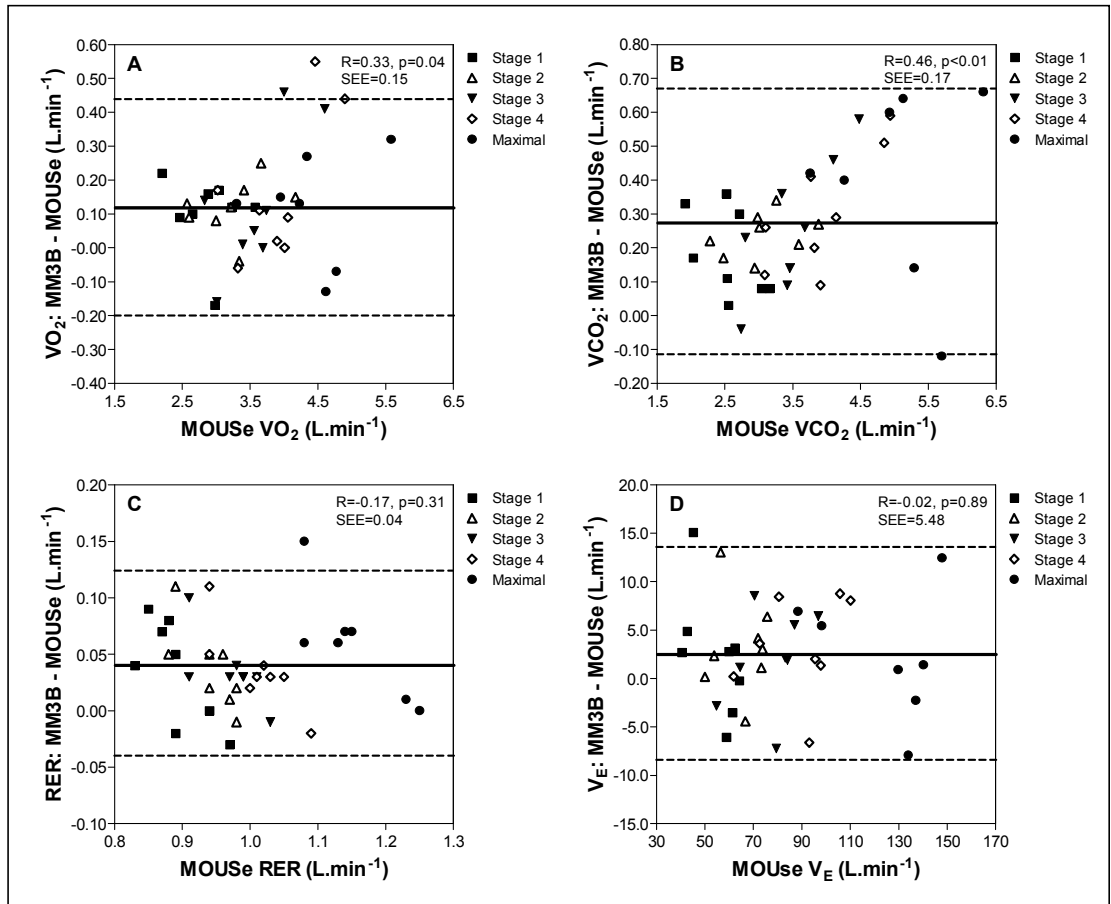


Figure 4-3: Bland-Altman plots of individual errors (MM3B - MOUSe) from each of the workloads during the incremental rowing test for oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), respiratory exchange ratio (RER) and ventilation ($\dot{V}E$). *Solid lines* represent mean bias (pooled across all workloads); *dashed lines* represent 95% limits of agreement.

4.4 DISCUSSION

In the current study, the MM3B overestimated $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ by ~4%, 7% and 4%, respectively, compared with the criterion of an automated Douglas bag system, and therefore displayed similar accuracy to other current designs of portable metabolic systems. While our accuracy and reliability evaluations using biological trials would ideally have involved simultaneous measurements from the MM3B and our criterion MOUSE system, previous investigations that have attempted this approach have often reported that interference between the two test systems has resulted in spurious measurements (Duffield *et al.* 2004; Crouter *et al.* 2006). We therefore conducted biological testing using separate trials that were closely matched for power output, and included duplicate comparisons using a metabolic calibrator to eliminate the between-day biological variation that is inherent to human subjects. In combination with error from technical sources, between-day biological variation has previously been estimated to be 3-4% for $\dot{V}O_2$ (Stuart *et al.* 1981; Armstrong and Costill 1985; Vogler *et al.* 2007) and $\dot{V}E$ (Armstrong and Costill 1985). While there is also some known uncertainty regarding the precision of individual simulations with the metabolic calibrator, deviations from the target values were estimated to be smaller ($\dot{V}E$), or at the lower end of the range estimated for between-day variations ($\dot{V}O_2$). So although the metabolic calibrator removes the potential for between-trial and between-system differences due to biological variation, both our evaluation methods leave some uncertainty regarding the degree to which the observed differences can be attributed to technical error from the MM3B alone. There was also potential for differences to result from true between-trial variations in workload; but these are likely to be minimal as subjects' were able to reproduce their efforts to within 1W during submaximal workloads and 4 W during the maximal performance trials.

4.4.1 Reliability of repeated MM3B measurements

One of the main findings of this study is that the MM3B provides reliable measurements for $\dot{V}O_2$, $\dot{V}CO_2$, RER and $\dot{V}E$. The TE results displayed in Table 4-3 for the MM3B are superior to those reported in the methods section for the criterion MOUSE system. While the confidence limits were rather broad given our small sample size ($n=8$), between-trial effects still displayed strong likelihoods for

trivial differences for almost every comparison when MOUSe reliability characteristics were the reference for SWC. So although there is some uncertainty as to whether TE results from the MM3B are actually superior to the MOUSe, our ‘trivial-difference’ findings indicate that the reliability of the MM3B is comparable to that of the automated Douglas bag system that has been in use at the AIS for over 10 years. Additionally, mean between-trial differences from our evaluation using simulated metabolic outputs were in close agreement with those from biological testing when expressed as percent error, which also confirms the reproducibility of MM3B measurements. While we have reported TE as our main indication of reliability, other investigations have reported technical error of measurement (Duffield *et al.* 2004), coefficient of variation (Crouter *et al.* 2006), intra-class correlation coefficient (Kawakami *et al.* 1992; Meyer *et al.* 2001; Duffield *et al.* 2004) or mean bias \pm 95% limits of agreement (Meyer *et al.* 2001; Duffield *et al.* 2004). On this latter basis, it is possible to compare our results for the MM3B portable system with the Cosmed K4b² (Duffield *et al.* 2004), Medical Graphics VO2000 (Crouter *et al.* 2006) and MetaMax I (Meyer *et al.* 2001). Mean bias \pm 95% limits of agreement have been reported for the K4b² during repeated treadmill running tests, between-trial differences were 0.08 ± 0.82 L.min⁻¹ ($\dot{V}O_2$), 0.06 ± 0.67 L.min⁻¹ ($\dot{V}CO_2$) and 1.27 ± 16.3 L.min⁻¹ (VE; Duffield *et al.* 2004). Reliability results for the same variables measured by the VO2000 system were 0.04 ± 0.37 L.min⁻¹, 0.04 ± 0.38 L.min⁻¹ and 1.22 ± 11.05 L.min⁻¹ (Crouter *et al.* 2006). Mean differences were similar for the MM3B (0.07, 0.03 and 0.74 L.min⁻¹ for $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$, respectively), although 95% confidence limits were tighter during our evaluation (0.23, 0.30 and 8.12 L.min⁻¹, respectively). Our results are also very similar to those reported for the earlier MetaMax I model also manufactured by Cortex. In this instance, Meyer *et al.* (2001) reports that 95% limits of agreement for between-trial differences are within 0.30 L.min⁻¹ for $\dot{V}O_2$ and $\dot{V}CO_2$, and 9 L.min⁻¹ for $\dot{V}E$, which compares to 0.33 L.min⁻¹ ($\dot{V}O_2$ and $\dot{V}CO_2$) and 8.86 L.min⁻¹ ($\dot{V}E$) in the current study. The MM3B therefore displays good reliability compared with other portable metabolic systems.

4.4.2 Accuracy of the MM3B compared with an automated Douglas bag system (MOUSe)

Comparisons between measurements from the MM3B and predicted metabolic

outputs from the metabolic calibrator show that $\dot{V}E$ measurements were within 4% of the target value across the physiological range, although $\dot{V}O_2$ and $\dot{V}CO_2$ were more variable with differences ranging -3% to 8% and -1% to 10%, respectively. While values within 4% of the target may be considered acceptable given some uncertainty regarding the true value of metabolic simulations, some $\dot{V}O_2$ and $\dot{V}CO_2$ measurements were clearly outside this range. It is interesting to note that the observed errors in gas fractions and $\dot{V}E$ do not necessarily affect $\dot{V}O_2$ and $\dot{V}CO_2$ as may be expected according to estimations provided by Withers *et al.* (2000), where 0.10% and 1% errors in gas fractions and $\dot{V}E$ result in 3% and 1% errors for $\dot{V}O_2$ and $\dot{V}CO_2$, respectively. However, as the largest discrepancies between gas fraction values occurred for simulations of the outer physiological range for O_2 extraction and CO_2 excretion (metabolic calibrator setting 1; Table 4-2), the accuracy of MM3B gas fraction measurements may have been impaired as these gas concentrations were at the limit of the range used during calibration of the MM3B's gas analysers (16.05% O_2 and 4.99% CO_2). Despite this, $\dot{V}O_2$ measurements were within 4% of target values for three of the five evaluated metabolic outputs, although $\dot{V}CO_2$ results fell within this range for only two of the simulations. As a result of these variations, RER values also differed from the 1.00 target. The substantial changes in $\dot{V}O_2$ from 3% under to 8% over the target values more likely reflects changes consequent to re-calibration of the MM3B, rather than true fluctuations in the metabolic calibrator. The magnitude of such variations reinforces the critical importance of careful and consistent MM3B calibration and the need to check the gas analysers for drift immediately after testing.

While the accuracy of the MM3B seemed impaired when sampling gas fractions from the outer physiological range during metabolic simulations, accuracy results compared with the MOUSe were relatively consistent across the workloads tested during biological trials (Table 4-4). Although F_{EO_2} and F_{ECO_2} were not considered during biological testing because $\dot{V}O_2$ and $\dot{V}CO_2$ results were of more practical interest, the consistency of $\dot{V}O_2$ and $\dot{V}CO_2$ errors under these circumstances (approximately 3-4% and 6-8%, respectively) suggests that changes in F_{EO_2} and F_{ECO_2} across increasing workloads had less impact during biological testing. Excepting the trend for larger $\dot{V}O_2$ and $\dot{V}CO_2$ errors from outer-limit O_2 and CO_2

expired gas fractions during simulated testing, biological trials and metabolic simulations both confirmed that the MM3B measures higher values for $\dot{V}E$, $\dot{V}O_2$, $\dot{V}CO_2$ and RER compared to both our criterion indirect calorimetry systems. During biological testing, $\dot{V}O_2$ was significantly higher during Stage 2, as was RER during Stage 3 and the maximal performance trial; $\dot{V}CO_2$ was significantly higher during all workloads. However, effect size analyses indicated that the between-system differences in submaximal $\dot{V}O_2$ were greater than those anticipated from normal between-day variation as estimated by the reliability of the MOUSE system, and were therefore likely to result from error in MM3B measurements. RER and $\dot{V}CO_2$ were also substantially higher across the submaximal workloads and maximal performance trial. It therefore follows that data derived with a MM3B system are likely to be inaccurate compared with data from a carefully calibrated laboratory-based indirect calorimetry system, and this result is not too surprising given the challenges inherent in miniaturisation.

The differences observed in the present investigation are similar to those reported for other portable metabolic systems that have been validated against the Douglas bag method or another laboratory-based criterion system. McLaughlin *et al.* (2001) examined the accuracy of the Cosmed K4b² relative to Douglas bag measurements during duplicate submaximal cycle ergometer tests (50-200 W) and reported mean bias \pm 95% limits of agreement (estimated from a Bland-Altman plot) were 0.10 ± 0.23 L.min⁻¹ ($\dot{V}O_2$), 0.10 ± 0.34 L.min⁻¹ ($\dot{V}CO_2$) and 2.00 ± 7.50 L.min⁻¹ ($\dot{V}E$). Duffield *et al.* (2004) compared a Cosmed K4b² with a custom-designed metabolic cart and obtained considerably larger mean errors for $\dot{V}O_2$ and $\dot{V}CO_2$ with overestimations ranging 0.45-0.60 L.min⁻¹ (criterion values: 2.80-4.09 L.min⁻¹) and 0.32-0.57 L.min⁻¹ (criterion values: 2.38-4.59 L.min⁻¹). The accuracy of the Medical Graphics VO2000 system has also been validated against the Douglas bag for workloads between 50-250 W, for this device mean bias \pm 95% limits of agreement are -0.11 ± 0.43 L.min⁻¹, -0.06 ± 0.38 L.min⁻¹ and 1.54 ± 6.93 L.min⁻¹ for $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$, respectively (Crouter *et al.* 2006). Thus, the accuracy of our MM3B $\dot{V}O_2$ measurements are similar to those from the VO2000 (Crouter *et al.* 2006) and the K4b² evaluation by McLaughlin *et al.* (2001). However, our mean error for $\dot{V}CO_2$ (0.27 L.min⁻¹) was higher compared to these evaluations, although the

corresponding 95% confidence limits ($\pm 0.39 \text{ L}\cdot\text{min}^{-1}$) were similar (Crouter *et al.* 2001; McLaughlin *et al.* 2001), thereby showing that errors were at least equally as consistent. The magnitude of the $\dot{V}\text{CO}_2$ errors for the MM3B are in contrast to those from the Cortex MetaMax II model, where mean bias and 95% limits of agreement compared to Douglas bag results were $-0.08 \pm 0.33 \text{ L}\cdot\text{min}^{-1}$ (Larsson *et al.* 2004). Indeed, $\dot{V}\text{O}_2$ ($0.04 \pm 0.22 \text{ L}\cdot\text{min}^{-1}$) and $\dot{V}\text{E}$ ($1.90 \pm 5.90 \text{ L}\cdot\text{min}^{-1}$) measurements were also more accurate for the MetaMax II, although measurements for both systems were successfully conducted simultaneously, which will eliminate biological sources of variation compared to evaluations conducted on separate days. Mean error results for MM3B $\dot{V}\text{E}$ measurements were also similar to the other portable devices although confidence limits ($\pm 10.95 \text{ L}\cdot\text{min}^{-1}$) were higher. This may be partially explained by our protocol, which included maximal intensity exercise, and by the mode of exercise, given that rowing stroke can impact on $\dot{V}\text{E}$ (Steinacker *et al.* 1993a).

Given the complexity of the movement patterns during the rowing stroke, the study also considered the practical suitability of the MM3B for rowing applications. While the connections between the base module and volume turbine assembly had the potential to interfere with the rower's hand movements during the stroke cycle when the MM3B was worn in the standard configuration with the system harnessed to the chest, the problem was easily overcome when the harness was reversed so the MM3B was worn on the back. The only drawback to this approach was that the connections between the volume turbine assembly and base module limited head movement in one direction, which could potentially limit vision during on-water rowing as athletes sometimes need to turn their head both ways in order to check their course. Despite this, all subjects reported that the reverse-harness set-up did not interfere with their rowing technique and that they would be confident to use the system during on-water rowing. However, any capsizing on-water would have disastrous consequences for the electronics of the MM3B.

4.5 CONCLUSIONS

Overall, the MM3B overestimated $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ by approximately 4%, 7% and 4%, respectively, compared with the criterion of an automated Douglas bag system, although duplicate trials of the MM3B on an metabolic calibrator varied by $\sim\pm 5\%$. These results suggest that MM3B measurements are not perfectly comparable with our criterion system but, on average, the portable metabolic system provided a satisfactory indication ($\sim\pm 5\%$) of the actual metabolic demands of an activity and displayed a similar degree of accuracy to other current designs of portable metabolic system. On the other hand, the MM3B yielded excellent reproducibility, with TE results of 2-3% for $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$. Furthermore, as the current TE results are similar to those previously determined for our automatic Douglas bag system, both systems could conceivably monitor longitudinal aerobic fitness changes equally well. Assuming these laboratory-based results translate directly to the field environment, the MM3B has potential as a useful field testing device for rowing and other sport-specific applications.

CHAPTER 5

COMPARISON OF ERGOMETER AND ON-WATER INCREMENTAL ROWING TESTS

5.1 INTRODUCTION

Laboratory-based ergometer testing has been used extensively by the rowing community to measure training related changes in fitness traits and prescribe submaximal training intensities that can be applied to training on and off the water. Specifically, sport scientists use blood lactate (BLa)-power output and heart rate (HR)-BLa relationships obtained from laboratory testing so that the HR corresponding to the blood lactate threshold can be used to prescribe individualised on-water training intensities (Urhausen *et al.* 1993b). In recent years, it appears that the intended transfer of data from laboratory-based tests to the field environment has not been used by many coaches because the relevance and specificity of the ergometer based testing has been challenged with regard to on-water rowing (unpublished personal observation).

A variety of methods have previously been used to evaluate the specificity of ergometer rowing with respect to the criterion of on-water performance. Kinematic analyses suggest that movement patterns differ between the two modes of rowing (Martindale and Robertson 1984; Lamb 1989) and that the interaction between the rower's body mass and the rowing device (either ergometer or boat shell) contributes to this (Martindale and Robertson 1984). Similarly, investigations addressing rowing mechanics suggest that stroke timing and consistency also differ (Smith *et al.* 1993; Dawson *et al.* 1998; Elliott *et al.* 2002). While these studies have investigated isolated aspects of the rowing stroke, comparisons have also been made according to performance outcomes. Spearman rank order correlations between 2000-m rowing performance during ergometer time-trials and competitive rowing are strong and suggest an association between factors contributing to time-trial performance under either condition (Ryan-Tanner *et al.* 1999a). Thus, the conclusions from these studies

have been equivocal, either supporting that ergometer and on-water rowing are equivalent (Martindale and Robertson 1984; Lamb 1989; Ryan-Tanner *et al.* 1999a), or that the differences are substantial (Smith *et al.* 1993; Dawson *et al.* 1998; Elliott *et al.* 2002). Physiological differences are also apparent when on-water and ergometer rowing are compared. Payne *et al.* (1996) concluded that differences in physiological responses between the two modalities may be the result of biomechanical variations between the two conditions. Of the variables considered in the literature, HR and BL_a have been most commonly addressed. HR is generally reported to be higher on-water (Urhausen *et al.* 1993b; Ryan-Tanner *et al.* 1999b), although Steinacker *et al.* (1987) suggested that ergometer performance elicits a higher HR. Conversely, maximal BL_a is higher during ergometer rowing (Urhausen *et al.* 1993b; Ryan-Tanner *et al.* 1999b), possibly by as much as 35% (Ryan-Tanner *et al.* 1999b). Other measured variables include catecholamines (Urhausen *et al.* 1993b), which are higher during ergometer performance, and maximal oxygen consumption ($\dot{V}O_{2\max}$), which was within 3% between ergometer and on-water tests (Chènier and Leger 1991). Given the potential for biomechanical differences between the two performance scenarios and the resulting variations in physiological responses, ergometer-based rowing tests may not be adequately representative of on-water rowing to accurately prescribe on-water training intensities. Thus, formalised on-water tests may improve the specificity of physiological assessments for rowing and improve the association between test results and the subsequent training recommendations.

While on-water rowing tests have been successfully conducted (Steinacker *et al.* 1987; Payne *et al.* 1996; Coen *et al.* 2003), the dynamic nature of environmental conditions means that accurate and reliable testing on-water is difficult when attempting to standardise workloads within and between sessions (Steinacker *et al.* 1987; Coen *et al.* 2003). Factors such as wind direction and velocity can potentially change during an effort and have a substantial impact on boat velocity. So, although rowing velocity is a key determinant of on-water performance, environmental influences mean it is virtually unusable as an independent variable for monitoring the responses to a given training workload. Also, substantial variation in stroke rate (SR; Smith *et al.* 1993) and HR (Urhausen *et al.* 1993b) between field and laboratory conditions limits the effectiveness of these parameters as independent variables for prescribing intensity during on-water work. The best independent measure of work is

therefore the power output exerted by the rower to propel the boat in a forward direction. In Australia, a commercially available rowing biomechanics system (WEBA Sport Rower Expert Light; Wien, Austria) is sometimes used to provide routine feedback to coaches and athletes regarding biomechanical parameters that are known to influence rowing performance. As the WEBA Sport system (WEBA; Plate 5-1) allows rowing power output to be measured, it is ideal to monitor workloads during routine training or on-water testing. Furthermore, oxygen consumption ($\dot{V}O_2$) data from a portable indirect calorimetry system (Cortex MetaMax 3B; MM3B, Leipzig, Germany) allows assessments of metabolic load to accompany power measurements, thereby providing further information about the reproducibility of on-water workloads and the relationship between on-water and ergometer assessments.

The availability of new technology which has already been shown to be reliable (in the case of the MM3B; Chapter 4) that can be directly applied to rowing means that measurements that were previously only available in the laboratory are now possible in the field, thereby allowing a standardised test protocol to be replicated on-water. Thus, the aims of the current investigation were: a) to evaluate the feasibility of an on-water rowing protocol based upon a standardised ergometer test; b) compare the physiological responses between on-water and ergometer tests in order to determine the validity of ergometer-based physiological assessments; and c) to establish the reliability of measures obtained in the field compared with the laboratory.

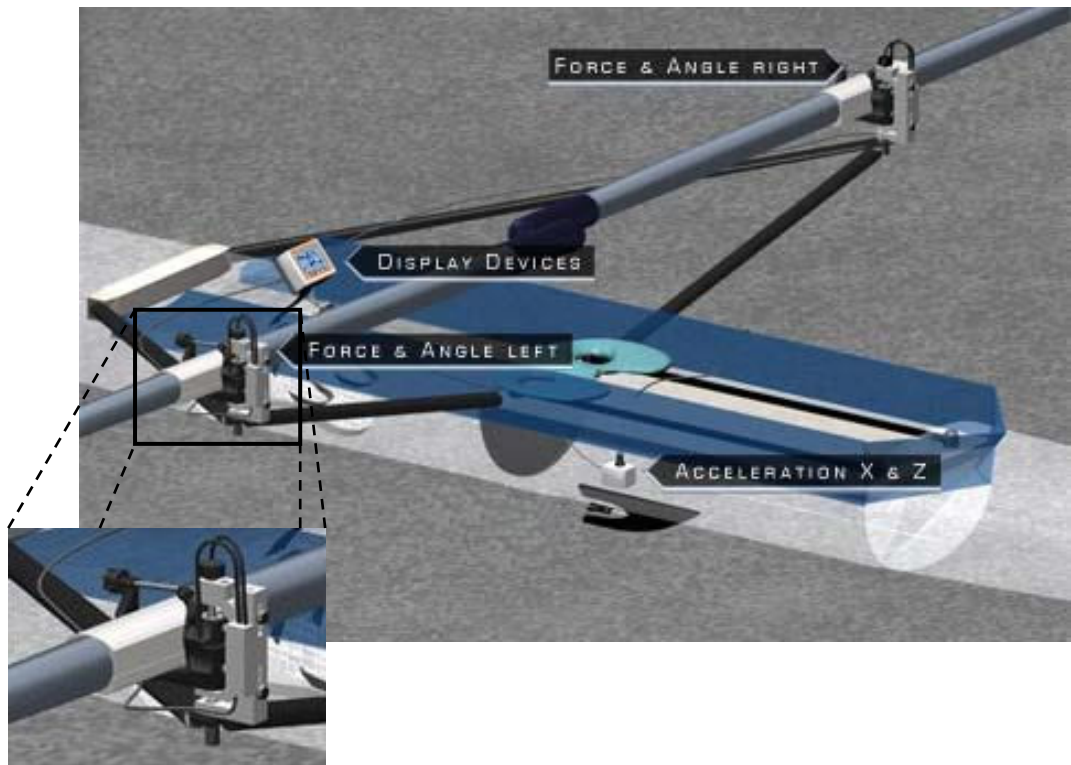


Plate 5-1: The WEBA Sport biomechanics system, including a close-up of the instrumented oarlock used to measure handle force and oar angle (inset). *Adapted from www.weba-sport.com/weba/rowx_outdoor.*

5.2 METHODS

5.2.1 Subjects

Seven male heavyweight rowers provided written informed consent to participate in this investigation; all athletes were competing at a national level in the Under 23 or Open categories. The subjects' physical characteristics are described in Table 5-1. All biological testing procedures were approved by the AIS Human Ethics Committee and the Flinders University Clinical Research Ethics Committee.

5.2.2 Experimental protocol

Each rower completed four sessions (2 x laboratory and 2 x on-water) during a 5-d rowing camp. The two laboratory sessions were conducted at the AIS Physiology Laboratory while the two on-water sessions were undertaken on Lake Burley Griffin (Canberra, Australia), which is a still-water lake that features a buoyed 1800-m rowing course. Plate 5-2 displays a rower during an on-water testing session. As data were collected during two separate camps, data sets from both occasions have been included in the analyses for one subject who attended both camps, thereby increasing the total number of experimental observations to $n=8$. Testing was conducted under fair weather conditions during late autumn and early spring; mean (SD) temperatures were 20.1 (1.3) °C and 16.4 (4.6) °C during the laboratory and on-water sessions, respectively.

Two laboratory tests completed on a Concept 2D ergometer (ERG) were conducted to permit $\dot{V}O_2$ measurements with both the standard laboratory metabolic cart (MOUSE; AIS, Canberra, Australia; Vogler *et al.* 2007) and the MetaMax portable metabolic system (MM3B) described previously (Chapter 4). The MM3B was also used for duplicate on-water tests (OW). The order of the ERG trials was counterbalanced so that half the participants completed their first trial using the MOUSE for $\dot{V}O_2$ measurements, and half using the MM3B. But as an ERG test needed to be completed first in order to determine specific workloads for the subsequent OW tests, this aspect of the experimental protocol was not counterbalanced.

Table 5-1: Physical characteristics of the subjects ($n=7$).

Measure	Mean (SD)	Range
Age (yr)	20.4 (2.0)	18.3-25.0
Height (m)	1.94 (0.02)	1.90-1.97
Mass (kg)	91.4 (4.5)	84.9-99.0
$\dot{V}O_{2\text{ peak}}$ (L.min ⁻¹)	5.40 (0.17)	5.11-5.70
Maximal power (W)	419 (17)	397-446

$\dot{V}O_{2\text{ peak}}$ = peak oxygen consumption measured by the laboratory metabolic cart during the 4-min maximum performance trial on the ergometer; Maximal power (W) = average power output during the 4-min maximum performance trial on the ergometer.



Plate 5-2: A rower undertaking an on-water test on the Lake Burley Griffin rowing course.

Laboratory test protocol

The laboratory step-test protocol was an abbreviated version of the standard 7-stage protocol currently used for testing Australian rowers. Subjects presented to the laboratory well rested and having refrained from intense exercise for the previous 24h. Upon arrival, subjects weighed-in wearing a rowing suit only and were fitted with a Polar HR monitor (Polar S810i, Kempele, Finland). Prior to the test, a resting BLa measurement (Lactate Pro, Arkray, Japan) was obtained from a capillary blood sample drawn from an earlobe. The incremental exercise protocol consisted of five submaximal workloads and one maximal effort on a Concept2 Model D rowing ergometer (Concept2, Morrisville, USA); each workload was 4-min in duration. As all rowers were heavyweight males, the Concept2 drag factor was standardised at 130. Submaximal workloads were controlled by target power outputs and increased 35 W each stage from 140 W to 280 W. Recovery periods were provided between workloads and were extended from the standard 1-min interval to 2-min intervals in order to match the time required during the OW protocol to collect bloods and manoeuvre the rower's boat. At the completion of the fifth workload a 5-min recovery was provided before the final 4-min maximal stage. $\dot{V}O_2$ (MOUSE or MM3B) and HR were monitored throughout each test. For all tests, mean $\dot{V}O_2$ results were recorded from steady-state conditions achieved during the final 2-min of each ERG and OW workload. BLa was sampled at the completion of each submaximal stage, immediately following the maximal stage and 4-min after the finish of the maximal stage. Average SR, average power output and distance completed were also obtained from the ergometer monitor unit during the 2-min recovery period. A rating of perceived exertion (RPE, Borg 15-point scale; Borg 1973) for the previous workload was also ascertained at this time.

On-water test protocol

The on-water rowing step test protocol was designed to replicate the laboratory protocol as closely as possible and therefore also comprised 5 x 4-min submaximal stages and 1 x 4-min maximal performance trial. Prior to testing, a single scull (Sykes Racing, Geelong, Australia) was instrumented with a WEBA rowing biomechanics system to determine the power output achieved during each incremental stage of the OW protocol. The WEBA system was installed in accordance with the set-up shown in Plate 5-1 (p. 97). Force sensors were calibrated by the manufacturer, while the gate angle sensors were calibrated at known points

throughout the expected range of a rowing stroke prior to each test. As rowing power output could not be displayed in 'real-time', SR and RPE were used to control the workload progression. Rowers were therefore instructed to increase SR by 2 strokes·min⁻¹ each stage across a range of 14-24 strokes·min⁻¹; additionally, a RPE intensity was also prescribed for each stage that corresponded to the value obtained for the equivalent stage during the ERG laboratory test. Average SR and distance covered were obtained using a MiniMaxX (Catapult Innovations, Scoresby, Australia) GPS/accelerometer data acquisition system. Workloads were separated by 2-min recovery periods, during which a BLa sample was obtained from the finger-tip (which was more readily accessible compared with the earlobe) and the rower turned the boat 180° in readiness for the start of the next stage. $\dot{V}O_2$ was measured continuously by the MM3B throughout the protocol; the MM3B also logged HR data from the Polar HR monitor. RPE for the previous increment was also obtained during the 2-min recovery to determine whether the target value was achieved. Similar to the laboratory test, rowers were provided with a 5-min recovery prior to the 4-min maximal stage and were instructed to row as far as possible, and to ensure they provided a maximal effort for the entire duration.

As one ERG trial used the MM3B for $\dot{V}O_2$ assessments, the $\dot{V}O_2$ data from this trial were compared directly with the MM3B results measured during the OW test; comparisons between ERG and OW tests therefore *always* used data from the ERG trial conducted with the MM3B. Thus, when ERG Trial 1 used the MM3B, between-location comparisons paired all data from this trial with OW Trial 1; similarly, when ERG Trial 2 used the MM3B, ERG data were paired with OW Trial 2.

Blood lactate thresholds

Automated software (ADAPT; AIS, Canberra, Australia) determined lactate thresholds from the BLa-power output relationship established during the ERG and OW tests using third order polynomial regression. Lactate threshold 1 (LT₁; aerobic threshold) was defined as the point at which BLa began to increase (0.2 mmol.L⁻¹) above resting levels. An increase of 0.2 mmol.L⁻¹ was used as this corresponds to the typical error (TE) of BLa measurements in the range of 1.0-2.0 mmol.L⁻¹, which is based on a TE of 14.3% for submaximal BLa measurements (Table 3-4, p. 59) and the typical range of BLa at LT₁ (Table 3-3, p. 57). Lactate threshold 2 (LT₂; anaerobic threshold, AT) was defined as the point on the polynomial regression

curve that yielded the maximum perpendicular distance to the straight line formed by joining LT₁ and peak BL_a (modified D_{max}; Bishop *et al.* 1998). HR, power output and $\dot{V}O_2$ at LT₁ and LT₂ were subsequently determined using ADAPT.

5.2.3 Data treatment

The mean power outputs during each stage of the ERG and OW tests were not identical (Figure 5-1) because the OW submaximal workloads were controlled by the athlete attempting to match target SR and RPE values. Consequently, the resulting OW power outputs were different from the fixed target power outputs of the ERG test, and hence, the submaximal response variables (e.g. BL_a, HR and $\dot{V}O_2$; Figure 5-2) could not be directly compared between each stage of the ERG and OW tests. However, as each of the response variables were strongly related to power output during the ERG and OW tests (Table 5-2), regression analyses were used to normalise the data so that comparisons between each stage of the ERG and OW tests both used similar power outputs. The normalised power outputs were selected to correspond to the target power outputs of the ERG tests: 140, 175, 210, 245 and 280 W; these five power outputs were designated as ‘standard power outputs’. Relationships between power output and selected physiological variables (i.e. HR, BL_a) were established for each of the rowers based on individual submaximal results, and regression analyses used to calculate values for each of the measured variables at intensities corresponding to the five standard power outputs. This normalisation procedure was applied to the submaximal data from *both* the ERG and OW tests, in order to compare the effect of test modality at power outputs that were assumed to be equivalent. The procedure was also used for both OW trials so that the between-OW trial reproducibility could be determined for each of the response variables based on equivalent power outputs.

Given the potential for differences between power output measurements from the Concept2 ergometer and the WEBA, the assumption of equivalent power output measurements from these two devices – which is central to the power normalisation treatment - was also assessed. Concept2 and WEBA power outputs were therefore normalised using the power output- $\dot{V}O_2$ relationship established from group results using raw submaximal data, thereby allowing power outputs to be compared between devices at equivalent $\dot{V}O_2$ intensities. Thus, linear regression was used to calculate

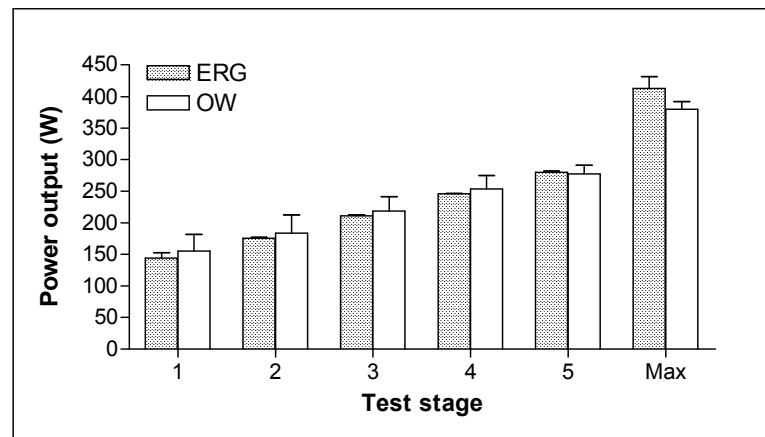


Figure 5-1: Mean power output during submaximal and maximal workloads for the ergometer (ERG) and on-water (OW) incremental tests. *Error bars denote ± 1 SD.*

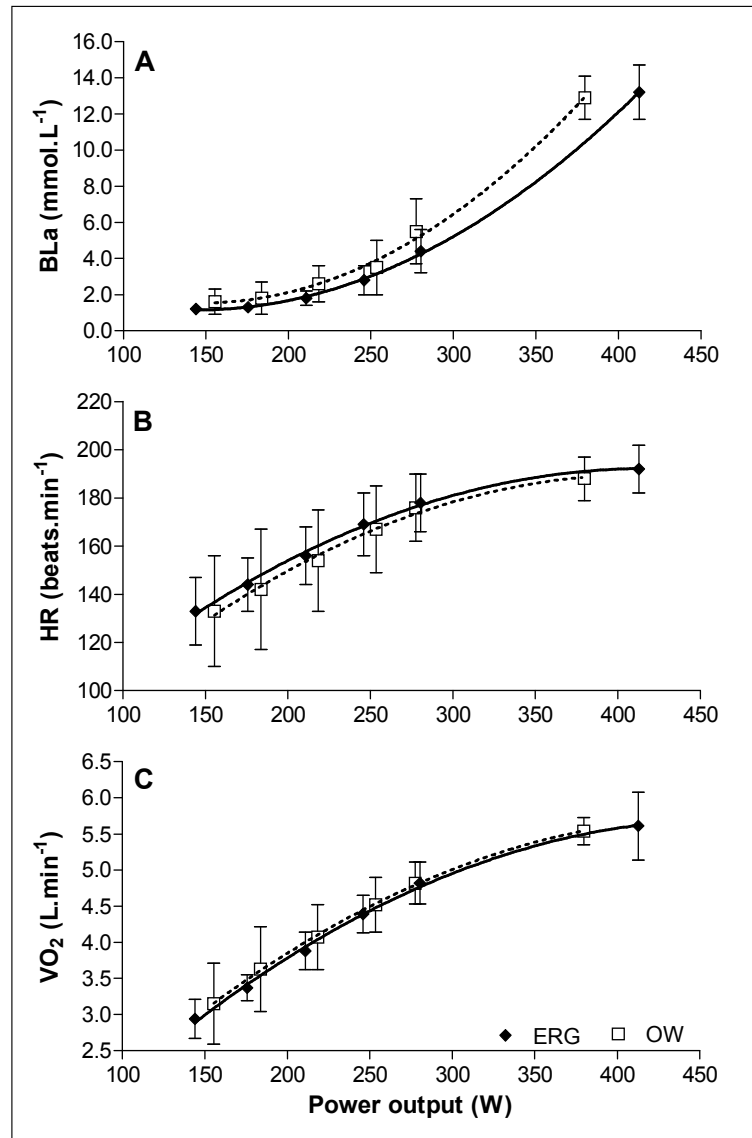


Figure 5-2: Mean results for A) blood lactate (BLa), B) heart rate (HR) and C) oxygen consumption ($\dot{V}\text{O}_2$) using untreated data that does not account for the differences in submaximal workloads between ergometer (ERG) and on-water (OW) incremental rowing tests. *Error bars denote ± 1 SD.*

Table 5-2: Regression analyses between measured variables and power output during ergometer (ERG) and on-water (OW) incremental rowing tests using pooled results from all subjects. ‘Raw’ data analyses illustrate the strength of the response variable-power output relationships under both conditions, while the ‘power normalised’ data shows the relationships established from the standard power outputs.

Data	Variable	Model	Test (power output)			
			ERG		OW	
			R	SEE	R	SEE
Raw (submaximal & maximal intensities)	HR (beats.min ⁻¹)	2 nd order polynomial	0.88*	11.1	0.89*	12.4
	BLa (mmol.L ⁻¹)	3 rd order polynomial	0.98*	0.8	0.97*	1.0
	$\dot{V}O_2$ (L.min ⁻¹)	2 nd order polynomial	0.96*	0.28	0.96*	0.24
	Distance (m)	Linear	0.99*	14.3	0.95*	32.4
	SR (strokes.min ⁻¹)	2 nd order polynomial	0.96*	1.8	0.96*	1.4
	Power normalised (submaximal intensity)	HR (beats.min ⁻¹)	Linear	0.84*	11.0	0.78*
BLa (mmol.L ⁻¹)		3 rd order polynomial	0.89*	0.6	0.85*	0.9
$\dot{V}O_2$ (L.min ⁻¹)		Linear	0.96*	0.21	0.94*	0.24
Distance (m)		Linear	0.99*	1.2	0.95*	22.9
SR (strokes.min ⁻¹)		Linear	0.93*	1.2	0.82*	1.6

R = Pearson correlation coefficient; * = statistically significant correlation ($p < 0.0001$); SEE = standard error of estimate; HR = heart rate; BLa = blood lactate concentration; $\dot{V}O_2$ = oxygen consumption measured by the MM3B; Distance = distance covered during each 4 min stage; SR = stroke rate.

Concept2 and WEBA power outputs corresponding to five $\dot{V}O_2$ intensities that evenly spanned the observed submaximal range: 2.75, 3.25, 3.75, 4.25 and 4.75 L.min⁻¹. While HR and BLA were also measured during both tests and could therefore have been used as the basis of our normalisation treatment, $\dot{V}O_2$ data were the least variable. As the calculation of Concept2 and WEBA power outputs at equivalent $\dot{V}O_2$ intensities was dependent on the reproducibility of the $\dot{V}O_2$ measurements, it was critical that between-test $\dot{V}O_2$ variation was minimal. Thus, $\dot{V}O_2$ measurements were obtained using the MM3B system under ERG and OW conditions, and our previous evaluation of the MM3B had shown that the measurements from this system were reliable; TE for submaximal $\dot{V}O_2$ = 2.3%, 90% confidence interval = 1.9-3.0%; Chapter 4.

5.2.4 Statistical analyses

To validate the laboratory test against the criterion of on-water performance, lactate thresholds and normalised physiological responses to the progressive incremental tests at the standard power outputs were compared according to test modality (ERG vs. OW). Additionally, between-trial results (Trial 1 vs. Trial 2) from the OW tests were examined to establish the reproducibility of duplicate OW measures. For both comparisons, submaximal data were analysed using 2 (test) x 5 (stage) factorial ANOVAs with repeated measures on both dimensions (SPSS 15.0 for Windows; SPSS, Chicago, Illinois, USA). Maximal data and lactate threshold results (ERG vs. OW comparison only) were compared using dependent *t*-tests. Statistical significance was established at $p < 0.05$ for all analyses. The effects of test modality and OW between-trial reproducibility were also analysed to determine the likelihood that the true value of the observed Cohen effect statistic was small (0.2), moderate (0.6) large (1.2), or very large (2.0; Hopkins 2003; Hopkins *et al.* 2009). Briefly, a clear effect size (ES) was established when the likelihood $\geq 75\%$ that the true value of the effect statistic was greater than one of the above thresholds (e.g. small or moderate). As the analysis also considers the likely direction of an effect (either positive or negative), an ES was unclear when the likelihood was $< 75\%$ for a positive ES and $> 5\%$ for a negative ES (Hopkins 2007; Hopkins *et al.* 2009), or vice-versa. Magnitude-based differences are reported as the largest likely effect size (ES) and associated percent probability (e.g. small, 85%). Furthermore, the reliability of repeated OW measurements was also determined using TE (Hopkins 2000a), and the

OW reliability results compared with the corresponding data from our previous reliability assessment of the laboratory-based protocol (Chapter 3). Reliability comparisons were based on the ratio between OW and ERG relative TE using the 90% confidence limits. When the ratio between OW and ERG TE confidence limits was <0.9 or >1.1 differences were considered to be substantial. A TE result would therefore be: greater than another if the ratios calculated from the upper and lower confidence intervals (CI ratios) were both >1.1 , or less than another if the CI ratios were both <0.9 ; a difference would be trivial if the CI ratios were within 0.9-1.1; and the difference would be unclear if the CI ratios overlapped 0.9 and 1.1 (Gore *et al.* 2005).

5.3 RESULTS

5.3.1 Comparison between test modalities (laboratory vs. on water)

Power output measurements

When Concept2 and WEBA power measurements were compared across the five reference submaximal $\dot{V}O_2$ intensities, the resulting power outputs ranged 139-268 W (Concept2) and 136-263 W (WEBA). Thus, power output measurements from both devices were within 1.8% during the submaximal portion of the ERG and OW tests. During maximal exercise, OW power output was 7.9% lower ($p=0.04$) than during the ERG test (Table 5-3).

Submaximal performance

Results from the data treatment procedure using the five standard power outputs are displayed in Figure 5-3 (left panel). The power normalised data showed strong correlations between both the ERG and OW testing modes for HR ($R=0.93$, $p<0.001$), BLa ($R=0.84$, $p<0.001$), $\dot{V}O_2$ ($R=0.91$, $p<0.001$) and distance completed ($R=0.95$, $p<0.001$). Despite OW trends for a lower HR (Figure 5-3A) and higher BLa (Figure 5-3B) and $\dot{V}O_2$ values (Figure 5-3C), relative to the ERG test, there were no statistically significant differences between test modalities, except for distance completed ($p<0.0001$, Figure 5-3D), where OW results were 170-200 m lower for all submaximal workloads compared with the ERG test. However, the magnitude of the between-modality differences as effect sizes were very large (100% probability) for distance completed, small (93%) for BLa, and trivial for $\dot{V}O_2$ (80%); HR was unclear (trivial effect, 71% probability). Furthermore, comparisons between individual results from the ERG and OW test showed that there was considerable variation in the magnitude, direction and slope of the between-test differences in physiological response, most notably for BLa (Figure 5-3B, right panel).

Maximal performance

Power output, HR, distance completed and SR were all significantly lower during the OW maximal stage compared with the ERG trial (Table 5-3). Magnitude-based differences were: very large effect size (100% probability) for distance, large (79%) for power output, moderate (80%) for SR and small (89%) for HR; results were unclear for BLa (small, 48%) and $\dot{V}O_2$ (trivial, 52%).

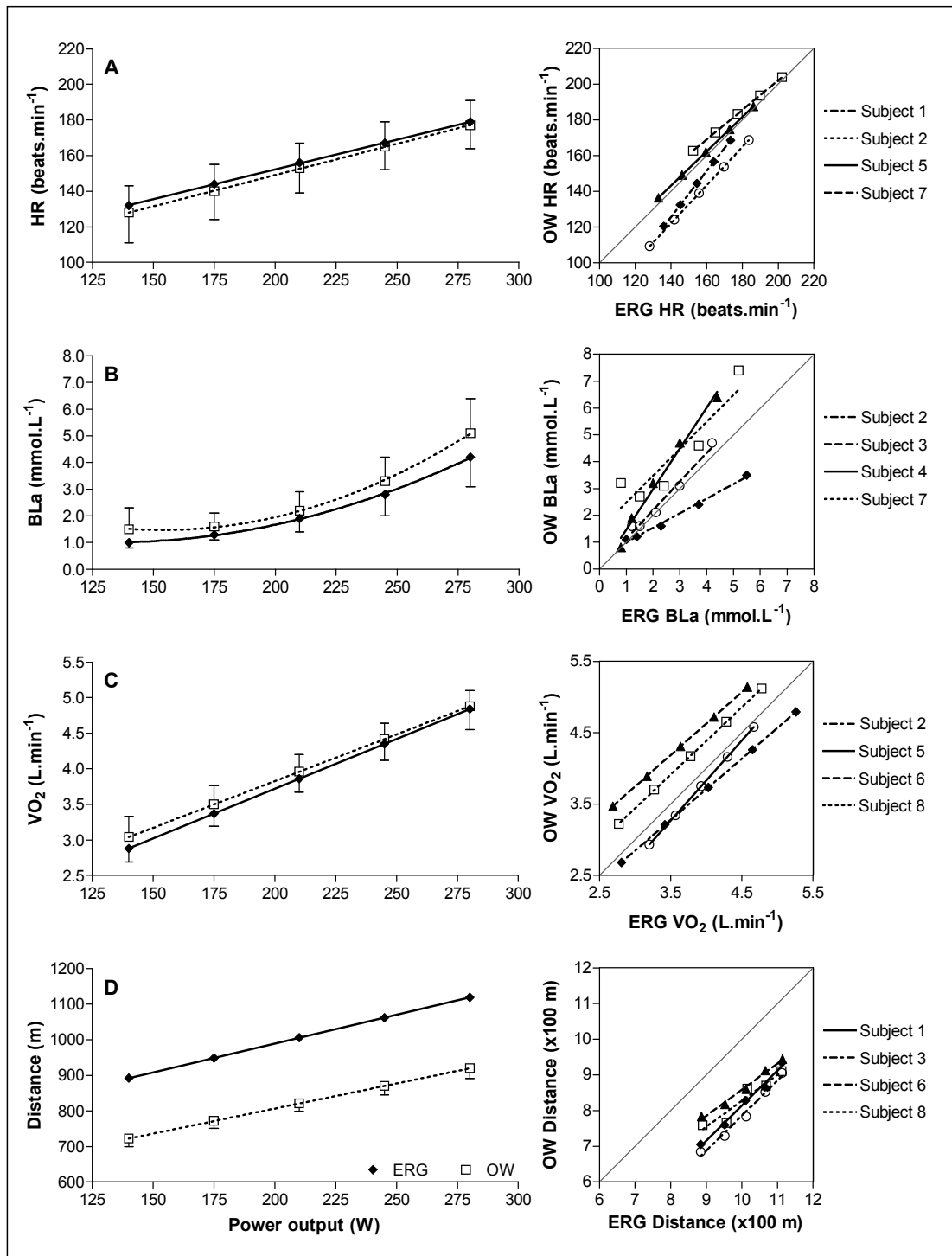


Figure 5-3: Mean submaximal results for A) heart rate (HR), B) blood lactate (BLa), C) oxygen consumption ($\dot{V}O_2$) and D) distance completed during ergometer (ERG) and on-water (OW) tests based on power normalised data using the standard power outputs. Error bars denote ± 1 SD. Left-hand panels display mean results for the entire group, while the right-hand panels show individual comparisons between ERG and OW results that are representative of the variation observed between individuals.

Table 5-3: Mean (SD) performance characteristics during the maximal stage of the ergometer (ERG) and on-water (OW) tests.

Variable	ERG	OW	p
Power output (W)	412.8 (18.9)	379.7 (20.9)	0.04
HR (beats.min ⁻¹)	192 (11)	188 (9)	0.02
BLa (mmol.L ⁻¹)	13.2 (1.5)	12.9 (1.0)	0.69
$\dot{V}O_2$ (L.min ⁻¹)	5.61 (0.47)	5.54 (0.22)	0.53
RPE (Borg 15-point scale)	19.8 (0.5)	19.6 (0.5)	0.44
SR (strokes.min ⁻¹)	33.1 (2.9)	30.6 (1.2)	0.04
Distance (m)	1267 (20)	1040 (22)	<0.0001

HR = heart rate; BLa = blood lactate concentration; $\dot{V}O_2$ = oxygen consumption measured by MM3B; RPE = Borg's rating of perceived exertion; SR = stroke rate; Distance = distance covered during the 4 min-maximal stage; p = probability resulting from a paired *t*-test between ERG and OW data.

Table 5-4: LT₁ (aerobic) and LT₂ (anaerobic) thresholds calculated from blood lactate-power output relationships using untreated data from the ergometer (ERG) and on-water (OW) tests.

Threshold	Variable	ERG	OW	p
		Mean (SD)	Mean (SD)	
LT ₁	Power (W)	180.4 (28.4)	190.3 (20.4)	0.24
	HR (beats.min ⁻¹)	145 (12.2)	145 (16.3)	0.43
	BLa (mmol.L ⁻¹)	1.2 (0.1)	1.7 (0.6)	0.04
	$\dot{V}O_2$ (L.min ⁻¹)	3.45 (0.31)	3.71 (0.38)	0.03
LT ₂	Power (W)	282.1 (26.1)	279.4 (24.9)	0.42
	HR (beats.min ⁻¹)	177 (9.6)	176 (9.5)	0.20
	BLa (mmol.L ⁻¹)	4.4 (0.5)	4.8 (0.6)	0.10
	$\dot{V}O_2$ (L.min ⁻¹)	4.77 (0.23)	4.76 (0.33)	0.49

SD = standard deviation; HR = heart rate; BLa = blood lactate concentration; $\dot{V}O_2$ = oxygen consumption measured by the MM3B; p = probability resulting from a paired *t*-test between raw ERG and OW data.

Blood lactate thresholds

As data treatment procedures were not necessary for the determination of blood lactate thresholds, raw data were used for all calculations related to blood lactate thresholds. Differences between the ERG and OW BLa-power output relationships (Figure 5-3, left panel) resulted in mean LT₁ and LT₂ BLa thresholds that differed by 0.5 mmol.L⁻¹ (p=0.04; large effect size, 84% probability) and 0.4 mmol.L⁻¹ (p=0.10; small, 86%), respectively. However, despite the higher LT₁ and LT₂ BLa results from the OW test, the corresponding mean HR results from the ERG and OW tests were within 1 beat.min⁻¹ (Table 5-4). Pearson correlations (R) and SEE between ERG and OW results for the HR at LT₁ and LT₂ were R=0.69 (p=0.06), SEE=12.9 beat.min⁻¹ and R=0.86 (p=0.01), SEE=5.3 beat.min⁻¹, respectively.

5.3.2 Reliability of measures on water

Submaximal performance

HR, BLa and $\dot{V}O_2$ were all lower during Trial 2 than Trial 1 (Figure 5-4). However, only BLa was significantly lower (p=0.04) during Trial 2, although the difference was a small effect (96% probability). The between-trial differences for $\dot{V}O_2$ and HR were small (75%) and trivial (87%), respectively.

Maximal performance

Mean OW power output was higher (p=0.03; moderate effect, 89% probability) in Trial 2 than Trial 1 [398.2 (25.1) W vs. 378.9 (12.7) W, respectively], but there were no other statistically significant between-trial differences during maximal exercise. Magnitude-based differences between the repeated OW trials were unclear, although the effects were most likely small for BLa (40%) and $\dot{V}O_2$ (60%), and trivial for HR (64%) and distance completed (50%).

Typical error results

The reliability of ERG and OW results as indicated by TE are shown in Table 5-5. Despite the stability of between-trial results for most variables, CI ratios between TE results from the OW and ERG tests showed that the reliability of measurements usually differed between tests. During maximal workloads, power output, distance completed and RPE were less reliable OW than during the ERG test (CI ratios: 1.3-2.0), while BLa displayed superior reliability OW compared to the corresponding

ERG TE data (CI ratio = 0.5). Between-test TE results were similar for HR_{max} (CI ratios: 1.1) and $\dot{V}O_{2\text{ peak}}$ (CI ratios: 0.9 and 1.1). Submaximal power output, BLa, $\dot{V}O_2$ and distance completed were all less reproducible (CI ratios: 1.8-16.0) than the corresponding ERG results. Only submaximal HR displayed similar reliability between OW and ERG tests, although this was not conclusive as the CI ratios were 0.8 and 1.2. However, during submaximal workloads, and despite the potential for differences due to environmental conditions during the OW test, the reproducibility of HR, $\dot{V}O_2$ and distance completed were all <5%; whereas the corresponding reliabilities were 3% or less in the laboratory (Table 5-5).

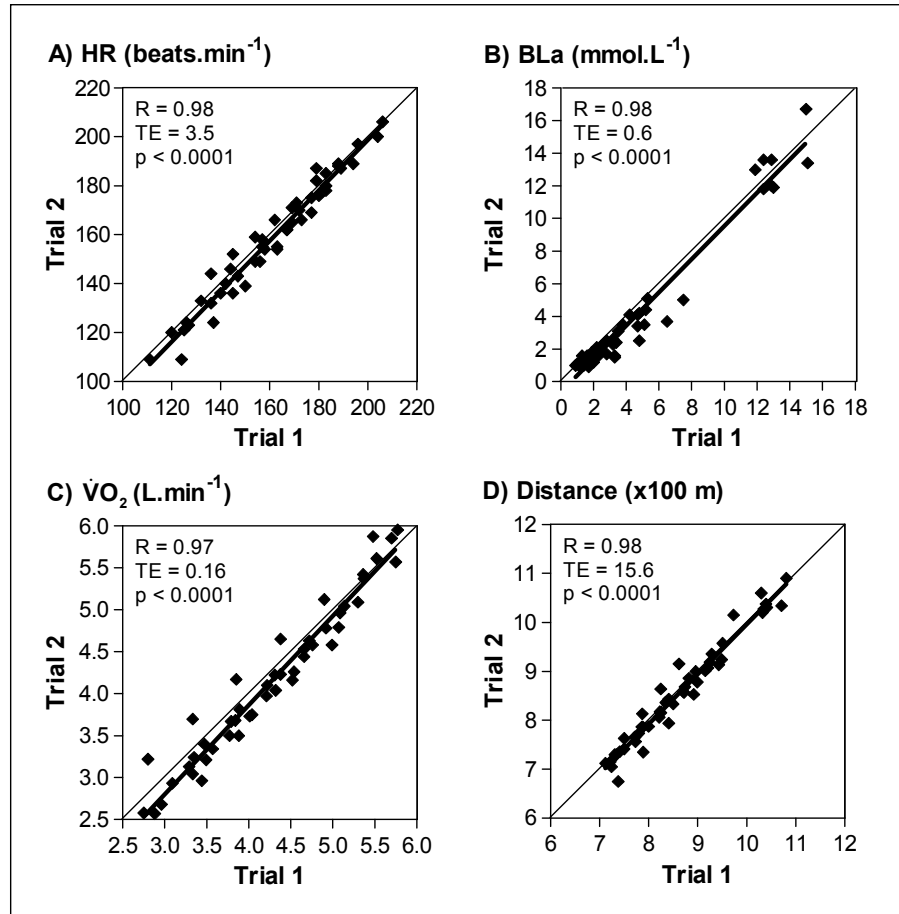


Figure 5-4: Trial 1 (x axis) vs. Trial 2 (y axis) scatter plots and linear regression trendlines for A) heart rate (HR), B) blood lactate concentration (BLa), C) oxygen consumption ($\dot{V}O_2$) and D) distance completed during repeated on-water (OW) incremental rowing tests. Submaximal results are based on power normalised data using the standard power outputs (140-280 W).

Table 5-5: Reliability of repeated measurements during submaximal and maximal performance of on-water (OW) and ergometer (ERG) incremental rowing tests as indicated by relative typical error (%TE) and 90% confidence limits (90% CL).

Variable	OW %TE (90% CL)		ERG TE (90% CL)	
	Submaximal	Maximal	Submaximal	Maximal
Power output (W)	5.2 (4.4-7.0) ^a	4.2 (2.8-9.0) ^a	0.4 (0.3-0.5)	2.9 (1.9-6.1)
HR (beats.min ⁻¹)	2.5 (2.1-3.3)	1.3 (0.9-2.7)	3.0 (2.5-4.0)	1.2 (0.8-2.5)
BLa (mmol.L ⁻¹)	19.2 (17.1-28.0)	6.8 (4.6-14.8)	11.0 (9.4-15.2)	12.5 (8.6-29.0)
$\dot{V}O_2$ (L.min ⁻¹)	4.6 (3.8-6.1)	2.5 (1.7-5.2)	2.6 (2.1-3.4) ^b	2.5 (1.8-4.7) ^b
Distance (m)	1.9 (1.6-2.5)	1.7 (1.2-3.6)	0.1 (0.1-0.2)	1.0 (0.6-2.0)

HR = heart rate; BLa = blood lactate concentration; $\dot{V}O_2$ = oxygen consumption (OW=MM3B; ERG=MOUSE); RPE = Borg's rating of perceived exertion; SR = stroke rate; Distance = distance covered during the 4 min-maximal stage.

^a Raw power output resulting from SR and RPE instructions (i.e. not based on treated data using reference power outputs). ^b Reliability assessment of $\dot{V}O_2$ measurements from MOUSE (Chapter 3).

5.4 DISCUSSION

This investigation compared the physiological responses between ergometer rowing and on-water sculling, with the aim of establishing the validity of laboratory-based rowing testing against the criterion of on-water performance. Our results confirmed the potential for physiological responses to be substantially different between ergometer and on-water rowing, and that these differences can display considerable between-athlete variation. Additionally, the reliability of the on-water test was established from duplicate on-water trials.

To date, few scientific publications have attempted a formalised incremental rowing protocol that is performed in the on-water environment. Those that have attempted field-based tests have adopted different protocols with respect to number of stages, stage duration, workload to recovery ratio and method of progression. Typically, assessments have been limited to pair-oared boats (Steinacker *et al.* 1987; Payne *et al.* 1996; Coen *et al.* 2003), although Steinacker *et al.* (1987) also considered single sculls. The number of stages performed and stage duration has varied from 4 x 6 min exercise bouts (Coen *et al.* 2003) to 8 x 3 min stages (Payne *et al.* 1996) with both constant duration stages (Payne *et al.* 1996; Coen *et al.* 2003) and fixed distance stages (Steinacker *et al.* 1987) being attempted. The recovery between stages has also varied from 1.5 min (Payne *et al.* 1996) to ~9 min (Steinacker *et al.* 1987) and has largely been influenced by the time required to collect data and prepare for the subsequent stage. Intensity and stage progression have been controlled by either boat velocity (Coen *et al.* 2003) or SR (Steinacker *et al.* 1987; Payne *et al.* 1996). While these methods of progression ensure the desired increments in intensity, they are susceptible to the influence of environmental factors; for instance, given that the test duration can be up to ~50 min, changes in wind direction, wind speed, or both, can often occur. This environmental effect is likely reflected in our reliability results for the distance completed during each stage (Table 5-5), although relative TE was <2% during all workloads, this still corresponds to ~20 m differences between trials. Wind speed and direction relative to the boat, as well as water conditions therefore have a profound effect on boat velocity and relative intensity at a given SR. This theoretically means that any field-based protocol relying on these independent variables for the control of workload should only be performed in environmental conditions that do not differ either within or between trials. However, the current

investigation used a combination of SR and RPE to prescribe workloads during the OW test and the resulting power outputs were then quantified for each workload using the WEBA biomechanics system. Although weather and water conditions were generally good, environmental conditions did change within OW tests and between separate trials. Nevertheless, Figure 5-1 shows that our method of workload prescription resulted in power output increments that were similar to the ERG test. While the workloads resulting from SR and RPE instructions did not permit direct comparisons between ERG and OW tests or repeated OW trials, OW power measurements allowed response variables to be compared at fixed power outputs. Response variable-power output relationships (Figure 5-3) could therefore be reliably compared at matched OW workloads (Table 5-5), and allowed comparisons between ERG and OW results at power outputs that were within ~2%, given the small difference between Concept2 and WEBA power measurements. Furthermore, the progressive increase in workload achieved by our method allowed lactate thresholds to be successfully calculated from the OW test. Thus, all measurements that are obtained from our standard laboratory-based rowing test can also be undertaken in the sport-specific rowing environment.

5.4.1 Comparison between test modalities (laboratory vs. on water)

Although based on a small sample size, our results showed small variations to the physiological responses between ergometer and on-water rowing. Compared to the OW test, mean HR was higher and BLa lower during the ERG test, which is opposite to the differences most commonly reported in previous comparisons (Urhausen *et al.* 1993b; Ryan-Tanner *et al.* 1999b). Only Steinacker *et al.* (1987) have reported higher mean HR results during ergometer performance, and have suggested that this may be due to the relatively greater movement of the rower's body mass during ergometer rowing compared to sculling. This factor has also been highlighted during movement pattern comparisons between the two modes of rowing (Martindale and Robertson 1984; Lamb 1989). But given the potential for between-individual variations in HR and BLa responses to ergometer rowing and sculling (Figure 5-3, right panel), comparisons between mean results from a sample of rowers may not adequately reflect the magnitude and direction of physiological differences as there does not appear to be a typical response. While the reasons for the apparent uncoupling between ergometer and on-water physiological responses are unclear, the individual nature of these differences suggests that between-athlete variation in

sculling technique may be equally as influential on physiological response variations as the differences reported between the movement patterns of ergometer rowing and sculling (Smith *et al.* 1993; Dawson *et al.* 1998; Elliott *et al.* 2002). It is also likely that the ergometer flywheel does not exactly replicate the resistance characteristics of on-water rowing and that this may contribute to the observed physiological differences between ergometer and on-water conditions. While a previous investigation comparing physiological responses between ergometer tests using different resistance settings did not find any statistically significant differences (Kane *et al.* 2008), divergence between the resistance characteristics of on-water rowing and ergometer simulations is likely to be greater compared to the ergometer tests using different resistance settings. Differences between movement patterns, resistance characteristics and between-individual variations in sculling technique may result in muscle coordination and recruitment differences between the conditions which mediate the observed variations in physiological responses. However, conclusions regarding the actual mechanisms responsible for the physiological differences are beyond the scope of this investigation.

The present study also provides a more thorough assessment of the oxygen cost of on-water rowing. Previous investigations use either Douglas Bags (Jackson and Secher 1976; Chènier and Leger 1991) or a Cosmed K2 portable metabolic system (Kawakami *et al.* 1992) to measure on-water $\dot{V}O_2$, although results are from only one or two athletes (Jackson and Secher 1976; Kawakami *et al.* 1992), or are limited to maximal intensity exercise (Jackson and Secher 1976; Chènier and Leger 1991). Mean $\dot{V}O_{2\max}$ has ranged 4.04-6.40 L.min⁻¹ depending on the calibre of the rowers tested and is reported to be comparable to the values attained on a rowing ergometer (Chènier and Leger 1991). This is supported by the current results, where ERG and OW $\dot{V}O_{2\text{peak}}$ values were virtually identical (Table 5-3). Submaximal $\dot{V}O_2$ was also measured, and showed that although the mean $\dot{V}O_2$ -power output relationships were very similar during ERG and OW tests, there was potential for individual variation between the relationships established from the ERG and OW tests (Figure 5-3, right panel). Although the between-individual variation detracts from the validity of the mean group results representing the typical response, the mean $\dot{V}O_2$ -power output relationship was still the only approach by which the Concept2 and WEBA power outputs could be compared. Based on our power normalisation

procedure using the five reference $\dot{V}O_2$ intensities, power measurements from the WEBA were ~2% lower than those from Concept2 during submaximal workloads.

During maximal intensity exercise, physiological differences between the ERG and OW tests were classified as small effects. However, as maximal data were not normalised for power output, the physiological responses during the OW test were likely lower than the corresponding ERG results because mean OW power output was ~8% lower during the maximal stage. Payne *et al.* (1996) is the only other investigation that has included on-water power output measurements, reporting mean values ranging approximately 140-310 W during their incremental protocol to exhaustion. This is similar to the 150-380 W mean power output range for our rowers, although maximal power output was likely higher during our test as it involved fewer workloads and provided more recovery prior to the maximal stage. Payne *et al.* (1996) also showed that on-water power outputs were lower compared to ergometer rowing, and the difference was relatively greater during maximal performance compared with light workloads (~20% vs. ~5-10%, respectively). They explained that their rowing biomechanics system did not include the force applied to the footstretcher, and that this was responsible for the power output differences between ergometer and on-water conditions. When footstretcher forces are also included in power calculations, the resulting on-water power output measurements are ~17% higher than the same measurements using only the handle force (Kleshnev 2000). As the WEBA system used in our study did not include footstretcher forces (only the forces at the gates), this is likely to account for our discrepancy between ergometer and on-water power outputs. While this may also have contributed to the relatively greater difference between ERG and OW power outputs during maximal exercise compared with submaximal workloads (~8% vs. ~2%, respectively), the relatively greater technical complexity of on-water sculling compared with ergometer rowing may have made it more difficult for subjects to display their true maximum during the OW test. This was also reflected by lower HR, BLA and SR results during the OW test. But despite the relatively small power output differences between the Concept2 ergometer and WEBA biomechanics system, large differences were found between the distance measurements of the Concept2 display unit and the MinimaxX GPS-derived distances measured during the OW test (Figure 5-3 and Table 5-3). While there was a strong correlation between ERG and OW distance results ($R=0.98$), compared to the distances estimated by the Concept2 display unit, OW

distances were 170-200 m lower across each of the five reference power outputs and 228 m lower during maximal exercise (although power outputs were not matched for the maximal data). Strong agreement between race times measured by the MinimaxX and official race results ($R=0.99$, $SEE=0.45$ s) suggest a displacement error of 2-3 m over the 2000-m race distance, and confirm the accuracy of MinimaxX distance measurements (Vogler *et al.* 2008). Thus, the Concept2 ergometer display unit over estimates rowing distance. This is not an entirely new finding as time-trial performances are faster on Concept2 ergometers compared with single sculls. For example, a heavyweight male will complete a 2000-m race in a single scull in $\sim 6:58$ (min:s; Table 1-1, p.4), which compares to $\sim 5:50$ (min:s) on a Concept2. Thus, performance time is ~ 1.2 times faster on the Concept2, just as the ergometer over-represents distance by a factor of ~ 1.2 (Table 5-3, p.111).

The mean BLa concentrations at the LT_1 and LT_2 blood lactate thresholds showed large and small effect size differences, respectively, between the ERG and OW tests. However, the corresponding mean HR results were very similar (Table 5-4). Previous studies have also found good agreement between HRs at blood lactate thresholds determined from ergometer and on-water tests, with mean HR results differing by no more than 2 $\text{beats}\cdot\text{min}^{-1}$ (Steinacker *et al.* 1987; Coen *et al.* 2003). But comparisons based only on mean data assume that any physiological differences between ergometer and on-water rowing are uniform and consistent, and do not consider the potential for larger between-modality differences in individual results. Hence, when on-water rowing has been performed at the HR intensity prescribed by an ergometer test, actual on-water BLa concentrations have sometimes been different to the blood lactate threshold predicted by the ergometer test (Steinacker *et al.* 1987; Payne *et al.* 1996). Pearson correlations between HRs at blood lactate thresholds from ergometer and on-water tests provide a better indication of the agreement between individual results, and have ranged $R=0.70-0.84$ (Steinacker *et al.* 1987; Payne *et al.* 1996). However, Payne *et al.* (1996) reported that their correlation of $R=0.63$ was associated with an SEE of $6.4 \text{ beats}\cdot\text{min}^{-1}$ and that the HR predicted by the ergometer test would therefore result in an on-water BLa concentration of $2.8-5.9 \text{ mmol}\cdot\text{L}^{-1}$. Based on our SEE of $5 \text{ beats}\cdot\text{min}^{-1}$ for LT_2 HR and using our mean results, the ERG-derived HR at LT_2 would result in an actual on-water BLa of $4.3-5.6 \text{ mmol}\cdot\text{L}^{-1}$. So although mean lactate threshold results seem to suggest that on-water training can be accurately prescribed from the ERG test, individual variation in BLa-

power output and HR-power output relationships (Figure 5-3, right panel) suggests that on-water intensities may in fact be over- or under-predicted when using LT₁ and LT₂ HRs to prescribe on-water training intensity for individual athletes. Compared with the criterion of the OW test, laboratory testing under-represented LT₁ HR for 3 of the 8 comparisons as a result of lower LT₁ BLa thresholds being determined from the ERG test. LT₂ HRs were generally similar between tests, although one subject displayed a lower threshold HR during the ERG test. Thus, for these individuals, the LT₁ and LT₂ HRs prescribed by the ERG test would result in on-water training intensities that were too low compared with those provided by the OW test. Differences between the LT₁ and LT₂ BLa thresholds determined during ergometer rowing and on-water sculling, and decoupling of the HR-BLa relationship, therefore mean that HR intensity recommendations derived from laboratory tests are not applicable to on-water training for all athletes. Table 5-6 shows that divergence between LT₁ and LT₂ HR results from the ERG and OW tests may translate into HR differences of 5-17 beats.min⁻¹ for the corresponding training zones, and compared to the criterion of the on-water test, the HRs prescribed by the ergometer test may be too low or too high. Differences of these magnitudes are likely to be of practical significance for elite athletes, as it is essential for high calibre athletes to maximise the quality of their training. However, individual lactate threshold results from most participants showed good agreement between ERG and OW tests. For these individuals, training intensity prescriptions will be virtually identical regardless of whether the test is performed in the laboratory or on-water. Laboratory tests on Concept2 ergometers therefore provide valid results for most athletes; they are also more expedient and less labour intensive than the OW test, and remain a suitable primary evaluation method. But as the OW test ensures accurate training intensity recommendations for all athletes, the OW test should supplement laboratory testing on a regular basis to fine tune exercise prescriptions for on-water training.

5.4.2 Reliability of measures on water

Despite the improved specificity of measurements obtained from our OW test, previous investigations have alluded to difficulties standardising tests within and between sessions, given the dynamic nature of weather and water conditions (Steinacker *et al.* 1987; Coen *et al.* 2003). Only Payne *et al.* (1996) has considered the reliability of on-water measurements, reporting Pearson correlations and SEE for HRs corresponding to BLa concentrations of 2 mmol.L⁻¹ (R=0.76; SEE=6.2

Table 5-6: Heart rate based training zones for two athletes displaying divergence between LT₁ and LT₂ heart rate results from the ergometer and on-water rowing tests. The heart rates prescribed by the ergometer test may be too low (Athlete 1) or too high (Athlete 2) compared to the criterion of the on-water test.

Training zone	Athlete 1 (HR too low)		Athlete 2 (HR too High)	
	Ergometer	On-water	Ergometer	On-water
T5: Maximal aerobic	>177	>182	>180	>168
T4: Threshold	173 – 176	178 – 181	176 – 179	164 – 167
T3: Heavy aerobic	158 – 172	164 – 177	162 – 175	148 – 163
T2: Moderate aerobic	141 – 157	149 – 163	147 – 161	130 – 147
T1: Light aerobic	<140	<148	<146	<129

HR = heart rate.

beats.min⁻¹) and 4 mmol.L⁻¹ (R=0.67; SEE=5.9 beats.min⁻¹). It was therefore essential to establish the reliability of our OW incremental protocol to determine whether measured variables were sufficiently reproducible to allow longitudinal monitoring of athletes using this method. In the current investigation, TE was primarily used to evaluate the reproducibility of repeated measurements, although correlations between Trial 1 and Trial 2 results for HR, BLa and $\dot{V}O_2$ were all very high (R>0.97; Figure 5-4). Despite these strong correlations, ERG results were sometimes more reliable than the corresponding OW data (Table 5-5). While the presented power output data for the OW test does not display the same reliability, TE values could only be calculated for the raw power outputs resulting from the SR and RPE guidelines used to control OW workloads, and despite no other intensity feedback during the OW scenario, this method still produced satisfactorily reproducible results. While there are multiple sources of error that would negatively affect the reliability of OW data (including biological and environmental variation), technical error from power output measurements could also contribute. But the reproducibility of WEBA power output measurements was implied given the observed reliability of the physiological response variables, all of which were based on their relationship to power output. Should the reproducibility of WEBA power measurements have been poor, this would have been reflected in the reliability of our HR, BLa and $\dot{V}O_2$ results. Based on the TE results for submaximal $\dot{V}O_2$ (Table 5-5), the additional error observed on-water (OW TE - ERG TE) could result from between-trial power output variation of ~2%; however, one may speculate that environmental influences must also contribute. Of the physiological variables, BLa and $\dot{V}O_2$ measured during the submaximal workloads of the OW test showed reliability results that were inferior to the corresponding ERG test (both CI ratios: 1.8). Despite the subject group consisting of experienced rowers with prior testing experience, and having been thoroughly familiarised with the equipment required for OW testing, submaximal HR, BLa and $\dot{V}O_2$ were all lower during Trial 2 compared to Trial 1 (Figure 5-4), which may be indicative a familiarisation effect. But based on the OW submaximal reliability results being poorer than the corresponding results from the ERG test, except for HR, the OW test is less suitable as a means for monitoring longitudinal submaximal fitness, as it is less sensitive to detecting change. However, the OW and ERG tests should be equally sensitive to tracking change in maximal fitness adaptations as reliability results from maximal exercise

were generally similar between both test methods. Despite the OW test's potential reduction in sensitivity to submaximal fitness changes compared with the ERG test, the enhanced specificity of the OW method could conceivably allow the field test to detect relevant fitness adaptations that may not be identified by the ERG test. Further research evaluating the efficacy of longitudinal fitness monitoring using the OW test is therefore warranted to find out whether potential benefits from improved specificity outweigh the OW tests diminished sensitivity to longitudinal fitness changes.

5.5 CONCLUSION

The specificity of rowing testing can be improved with an on-water incremental protocol that uses commercially available equipment to enable field-based assessments that satisfactorily replicate laboratory-based ergometer tests. But results from laboratory tests are generally more reliable than those from our OW protocol, although both modes of testing display adequate reproducibility. Individual lactate thresholds usually show good agreement between ERG and OW tests, but between-individual variation in physiological response differences between ergometer rowing and on-water sculling means that training intensity recommendations from the ERG test will not be directly applicable to on-water training for some athletes. As rowing tests performed on Concept2 ergometers provide valid training prescriptions for most athletes, and are more convenient than the on-water alternative, laboratory-based rowing tests are a suitable primary evaluation method. However, as the OW test ensures accurate training intensity recommendations for all athletes, the field test could be used as regular supplement to laboratory tests.

CHAPTER 6

MONITORING FITNESS AND PERFORMANCE WITH ERGOMETER AND ON-WATER INCREMENTAL ROWING TESTS

6.1 INTRODUCTION

The external validity of laboratory-based rowing testing has been questioned as the movement patterns (Martindale and Robertson 1984; Lamb 1989), stroke mechanics (Smith *et al.* 1993; Dawson *et al.* 1998; Elliott *et al.* 2002; Kleshnev 2005) and physiological responses (Steinacker *et al.* 1987; Chènier and Leger 1991; Urhausen *et al.* 1993b; Payne *et al.* 1996; Ryan-Tanner *et al.* 1999b) from simulated rowing on an ergometer differ compared with the criterion of on-water performance. So although ergometer tests aim to monitor fitness adaptations and prescribe exercise intensities for rowing training, some rowing coaches have developed reservations about applying these recommendations to on-water training. Given the perceived practical limitations of ergometer-derived training prescriptions, the primary role of laboratory testing has become to track the progress of fitness adaptations and provide insights into the effectiveness of preceding training blocks. However, as formalised incremental rowing tests can be performed in the on-water environment to improve the specificity of training prescriptions from rowing tests, longitudinal fitness changes could also potentially be monitored using this method.

The on-water incremental rowing protocol described in Chapter 5 successfully replicated a laboratory-based rowing test and quantified the reliability of the on-water method, but an effective test must also track changes in physiological conditioning and ideally provide a reflection of an athlete's readiness to perform in a competitive setting. Previous investigations using rowing ergometry to assess seasonal variations in fitness and rowing performance reported improvements across the season of ~18% for maximal oxygen consumption ($\text{VO}_{2\text{max}}$; Hagerman and Staron 1983; Mahler *et al.* 1985), 8-10% for power output at a blood lactate threshold of 4.0 mmol.L^{-1} (Vermulst *et al.* 1991) and 10-14% for average power

output during a sustained maximal effort (~90 s-6 min duration; Hagerman and Staron 1983; Mahler *et al.* 1985; Vermulst *et al.* 1991). However, when the pattern of fitness adaptations were investigated using three serial rowing tests conducted at ~12 wk intervals, 50% of the 0.40 L.min⁻¹ increase in $\dot{V}O_{2\max}$ and 15% of the 40 W maximal power output improvement occurred between the final two tests (Mahler *et al.* 1985). This demonstrates the principle of diminishing returns with longitudinal training and reflects the pattern of fitness adaptation typically experienced by elite athletes. Beyond this phase, improvements in variables such as $\dot{V}O_{2\max}$ are likely to be small, and although changes in BLA-performance kinetics may reflect increased high intensity work in the training program, rowing performance often continues to improve after physiological measures have displayed a plateau (unpublished personal communication, Prof Allan Hahn). Furthermore, on-water rowing performance appears to improve disproportionately more than ergometer rowing performance during the latter phases of preparation and may contribute to the modest shared variation ($R^2=0.52-0.81$) between ergometer time-trial results and competitive on-water scenarios (Jürimäe *et al.* 1999; Ryan-Tanner *et al.* 1999a; Jürimäe *et al.* 2000; Barrett and Manning 2004). Observations such as these could be due to improved on-water technique, different physiological responses between ergometer and on-water rowing, or a combination of both. However, no previous investigation has attempted to measure training-induced fitness adaptations using an on-water test or considered the efficacy of formalised on-water assessments as a method of performance monitoring.

While fitness monitoring forms an integral part of preparations for the competitive rowing season by tracking an athlete's progression in response to training, rowing tests would also ideally provide an effective indication of an athlete's readiness to perform in a competitive setting. However, predicting performance from the variables measured during routine monitoring has had only limited success. Physiological and anthropometric measures have been used in regression analyses to predict 2000-m rowing performance (Jürimäe *et al.* 1999; Jürimäe *et al.* 2000; Ingham *et al.* 2002b; Yoshiga and Higuchi 2003; Bourdin *et al.* 2004), but have displayed mixed results in predicting 2000-m rowing time or average velocity for ergometers and single sculls. When 2000-m performance times were the criterion, complex models using multiple variables derived from ergometer rowing displayed correlations ranging $R=0.71-0.99$ ($SEE=10.6-1.42$ s; Jürimäe *et al.* 1999; Yoshiga

and Higuchi 2003). In contrast, prediction of on-water performance was generally less successful ($R=0.81-0.94$, $SEE=11.3-6.3$ s; Jürimäe *et al.* 2000), which is not unexpected given the confounding affect of environmental factors. Although some of these investigations considered the relationship between selected variables and on-water time-trials, all independent variables in these models were derived from ergometer-based assessments; no publications utilised variables measured during on-water rowing. Given the potential for biomechanical (Martindale and Robertson 1984; Lamb 1989; Smith *et al.* 1993; Dawson *et al.* 1998; Elliott *et al.* 2002; Kleshnev 2005) and physiological (Steinacker *et al.* 1987; Chènier and Leger 1991; Urhausen *et al.* 1993b; Payne *et al.* 1996; Ryan-Tanner *et al.* 1999b) differences between ergometer and on-water rowing, it may be that performance inferences from the results of ergometer and on-water rowing assessments are specific to the performance modality used (either ergometer or on-water time-trials). Thus, the results from on-water rowing tests may provide a better indication of an athlete's performance potential for on-water racing.

The aims of this study were therefore to: 1) evaluate the feasibility of an on-water rowing test as a means of monitoring fitness adaptations; 2) establish whether the magnitude of fitness changes are the same for both ergometer and on-water tests, and 3) determine if the results from the on-water test provide a better indication of time-trial performance potential.

6.2 METHODS

6.2.1 Subjects

Seven rowers (6 males and 1 female) provided written informed consent to participate in this investigation; all athletes were competing at a national level in Under 23 rowing competition. The group consisted of two heavyweight rowers and five lightweight athletes, although the lightweight rowers were not under any weight restrictions at the time of the investigation. The subjects' physical characteristics are described in Table 6-1. All biological testing procedures were approved by the AIS Human Ethics Committee.

6.2.2 Experimental protocol

Each rower completed three exercise trials during two testing blocks that were separated by a 6-wk training period in which the athletes continued their regular training under the guidance of their coach. Standardised training programs were not possible as the participants came from two separate training squads, and the coaches from both groups wished to retain control over the athletes' training. All training completed during this time was logged in self-reported training diaries. The baseline and post-training testing blocks both consisted of ergometer and on-water incremental rowing tests, as well as a 2000-m ergometer time-trial to assess rowing performance. While the rowing performance test would ideally have been conducted on-water in single sculls, individual time-trials could not be conducted this way due to the dynamic nature of weather and water conditions, and the effect these would have on performance times between subjects and across testing blocks. Although an on-water performance test in which all subjects raced simultaneously would have minimised between subject differences due to environmental conditions and allowed rank-order comparisons between baseline and post-testing blocks, this was not possible for logistical reasons relating to the availability of the required number of boats. So despite all the compelling reasons, a time-trial was not done on-water, instead the time-trial performance capabilities of each rower were assessed on an ergometer.

The 2000-m ergometer time-trial (TT) and ergometer incremental rowing test (ERG) were conducted at the AIS Physiology Laboratory, while the on-water incremental rowing test (OW) was at Lake Burley Griffin (Canberra, Australia). Trial order was

Table 6-1: Physical characteristics of the 7 subjects (6 male and 1 female).

Measure	Mean (SD)	Range
Age (yr)	20.3 (0.7)	18.8-21.1
Height (m)	1.86 (0.08)	1.74-2.01
Mass (kg)	80.9 (7.0)	72.7-95.4
$\dot{V}O_{2\text{ peak}}$ (L.min ⁻¹)	4.78 (0.54)	3.82-5.53
Maximal power (W)	327 (37)	264-372

$\dot{V}O_{2\text{ peak}}$ = peak oxygen consumption during the 4-min maximum performance trial on the ergometer; Maximal power (W) = average power output during the 4-min maximum performance trial on the ergometer.

the same for baseline and post-testing: the TT was conducted first, with the ERG and OW tests approximately counterbalanced so that the ERG test was the second trial for 3 of the subjects, and the OW test second for 4 participants; trial 3 then consisted of the remaining ERG or OW test. During both testing blocks all trials were completed within 3-5 d with at least 24 h between tests.

2000-m ergometer time-trial

Rowers completed baseline and post-training performance tests using the same Concept2 rowing ergometer (Concept2, Morrisville, USA). A combination of Model C and Model D ergometers were used so that there were enough machines to allow simultaneous time-trials to be completed under competitive conditions. Participants always undertook each test with the same group of two to four athletes, and wherever possible, athletes used the same ergometer for all aspects of TT and ERG testing. It has previously been shown that physiological responses and performance do not differ between these model of Concept2 ergometer (Vogler *et al.* 2007). The Concept2 drag factor was standardised at 120 for the lightweight males and heavyweight female, although 130 was used for the heavyweight male, which is consistent with our standard testing practice. Subjects undertook a self-selected 10-min warm-up, which was followed by 3-min rest. The same warm-up was repeated before each TT. During the rest period, the ergometer work monitor unit was programmed for a distance of 2000-m; the TT then commenced immediately following the rest. During the TT, instantaneous heart rate (HR; Polar S810i, Kempele, Finland) and stroke rate (SR) were recorded to coincide with the completion of each 500 m; verbal encouragement was provided throughout the duration of the test. Following the test, performance times were recorded from the ergometer work monitor. Blood lactate concentration (BLa; Lactate Pro, Arkray, Shiga, Japan) was measured immediately after completion of the TT and again 4 min later, and in combination with the HR data, was used to confirm that TT performances were maximal on both occasions.

Laboratory test

The laboratory step-test protocol was consistent with the standard 7-stage protocol currently used for testing Australian rowers. Prior to the test, a resting BLa measurement was obtained from a capillary blood sample drawn from an earlobe. The incremental exercise protocol consisted of 6 submaximal workloads and 1

maximal stage on a Concept2 Model D rowing ergometer; each workload was 4 min in duration. The Concept2 drag factor was standardised using the same settings as the TT. Submaximal workloads were controlled by target power outputs, with the initial workload and between-stage increments determined according to the results of the baseline TT. Starting workloads therefore ranged 125-150 W with power outputs progressing 20-30 W each stage. Each workload was separated by a 1-min recovery period. Oxygen consumption ($\dot{V}O_2$) was measured continuously throughout the test using a custom-designed metabolic cart (MOUSE; AIS, Canberra, Australia); mean $\dot{V}O_2$ results were recorded every 30 s from steady-state conditions during the final 1 min of each workload. $\dot{V}O_{2\text{ peak}}$ during the maximal stage of the test was recorded as the highest 1 min average. HR (Polar S810i, Kempele, Finland) was also monitored throughout the duration of each test, with the steady-state value recorded during the final 30 s of each stage. BLa (Lactate Pro, Arkray, Shiga, Japan) was sampled during each recovery period, immediately following the maximal stage and 4 min after the finish of the maximal stage. Average SR, average power output and distance completed were also obtained from the ergometer work monitor unit during the 1-min recovery period. A rating of perceived exertion (RPE, Borg 15-point scale; Borg 1973) for the previous workload was also ascertained at this time.

On-water incremental test

The on-water incremental rowing test protocol was the same as that described in Chapter 5 and therefore comprised 5 x 4-min submaximal stages and 1 x 4-min maximal stage. Rowers were instructed to increase SR by 2 strokes.min⁻¹ each stage across a range of 14-24 strokes.min⁻¹, although on this occasion RPE intensity targets were not matched to the ERG test, but instead increased 2-points for each stage from 7 to 15 on the Borg 15-point scale (Borg 1973). Prior to testing, a single scull (Sykes Racing, Geelong, Australia) was instrumented with a biomechanics system (Row X Outdoor, WEBA Sport, Wien, Austria) to determine the power output resulting from the SR and RPE targets for each stage of the OW protocol. Average SR and distance covered were obtained using a MiniMaxX (Catapult Innovations, Scoresby, Australia) GPS/accelerometer data acquisition system. Submaximal workloads were separated by 2-min recovery periods, during which a BLa sample was obtained from the finger-tip and the rower turned the boat 180° in readiness for the start of the next stage. $\dot{V}O_2$ was measured continuously by a portable metabolic system (MM3B,

Cortex Biophysiks, Leipzig, Germany); breath-by-breath measurements were averaged for every 30 s and mean steady-state results recorded from the final 2 min of each workload. $\dot{V}O_{2\text{ peak}}$ was recorded as the highest 1 min average from the maximal stage. The MM3B also logged continuous HR data from the Polar HR monitor; mean HR from the final 30 s of each workload was recorded to represent steady-state conditions. RPE for the previous increment was also obtained during the 2-min recovery to determine whether the target value was achieved. Following the final submaximal workload, rowers were provided with a 5-min recovery in preparation for the 4-min maximal stage. Instructions for the maximal stage were to attempt to maintain a maximal effort for the entire duration and row as far as possible.

Blood lactate thresholds

Automated software (ADAPT; AIS, Canberra, Australia) determined lactate thresholds from the BLa-power output relationship established during the ERG and OW tests using third order polynomial regression. Lactate threshold 1 (LT₁; aerobic threshold) was defined as the point at which BLa began to increase (0.2 mmol.L⁻¹) above resting levels. Lactate threshold 2 (LT₂; anaerobic threshold, AT) was defined as the point on the polynomial regression curve that yielded the maximum perpendicular distance to the straight line formed by joining LT₁ and peak BLa (modified Dmax; Bishop *et al.* 1998). HR, power output and $\dot{V}O_2$ at LT₁ and LT₂ were subsequently determined using ADAPT.

6.2.3 Data treatment

The mean power outputs during each stage of the ERG and OW tests were not identical because the ERG test used individualised workloads based on TT results, and the OW submaximal workloads were controlled by the athlete attempting to match target SR and RPE values. Consequently, the resulting OW power outputs were different from the individualised target power outputs of the ERG test, and hence, the submaximal response variables (e.g. BLa, HR and $\dot{V}O_2$) could not be directly compared between each stage of the ERG and OW tests, or between the baseline and post-training OW tests (Figure 6-1). But because each of the response variables were strongly related to power output during all the ERG and OW tests (Table 6-2), regression analyses were used to normalise the data so that comparisons

between each stage of all ERG and OW tests used the same power outputs. The normalised power outputs were: 140, 175, 210, 245 and 280 W; these five power outputs were designated as the 'standard power outputs'. Response variable-power output relationships were therefore established for each of the rowers based on individual submaximal results, and regression analyses used to calculate values for each of the measured variables at intensities corresponding to the five standard power outputs. This normalisation procedure was applied to the submaximal data from *all* the ERG and OW tests, in order to compare baseline and post-training test results between the ERG and OW tests, and to evaluate the effect of the 6-wk training block according to both modes of testing. However, as the highest two standard power outputs were too high to be reflective of the actual submaximal workloads achieved by one of the subjects during their tests, only data from the lowest three standard power outputs were included in the analyses for this athlete.

6.2.4 Statistical analyses

Classification of magnitude-based differences

The physiological responses at the standard power outputs and lactate thresholds from the ERG and OW tests were compared between the baseline and post-training testing blocks (i.e. ERG baseline vs. ERG post-training) to evaluate the effect of the 6-wk training period according to both tests. Additionally, ERG and OW results were compared within testing blocks (i.e. ERG baseline vs. OW baseline) to establish whether the results differed between the two modes of testing. The magnitude of these differences were analysed to determine the likelihood that the true value of the observed Cohen effect statistic was trivial (<0.2), or at least small (0.2), moderate (0.6), large (1.2) or very large (2.0; Hopkins 2003; Hopkins *et al.* 2009). Briefly, a clear effect size (ES) was established when the likelihood was $\geq 75\%$ that the true value of the effect statistic was greater than one of the above thresholds (e.g. small or moderate). As the analysis also considers the likely direction of an effect (either positive or negative), an ES was unclear when the likelihood was $<75\%$ for a positive ES and $>5\%$ for a negative ES (Hopkins 2007; Hopkins *et al.* 2009), or vice-versa. Magnitude-based differences are reported as the largest likely effect size and associated percent probability (e.g. small, 85%).

Additionally, a conventional statistical approach was used. The submaximal data were also analysed using 2 (test) x 5 (stage) factorial ANOVAs with repeated

measures on both dimensions (SPSS 15.0 for Windows; SPSS, Chicago, Illinois, USA). Maximal data and lactate threshold results were compared using dependent *t*-tests. Statistical significance was established at $p < 0.05$ for all analyses.

Practically substantial differences based on the smallest worthwhile change

Practical inferences regarding the fitness and performance outcomes of the 6-wk training period were considered by determining likelihoods for practically substantial effects based on the SWC (Hopkins 2002, 2003; Hopkins *et al.* 2009). Values for the SWC were based on the reliability results for ergometer and on-water incremental rowing tests reported in Chapters 3 and 5, respectively. The analysis provides the likelihood that the true value of the observed training effect is larger than the TE (Hopkins 2000a) for repeated ergometer and on-water rowing tests, and that the change is therefore not merely an artefact of measurement error. Results are presented as the percent likelihood that the change is real or trivial (within the TE of the measurement).

Prediction of rowing time-trial performance

The relationship between rowing performance (TT time or OW maximal power output) and selected physiological results from ERG and OW tests were also considered using Pearson correlation coefficients and SEE. To interpret the magnitude of these correlations, coefficients were defined as: nearly perfect (>0.9), very strong (0.7-0.9), strong (0.5-0.7), moderate (0.3-0.5), and small (0.1-0.3; Hopkins 2000b).

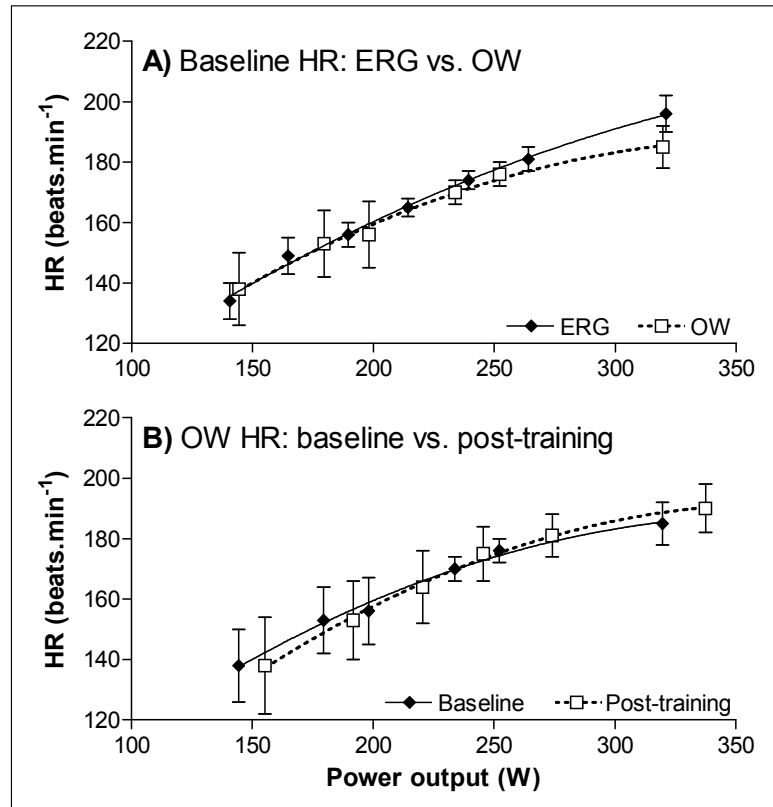


Figure 6-1: Mean results for heart rate (HR) using untreated data that does not account for the differences in submaximal workloads between A) the ergometer (ERG) and on-water (OW) incremental rowing tests, and B) the baseline and post-training tests using the OW protocol. *Error bars denote ± 1 SD.*

Table 6-2: Regression analyses between measured variables and power output during ergometer (ERG) and on-water (OW) incremental rowing tests using pooled results from all subjects. ‘Raw’ data analyses illustrate the strength of the response variable-power output relationships under both conditions, while the ‘power normalised’ data shows the relationships established from the standard power outputs. The displayed correlation coefficients are the *lowest* of those calculated from the baseline and post-training data.

Data	Variable	Model	Test (power output)			
			ERG		OW	
			R	SEE	R	SEE
Raw (submaximal & maximal intensities)	HR (beats.min ⁻¹)	2 nd order polynomial	0.91*	8.3	0.93*	7.6
	BLa (mmol.L ⁻¹)	3 rd order polynomial	0.87*	1.7	0.89*	1.8
	$\dot{V}O_2$ (L.min ⁻¹)	2 nd order polynomial	0.97*	0.18	0.88*	0.43
	Distance (m)	Linear	0.99*	9.5	0.89*	47.7
	SR (strokes.min ⁻¹)	2 nd order polynomial	0.86*	2.9	0.91*	2.2
Power normalised (submaximal intensity)	HR (beats.min ⁻¹)	Linear	0.93*	6.9	0.92*	7.9
	BLa (mmol.L ⁻¹)	3 rd order polynomial	0.83*	1.3	0.84*	1.3
	$\dot{V}O_2$ (L.min ⁻¹)	Linear	0.98*	0.14	0.88*	0.40
	Distance (m)	Linear	0.99*	3.5	0.93*	29.4
	SR (strokes.min ⁻¹)	Linear	0.76*	2.3	0.85*	2.1

HR = heart rate; BLa = blood lactate concentration; $\dot{V}O_2$ = oxygen consumption; Distance = distance covered during each 4-min stage; SR = stroke rate; R = Pearson correlation coefficient; SEE = standard error of estimate; * = statistically significant correlation ($p < 0.0001$).

6.3 RESULTS

6.3.1 Training logs

Six of the participants returned the self-reported training diary for the 6-wk period between tests. Results from these training logs are summarised in Table 6-3 according to the average intensity, frequency and duration of weekly training.

6.3.2 2000-m ergometer time-trial (TT)

Table 6-4 shows mean performance characteristics from the baseline and post-training TT. Mean performance time during the post-training test was 0.4 s slower than baseline testing, which corresponded to a mean power output decrease of less than 1 W. HR and BLa were also similar during the baseline and post-training tests (Table 6-4); HR_{peak} during both tests was greater than 92% of the age predicted maximum for all participants, thereby supporting the observation that athletes provided maximal efforts on both occasions. However, Figure 6-2 shows that individual performance results were variable, with 3 participants improving their post-training TT performance relative to baseline testing, while 3 athletes displayed a decline in performance. One athlete was unable to complete the post-training TT, thereby decreasing TT results to $n=6$; all other aspects of the testing procedure were successfully completed by this individual.

6.3.3 Ergometer and on-water incremental rowing tests

Magnitude-based differences between baseline and post-training results

Figure 6-3 displays the normalised submaximal results from the ERG and OW tests at the five standard power outputs. For the ERG trial, there were no substantial differences between the baseline and post-training results for submaximal BLa (trivial effect size, 98% probability; $p=0.96$), HR (trivial, 99%; $p=0.06$) or $\dot{V}O_2$ (trivial, 100%; $p=0.41$). However, the OW test showed post-training decreases for submaximal $\dot{V}O_2$ (small, 94%; main effect: $p=0.01$) and BLa (unclear small, 65%; interaction: $p=0.04$), but there was no substantial HR change (unclear trivial, 64%; $p=0.15$).

Table 6-5 shows that maximal power output during the OW test increased by 18 W following training (small, 91%), whereas the change during the ERG test was trivial

(78% probability). Baseline to post-training changes in $\dot{V}O_{2\text{ peak}}$ were unclear, but were most likely trivial (66%) for both the ERG and OW tests. LT_2 power output from the ERG test was unchanged after training (unclear trivial, 67%; $p=0.80$), while the OW test showed a possible improvement (unclear small, 67%; $p=0.43$).

Practical interpretation of the baseline to post-training changes

In contrast to the magnitude-based differences using Cohen's effect size units (as presented in the previous section), submaximal $\dot{V}O_2$ during the OW test was the only variable to display a *practically* substantial difference (94% probability) following the 6-wk training period, when $\dot{V}O_2$ was lower. Otherwise, the baseline to post-training changes from the OW test were trivial for submaximal HR (87%) and LT_2 power output (92%), but were unclear for submaximal BLa (trivial, 62%). There were no practically substantial differences between baseline and post-training results from the ERG test as the changes in BLa (99%), HR (100%), $\dot{V}O_2$ (100%) and LT_2 power output (80%) were all trivial.

It was unclear whether the post-training increase in OW maximal power output was practically substantial, although this was the most likely outcome (67% probability). However, maximal power output during the ERG test did not change following training (trivial, 90%). The baseline to post-training changes in $\dot{V}O_{2\text{ peak}}$ from the ERG and OW tests were most likely trivial in both instances (71% and 54%, respectively), although the effects were unclear.

Comparison of physiological responses to ergometer and on-water rowing

During baseline testing, BLa (small 82%; main effect: $p=0.04$), $\dot{V}O_2$ (small, 96%; $p=0.06$), SR (moderate, 99%; main effect: $p=0.02$) and distance completed (large, 100%; main effect: $p<0.001$) displayed differences between the ERG and OW tests during submaximal workloads. At maximal intensities these differences were: BLa (small, 87%; $p=0.13$), HR (unclear small, 73%; $p=0.07$), $\dot{V}O_2$ (small, 81%; $p=0.15$), SR (moderate, 95%; $p=0.01$) and distance completed (very large, 100%; $p<0.001$). The direction of the between-test differences were the same at all exercise intensities; BLa and $\dot{V}O_2$ were higher OW, whereas HR, SR and distance completed were higher during ERG performance.

Following the 6-wk training period, SR (moderate, 81%; $p=0.09$) and distance completed (very large, 100%; main effect: $p<0.001$) again displayed differences between the ERG and OW tests during submaximal stages, as did HR (small, 77%; $p=0.18$). Between-test differences were more common during maximal exercise as BLa (small, 81%; $p=0.22$), HR (small, 89%; $p=0.11$), SR (moderate, 80%; $p=0.03$) and distance completed (very large, 100%; $p<0.001$) all displayed effects. The direction of the differences was the same as during baseline testing.

Table 6-3: Summary of the training completed during the 6-wk training period based on self-reported training logs.

Training	Frequency (sessions/wk)		Weekly Duration (min)		Intensity (RPE)	
	Mean (SD)	Range	Mean (SD)	Range	Mean (SD)	Range
On-water	3.0 (1.5)	1.3-4.3	220.2 (76.5)	130.0-286.7	15.5 (1.3)	13.4-17.6
Ergometer	1.0 (0.2)	0.6-1.3	40.4 (10.2)	31.0-60.0	15.4 (3.9)	9.3-19.7
X-training	1.0 (0.9)	0.5-2.8	55.3 (59.6)	30.0-177.0	15.5 (2.4)	13.0-19.0
Gym	1.7 (0.4)	1.0-2.0	138.8 (54.1)	60.0-185.0	16.6 (1.7)	13.7-18.5
Aerobic	5.0 (1.2)	3.3-5.8	315.9 (80.2)	206.7-404.0	15.5 (1.9)	12.7-18.5
TOTAL	6.7 (0.9)	4.7-7.8	454.8 (117.0)	285.0-583.3	15.7 (1.5)	13.0-17.7

On-water = rowing training performed on-water; Ergometer = rowing training performed on a rowing ergometer; X-training = aerobic training activities other than rowing; Gym = resistance training; Aerobic = total of all aerobic training sessions (i.e. on-water, ergometer and x-training); TOTAL = total of *all* training sessions (including gym); Frequency = number of training sessions completed per week; Duration = minutes of training per week; Intensity = average rating of perceived exertion (RPE, Borg 15-point scale; Borg 1973) for weekly training sessions.

Table 6-4: Mean (SD) performance characteristics during the 2000-m ergometer time-trial (TT).

Variable	Baseline	Post-training	ES	p
Time (s)	412.8 (15.5)	413.2 (21.0)	Trivial, 57% (unclear)	0.89
Power output (W)	321 (34)	321 (47)	Trivial, 62% (unclear)	0.98
HR (beats.min ⁻¹)	193 (7)	191 (5)	Trivial (76%)	0.43
BLa (mmol.L ⁻¹)	10.9 (2.2)	11.6 (1.9)	Trivial, 47% (unclear)	0.49

HR = heart rate; BLa = blood lactate concentration; ES = magnitude-based effect-size (using Cohen units) and associated likelihood (%) for the change in TT performance; p = probability resulting from a paired *t*-test between baseline and post-training results.

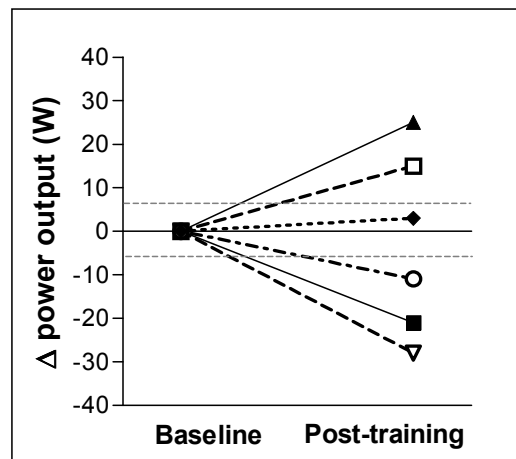


Figure 6-2: Average change in power output for individual athletes during the baseline and post-training 2000-m ergometer time-trials (TT). One athlete was unable to complete the post-training TT reducing the sample size to 6. Gray dotted lines represent the expected range of between-test performance variation based on the reliability of repeated 2000-m ergometer time-trials.

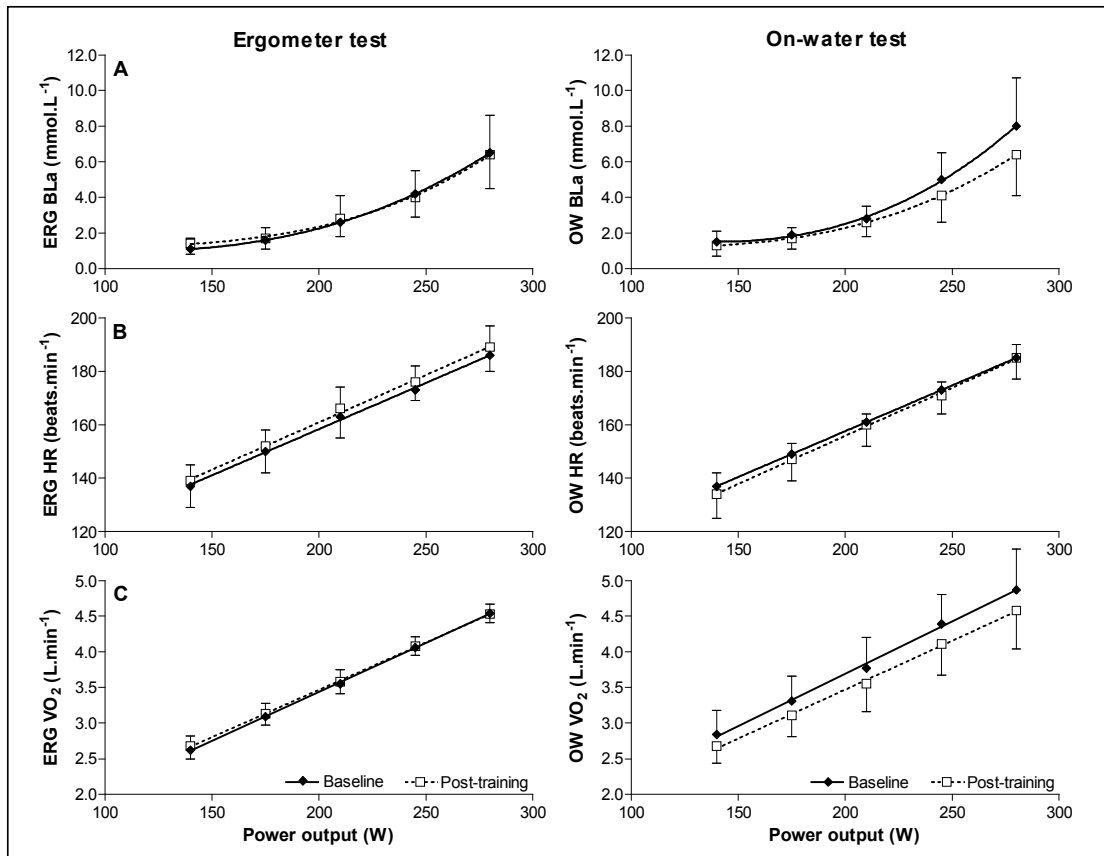


Figure 6-3: Mean results using normalised submaximal data based on the standard power outputs for A) blood lactate (BLa), B) heart rate (HR) and C) oxygen consumption ($\dot{V}O_2$) during the baseline and post-training ergometer (ERG; left) and on-water (OW; right) incremental rowing tests. *Error bars denote ± 1 SD.*

Table 6-5: Lactate threshold results and performance characteristics from the maximal stages of the ergometer (ERG) and on-water (OW) incremental rowing tests during baseline and post-training testing. Data are mean (SD).

Variable	ERG 1	ERG 2	ES	p	OW 1	OW 2	ES	p
LT ₂ BLa (mmol.L ⁻¹)	4.4 (0.8)	4.3 (0.6)	Trivial, 55% (unclear)	0.56	5.1 (1.1)	4.4 (1.0)	Small, 85%	0.15
LT ₂ power output (W)	248 (29)	247 (34)	Trivial, 67% (unclear)	0.80	250 (17)	258 (25)	Small, 67% (unclear)	0.43
Power output (W)	321 (33)	322 (38)	Trivial, 78%	0.89	320 (24)	338 (30)	Small, 91%	0.07
HR (beats.min ⁻¹)	196 (6)	194 (6)	Small, 59% (unclear)	0.50	185 (7)	189 (8)	Small, 80%	0.19
BLa (mmol.L ⁻¹)	10.8 (2.3)	11.2 (1.4)	Small, 53% (unclear)	0.42	12.4 (2.7)	12.1 (1.9)	Trivial, 59% (unclear)	0.60
$\dot{V}O_2$ (L.min ⁻¹)	4.66 (0.48)	4.74 (0.54)	Trivial, 66% (unclear)	0.31	4.88 (0.73)	4.77 (0.73)	Trivial, 66% (unclear)	0.22
Distance (m)	1165 (41)	1165 (47)	Trivial, 79%	0.95	984 (48)	982 (90)	Small, 44% (unclear)	0.96

LT₂ BLa = LT₂ (anaerobic threshold) blood lactate concentration; LT₂ power output = power output corresponding to LT₂; HR = heart rate; BLa = blood lactate concentration; $\dot{V}O_2$ = oxygen consumption measured by MOUSE during ERG tests and MetaMax during OW tests; Distance = distance covered during the 4-min maximal stage; ERG 1 = baseline ergometer test; ERG 2 = post-training ergometer test; ES = magnitude-based effect-size (using Cohen units) and associated likelihood (%) for between-test changes; p = probability resulting from a paired *t*-test between baseline and post-training results; OW 1 = baseline on-water test; OW 2 = post-training on-water test.

6.3.4 Relationship between incremental rowing test results and performance

Table 6-6 shows correlations between selected results from the ERG and OW tests and rowing performance. Correlations between ERG results and TT performance time were nearly perfect; OW results generally displayed lower correlations, although relationships were still very strong, except for LT_2 power which was small to moderate. When the average power output from the maximal stage of the OW tests was the performance criterion, ERG results displayed strong to very strong correlations (Table 6-6). The OW test showed nearly perfect correlations between $\dot{V}O_{2\text{ peak}}$ and OW performance, although the relationship for LT_2 power was lower, but strong.

Change in TT performance time (post-training minus baseline) displayed moderate to strong relationships with the corresponding changes in maximal power output ($R=-0.55$, $p=0.26$), $\dot{V}O_{2\text{ peak}}$ ($R=-0.40$, $p=0.43$) and LT_2 power output ($R=-0.49$, $p=0.32$) from the ERG test. The same results from the OW test showed correlations of $R=-0.28$ ($p=0.60$), $R=0.22$ ($p=0.68$) and $R=0.58$ ($p=0.23$), respectively. Relationships between the change in OW performance (maximal power output) and the changes in OW $\dot{V}O_{2\text{ peak}}$ and LT_2 power output were $R=0.62$ ($p=0.19$) and $R=-0.24$ ($p=0.64$), respectively.

Table 6-6: Linear regression analyses between selected results from the ergometer (ERG) and on-water (OW) incremental rowing tests and rowing performance (2000-m ergometer time-trial time and maximal power output from the on-water test) during the baseline and post-training test blocks.

Test	Variable	Performance criterion	
		2000-m time-trial (s)	OW maximal power (W)
ERG	Maximal power (W)	-0.92 [#] to -0.96 [#] (6.7-6.9)	0.64 to 0.89* (12.7-27.9)
	$\dot{V}O_{2\text{ peak}}$ (L.min ⁻¹)	-0.94 [#] to -0.95 [#] (5.7-7.6)	0.79 to 0.92 [#] (11.2-22.2)
	LT ₂ power (W)	-0.94 [#] to -0.97 [#] (5.9-6.1)	0.76 to 0.87* (14.1-23.7)
OW	Maximal power (W)	-0.71 to -0.94 [#] (5.9-16.5)	-
	$\dot{V}O_{2\text{ peak}}$ (L.min ⁻¹)	-0.84* to -0.89* (9.3-10.6)	0.91* to 0.92 [#] (11.9-14.5)
	LT ₂ power (W)	-0.19 to -0.39 (16.0-23.1)	0.52 to 0.60 (22.7-31.1)

Maximal power = average power output during the 4-min maximal stage; $\dot{V}O_{2\text{ peak}}$ = average oxygen consumption during the 4-min maximal stage; LT₂ power = power output equivalent to the LT₂ (anaerobic) blood lactate threshold; R = Pearson correlation coefficients from baseline and post-training testing; SEE = standard error of the estimate for baseline and post-training results; * = statistically significant correlation (p<0.05); [#] = statistically significant correlation (p<0.01).

6.4 DISCUSSION

This investigation demonstrated that the response to 6-wks of rowing training was different between ergometer and on-water tests. Additionally, the relationship between changes in fitness test results and rowing performance showed that the ergometer results provided a better predictor of rowing time-trial performance.

The training conducted during the 6-wk period between baseline and post-training testing had mixed results in terms of changes to ergometer time-trial performance. Mean performance time declined (was worse) by 0.4 s over the course of the investigation; three athletes displayed substantially slower TT results and the other three participants that completed both time-trials improved their performance (i.e. faster TT results) after the training block. However, for one of the latter three athletes, the observed change was within the range normal for between-test variation (2% coefficient of variation for power output and 0.6% for performance time; Schabort *et al.* 1999). Mean results from the self-reported training diaries suggested that the volume of training should have been at least sufficient to maintain fitness and performance, but unfortunately, the investigation was undertaken during the rowing off-season, so training loads had typically been reduced compared to in-season practices. Additionally, discussion with the athletes revealed that the focus of training was quite varied between individuals and that fitness maintenance or resistance training was sometimes the primary goal rather than development of aerobic fitness. So although performance changes were small, and sometimes included negative results, the 6-wk duration of the training period was sufficiently long to observe changes in ergometer time-trial performance.

6.4.1 Magnitude-based differences between baseline and post-training results

Given the training completed by the athletes during this investigation was not necessarily aimed at improving aerobic fitness, and the duration of the 6-wk training period was less than that of previous studies investigating seasonal fitness changes in rowers (Hagerman and Staron 1983; Mahler *et al.* 1985; Vermulst *et al.* 1991), it was not surprising that fitness adaptations were comparatively modest during the current study. However, the main aim of our study was to compare the magnitude of fitness changes measured by incremental exercise tests performed on a rowing ergometer or on-water in a single scull, in order to establish whether longitudinal fitness changes

could be effectively monitored by the on-water test. According to the ERG test, there were no substantial fitness changes between the baseline and post-testing occasions. While the modest training volume completed between testing occasions (Table 6-3) tends to support the conclusion from the ERG test, we can't preclude the possibility that ERG and OW tests produce different results, and that on-water training (which was ~70% of the total aerobic training) was sufficient to elicit a training response that was only detected by the OW test. Indeed, the OW test showed small post-training decreases for BL_a at fixed submaximal workloads (Figure 6-3) and a small improvement in maximal power output, thereby suggesting that fitness improved. However, interpretations regarding the post-training decrease in submaximal $\dot{V}O_2$ during the OW test are less clear, as our experience with laboratory-based rowing tests suggests that submaximal $\dot{V}O_2$ usually changes in parallel with $\dot{V}O_{2\max}$, such that submaximal $\dot{V}O_2$ as a proportion of $\dot{V}O_{2\max}$ remains quite stable (personal communication, Prof Allan Hahn). But given the magnitude of the training responses for maximal power output and submaximal BL_a measured by the ERG and OW tests were different (trivial vs. small, respectively), the improved specificity of the OW test may facilitate detection of training adaptations that are only evident during on-water performance. Stronger evidence for this conclusion would have been provided if the ERG and OW tests had both shown definitive post-training fitness improvements, such as decreased BL_a for a given submaximal workload, higher $\dot{V}O_{2\max}$, and higher maximal power output. Had the ERG and OW tests indicated small and moderate improvements, respectively, there would be little doubt that fitness had actually improved and that the OW test showed larger baseline to post-training changes. But as the fitness outcomes from the OW test contradicted those from the established ERG test, it is not clear whether this is actually the case. Additionally, due to the small sample size, many of the magnitude-based inferences about the training effects were unclear (particularly for maximal results), further confounding comparisons between the training outcomes of the ERG and OW tests. Moreover, the observed changes during the OW test could equally be an artefact of the increased potential for measurement variation due to environmental influences (Chapter 5), or from possible changes in sculling technique between the baseline and post-training OW tests. However, the actual reason for the observed differences between the fitness outcomes from the ERG and OW tests is not clear.

Practical interpretation of the baseline to post-training changes

Although magnitude-based classifications of the training responses measured by the ERG and OW tests were quantified as trivial and small, respectively, it is our normal practice to interpret physiological and performance changes between serial rowing tests based on the reliability established for the test protocol. A change of greater than 1 x TE has a likelihood of just 52% for being 'real' (Woolford and Gore 2004), which is an acceptable degree of imprecision for coaches who are looking for small improvements of 0.4-0.7% that can be the difference between winning a medal or not (Hopkins *et al.* 1999). The reliability of the OW method has been reported to be poorer compared to the ergometer protocol (Chapter 5), meaning that the OW test will be less sensitive to detecting practically substantial fitness changes. So although the training effects from the OW test were classified as being larger than those recorded from the ERG test, the baseline to post-training changes during the OW test may not be sufficient to be accepted as practically meaningful. When the response to the 6-wk training period was interpreted relative to the TE results reported for the OW test (Chapter 5), only submaximal $\dot{V}O_2$ displayed a clear practically substantial change (lower post-training). The training responses from the ERG test were confirmed as trivial based on practical interpretations of the baseline to post-training changes using reliability results for ergometer tests (Chapter 3). However, if the TE for ergometer-based tests were applied to interpret the observed OW changes, the shift in submaximal BL_a during the OW tests would be practically meaningful, thereby demonstrating that the inferior reliability of the OW method diminished the test's sensitivity to longitudinal fitness changes relative to ergometer assessments. But in practice, this procedure is not methodologically sound when interpreting changes measured by a test, as the TE data from the ERG and OW tests are specific to the tests from which they are derived. Nevertheless, the above example shows that although the magnitude of the training responses from the OW test were classified as being greater than those from the ERG test, the relatively poorer reliability of the OW method confounded practical interpretations of the observed training effects.

6.4.2 Comparison of ergometer and on-water physiological responses

The ERG and OW tests often displayed small differences in BL_a, HR and $\dot{V}O_2$. While submaximal differences were not entirely consistent between the baseline and post-testing occasions, the differences resulting from maximal exercise were similar

despite the possible influence of training effects from the 6 wks between tests. But as submaximal BLa and $\dot{V}O_2$ displayed differences during baseline testing only, whereas submaximal HR and LT_2 power output only showed differences post-training, the physiological response differences between ergometer and on-water rowing may be somewhat influenced by training and fitness status. However, the direction of the physiological differences between the ERG and OW tests were always the same and matched those reported in Chapter 5. SR and the distance completed during each workload also differed between the ERG and OW tests. Mean SR during each of the workloads (using the standard power outputs to normalise submaximal results) was between 2 and 4 strokes.min⁻¹ higher during the ERG test and may therefore have contributed to the observed physiological response differences. The distance completed during each of the workloads (using normalised submaximal results) was 150-210 m higher according to the ERG test, thereby confirming that the Concept 2 rowing ergometer over-represents distance estimates compared to on-water distance measurements using the MiniMax system (Chapter 5).

6.4.3 Relationship between incremental rowing test results and performance

Since this investigation confirmed that laboratory-based rowing tests can be replicated on-water, but showed that the training responses measured by ERG and OW tests may be different, it was important to critically evaluate the relationship between OW test results and rowing performance. Because average power output from a sustained maximal effort (R=-0.88 and 0.92; Jürimäe *et al.* 2002a; Bourdin *et al.* 2004), absolute $\dot{V}O_{2\max}$ (R=-0.76 to 0.88; Jürimäe *et al.* 1999; Jürimäe *et al.* 2000; Ingham *et al.* 2002b; Bourdin *et al.* 2004) and power output corresponding to AT (fixed BLa of 4 mmol.L⁻¹; R=0.92 to -0.96; Jürimäe *et al.* 1999; Jürimäe *et al.* 2000; Ingham *et al.* 2002b) have displayed strong relationships with ergometer time-trial performance (either elapsed time or average power output), the equivalent variables from the current study were used in linear regression analyses with TT performance time. Results from the ERG test displayed correlation coefficients that were very similar to those previously reported (Table 6-6), although the predictive potential of these single-variable models for individuals are limited as SEE results ranged 6-8 s. The correlations between OW test results and TT performance times were nearly always lower than the corresponding correlations for the ERG test

results; consequently, for the former, SEE results were higher. However, the relationship between maximal power output during an ergometer incremental rowing test and 2000-m rowing performance has been shown to vary depending on whether an ergometer time-trial ($R=-0.97$) or on-water single sculling time-trial ($R=-0.70$) was the performance criterion (Jürimäe *et al.* 2000). It was therefore anticipated that the relationships between test results and rowing performance may be stronger when the same mode of rowing (either ergometer or sculling) was used under both conditions. Because 2000-m on-water time-trials were deliberately not used during the present investigation to avoid the confounding effects of changes in environmental conditions, maximal power output during the OW tests was used as a surrogate indication of on-water performance potential. Correlations between OW test results and performance were higher when maximal OW power output was the criterion, just as ERG test results showed the strongest relationships with TT performance. However, the simple linear regression models using results from the OW test did not improve correlations with maximal OW power output relative to the ERG results. In fact, the correlations resulting from OW LT_2 power output ($R\leq 0.60$) were lower compared to the corresponding result from the ERG tests ($R\leq 0.87$; Table 6-6). Furthermore, although the relationship between the change in ERG LT_2 power output and the change in TT time displayed only a moderate correlation ($R=-0.49$), the correlation for the corresponding OW results was poor ($R=-0.24$), and in the opposite direction to that which was anticipated, given power output was the criterion. Alternatively, changes in $\dot{V}O_{2\text{ peak}}$ from both test methods correlated moderately with the changes in TT time and OW maximal power output (ERG: $R=-0.40$ and OW: $R=0.62$). However, our findings regarding OW LT_2 power output and its modest relationship to rowing performance challenges our assumption that the association between incremental test results and rowing performance would be improved when the mode of rowing was matched between performance-trial and test. But as the on-water performance test adopted by this study was not a stand-alone 2000-m on-water sculling time-trial, it is not clear whether our results translate to this criterion of on-water rowing performance.

6.5 CONCLUSIONS

The performance changes resulting from the 6-wk training period between baseline and post-training tests had mixed results; some athletes showed improvements, while others displayed detraining effects. However, the training effect was secondary to the main aim of this study, which was to establish the efficacy of on-water testing to track changes in fitness compared with tests conducted in the laboratory on a rowing ergometer. Compared with the standard ERG test, post-training fitness improvements were recorded only by the OW test; although it was not clear whether these differences were actually the result of genuine training adaptations that were evident only during the on-water performance, or were possibly an artefact of changes in environmental conditions during on-water performance. While the baseline to post-training changes from the OW test were classified as being larger than those from the ERG test, the inferior reliability of the on-water method diminished the test's sensitivity to detecting longitudinal fitness changes relative to ergometer assessments. Thus, practical interpretations regarding the outcomes of the 6-wk training period were similar between the ERG and OW tests. Similarly, results from the OW test did not improve the association with rowing time-trial performance relative to those from the ERG test. Although correlations between OW test results and rowing performance were higher when OW power output was the performance criterion, and ERG test results showed the strongest relationships with ergometer time-trial performance, ERG results consistently provided the highest correlations with rowing performance. So although physiological response differences between laboratory and on-water rowing tests suggest that on-water tests should improve the specificity of fitness test results, the practical reality is that formalised on-water rowing tests provide no obvious benefits as a means of monitoring longitudinal fitness changes or performance compared to laboratory-based rowing tests.

CHAPTER 7

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1 SUMMARY

This thesis evaluated the Concept2 Model D rowing ergometer against the previous criterion of the Concept2 Model C, thereby validating the Model D ergometer to be used as the standard testing device for subsequent laboratory tests comparing ergometer rowing with on-water single-sculling. Additionally, the accuracy and reliability of the Cortex MetaMax3B indirect calorimetry system was established with respect to our automated Douglas bag system, in order to evaluate the metabolic load of rowing in the on-water environment. Because both the Concept2 Model D ergometer and the MetaMax3B proved to be valid testing tools, matching laboratory and on-water incremental rowing tests were performed, which confirmed that physiological responses differed between simulated rowing on an ergometer and on-water single-sculling. Thus, the on-water test improved the specificity of training intensity prescriptions relative to the laboratory test, although the reliability (Typical error; TE) of the on-water test was generally poorer compared with that for laboratory tests. While the improved specificity of the on-water test may have contributed to the field test detecting larger fitness changes following 6 weeks of training compared with the standard laboratory test, the inferior reliability of on-water tests meant that these results were inconclusive. Hence, when the magnitude of the fitness changes measured by the laboratory and on-water tests were interpreted relative to the TE of the respective tests, longitudinal training monitoring was no more effective using the on-water method. Given that on-water incremental rowing tests are logistically difficult and provide few additional benefits compared to standard laboratory tests, it is concluded that formalised on-water rowing tests have limited application.

Despite the updated design of the Concept2 Model D ergometer and the potential for

altered resistance characteristics and rowing technique compared to the Concept2 Model C, the physiological responses to incremental exercise were virtually identical between the two ergometer models. Although $\dot{V}CO_2$ and RER displayed statistically significant differences during submaximal exercise, the actual differences across all exercise intensities were less than $0.06 \text{ L}\cdot\text{min}^{-1}$ for $\dot{V}O_2$, $0.12 \text{ L}\cdot\text{min}^{-1}$ for $\dot{V}CO_2$ and 0.03 for RER. The uniformity of the physiological responses was due to strong agreement between power outputs from both models of ergometer, which differed by less than 2 W during maximal exercise. Lactate thresholds (LT_1 and LT_2) were also similar between the Concept2 C and D models, threshold BLa and HR results were within $0.2 \text{ mmol}\cdot\text{L}^{-1}$ and $2 \text{ beats}\cdot\text{min}^{-1}$, respectively. Power outputs at the lactate thresholds also showed excellent agreement between ergometer models as the difference was always less than 5 W . Given the absolute differences between test results using these models of Concept2 ergometer were always minimal, the new design features of the Concept2 Model D rowing ergometer do not substantially alter the physiological response to rowing compared to the previous model. Hence, results from rowing tests using the Concept2 Model D ergometer are valid compared to the Model C and can be directly compared between these models. As equivalent results were obtained from both ergometer models, the Concept2 Model D was accepted as the reference ergometer for all subsequent laboratory tests. Additionally, results from duplicate incremental tests on the Model D ergometer were used to evaluate the TE of laboratory-based rowing tests, thereby quantifying the reliability of this protocol and providing the standard against which the on-water incremental rowing tests would be compared. TE results were $\sim 3\%$ for power output, $\dot{V}O_2$ and HR; BLa and threshold results were less reproducible (TE $\sim 15\%$), although the power output at LT_1 and LT_2 was better (TE $\sim 5\%$). As these results were an indication of the combined biological and technical error of the various laboratory measurements, any change larger than the TE was likely to be ‘real’ rather than an artefact of measurement error. These TE results were therefore used as the SWC for inferences regarding practically important magnitude-based differences during subsequent laboratory tests.

A major limitation of previous investigations comparing ergometer and on-water rowing is that no metabolic data have been included; in fact, there are very little data concerning direct measurements of the oxygen cost for on-water rowing. One

possible reason for this oversight may be on-going concern regarding the validity of measurements from portable indirect calorimetry systems (Meyer *et al.* 2005a), which would be ideally suited for on-water evaluations. However, compared to a laboratory-based automated Douglas bag system, the Cortex MetaMax3B portable indirect calorimetry system provided reliable results, and although measurements from the two systems were not directly comparable, the MetaMax3B estimated metabolic demand with a satisfactory degree of accuracy. During incremental ergometer rowing tests to exhaustion, MetaMax $\dot{V}O_2$, $\dot{V}CO_2$ and $\dot{V}E$ were higher by approximately 4%, 7% and 4%, respectively. However, as differences were larger than what would be anticipated for repeated measurements with the laboratory metabolic system (based on the TE established in Study 1 using the same system), between-system differences for $\dot{V}O_2$, $\dot{V}CO_2$ and RER were almost always practically substantial. Conversely, TE results from repeated MetaMax measurements were very similar to those from the automated Douglas bag system (established in Study 1), MetaMax TEs ranged 2.0% ($\dot{V}O_2$) to 3.6% ($\dot{V}E$). Overall, MetaMax accuracy was comparable to other portable metabolic devices (McLaughlin *et al.* 2001; Crouter *et al.* 2006) and the reliability was often better (Duffield *et al.* 2004; Crouter *et al.* 2006). Based on these results, the MetaMax portable system was used for all subsequent on-water tests (Chapters 5 and 6). However, some uncertainty remains as to whether accuracy and reliability results from a laboratory-based validity study are directly transferable to the on-water environment, especially given the potential for the additional humidity of on-water environment to interfere with the ‘drying’ of expirate and influence gas analysis results. Unfortunately, uncertainty regarding the transfer of results between the laboratory and field environments is an inherent limitation of validation studies for portable indirect calorimetry systems.

Recent developments in sport monitoring technology allow rowing tests that were once only possible under laboratory conditions to be successfully replicated in the sport-specific on-water environment. Compact and unobtrusive rowing biomechanics systems allow boats to be instrumented for power output measurements, and portable indirect calorimetry systems permit direct measurements of metabolic demand during field-based activities. Thus, all measurements from laboratory-based rowing tests can now also be obtained in the field with acceptable accuracy. Matching laboratory and on-water tests showed that the physiological responses to simulated ergometer

rowing and on-water sculling were different, but the magnitude and even the direction of the differences were highly individual. Mean results for BLa and $\dot{V}O_2$ were higher, and HR was lower during on-water performance at submaximal intensities, although the differences were not statistically significant. However, the magnitude of the mean difference of BLa, using Cohen's effect size units, was classified as small. But during maximal exercise, HR and power output were lower during the on-water test compared with laboratory conditions, suggesting that it may be more difficult to express a truly maximal effort during on-water rowing, possibly because of the greater technical complexity of sculling compared with ergometer rowing. However, as the physiological response differences varied considerably between individuals, there does not appear to be a 'typical' difference between rowing performed on the ergometer or on-water. It therefore seems likely that the physiological responses to rowing are also influenced by rowing technique, which in combination with disparity between movement patterns and resistance characteristics, may result in differences in muscle recruitment between ergometer and on-water conditions that mediate the variations in physiological responses. Hence, there is scope for future investigations to elucidate the mechanism responsible for the physiological response differences between ergometer and on-water rowing. Comparisons between training intensity prescriptions based on lactate threshold results from the laboratory and on-water tests also confirmed that laboratory test results were not always applicable to on-water training scenarios. Lactate thresholds results for LT_1 BLa and $\dot{V}O_2$ were significantly higher during on-water performance, although there were no significant differences at LT_2 . But compared to the criterion of the on-water test, laboratory testing under-represented LT_1 HR in 3 out of 8 cases because lower LT_1 BLa thresholds were determined from the laboratory test. LT_2 HRs were generally similar between tests, although the laboratory test again underestimated threshold HR for one subject and produced lower LT_2 BLa values in two cases. Thus, differences between the BLa thresholds determined during laboratory and on-water tests, and decoupling of the HR-BLa relationship, may mean that HR-based intensity prescriptions from laboratory tests are not applicable to on-water training for all athletes. While the on-water test improves the specificity of intensity prescriptions for on-water rowing training, field-based activities are subject to variable environmental conditions which can negatively affect the reproducibility of results. Indeed, measurements from repeated on-water tests displayed similar or lesser reliability (TE=1.9-19.2%) compared to the

TE established for the laboratory test during Study 1 (TE=0.1-11.0%), but still showed a good degree of reproducibility given the potential for the confounding influence of environmental conditions.

While the improved specificity of the on-water protocol increases the likelihood that test results will better reflect an athlete's fitness status and performance potential, inferior reliability compared to the laboratory test reduces the field test's sensitivity to fitness changes and may limit its effectiveness as a means of longitudinally monitoring fitness status. Following a 6 wk training block, the magnitude of the BLa and $\dot{V}O_2$ changes recorded by the on-water test were greater (small Cohen's effect size) compared with the laboratory test (trivial effect). However, the on-water and laboratory tests both indicated that training responses were negligible in relation to the TE established for the on-water and laboratory protocols. So although there was some evidence that the improved specificity of the on-water method facilitated the detection of training adaptations that were only evident during on-water performance, it was not possible to eliminate the prospect that these effects were merely artefacts of measurement error. Thus, the on-water test did not provide any additional benefits for monitoring training compared with the standard laboratory-based test. The on-water test also failed to improve the relationship between incremental test results and rowing time-trial performance. Correlations between test results and rowing performance were largest when the mode of rowing was matched between the incremental test and the performance criterion (either 2000-m ergometer time-trial or on-water maximal power output). However, the correlations were highest between laboratory test results and 2000-m ergometer time-trials ($R = -0.92$ to -0.97) compared with on-water physiological results and the maximal power output during the on-water tests ($R = 0.52$ to 0.92). Given that the on-water test provided no clear benefits for monitoring longitudinal fitness changes or performance compared with the laboratory test, and was also more time consuming and logistically challenging, the sole application for the field-based method lies in the prescription of specific training intensity zones for on-water rowing training.

7.2 PRACTICAL APPLICATIONS

Findings from this project that are directly applicable to fitness testing and training monitoring for rowing include:

- Results from rowing tests using the Concept2 Model C or Model D ergometer can be directly compared.
- Physiological and performance changes between serial laboratory tests can be interpreted relative to the normal between-test variation estimated by the typical error for the laboratory protocol.
- The Cortex MetaMax3B portable indirect calorimetry system provides highly reliable results with a satisfactory degree of accuracy and is therefore suitable for on-water rowing applications.
- The physiological responses to simulated rowing on an ergometer and on-water single sculling are different, but the actual differences vary substantially between individuals.
- On-water incremental tests performed in single sculls provide exercise intensity prescriptions that are specific to on-water rowing training, assuming that the environmental conditions during testing are similar to those during training.
- Results from on-water incremental rowing tests are less reliable than those from laboratory-based rowing tests.
- On-water incremental rowing tests can be used to monitor fitness changes, but are no more effective than laboratory based tests.
- Results from laboratory-based rowing tests provide a better indication of potential 2000-m ergometer time-trial performance compared with those from the on-water test.

7.3 FUTURE DIRECTIONS

This thesis has demonstrated that the physiological responses to simulated rowing on an ergometer are different to those from the criterion of on-water performance and that an on-water incremental rowing test can improve the specificity of exercise prescriptions for on-water training. However, the underlying mechanisms responsible for the physiological differences between ergometer rowing and on-water sculling were not established. Despite the improved specificity of the on-water protocol, the corresponding test results are subject to larger between-test variations compared with the laboratory method, thereby reducing the on-water test's sensitivity to detect longitudinal fitness changes. An alternative way to improve the transfer of results between laboratory tests and on-water training scenarios, without compromising the reliability of the test, may involve refining ergometer based rowing simulations to better replicate the on-water conditions, such as increasing the skill requirements to perform on an ergometer.

Future studies may therefore attempt to isolate the mechanisms responsible for the physiological response differences between ergometer rowing and on-water performance. Given previous investigations comparing the biomechanics of ergometer and on-water rowing have reported that movement patterns (Martindale and Robertson 1984; Kleshnev 2005), force production (Elliott *et al.* 2002; Kleshnev 2005) and drive-to-recovery proportion (Dawson *et al.* 1998) all differ depending on the mode of rowing, these factors would conceivably impact on the force-velocity relationship of muscular contractions and the pattern of motor unit recruitment. Investigations examining muscle activity and recruitment during rowing could potentially identify whether differences exist between ergometer and on-water performances, and whether individual variations might be responsible for the observed diversity in the physiological response differences between the ergometer rowing and on-water sculling. Additionally, as the submaximal workloads of incremental rowing tests are controlled by pre-determined target power outputs (or stroke rates and RPEs during our on-water test), it is possible that force production and power-output for a given stroke rate are artificially lowered during the incremental test, thereby altering the stroke rate-power-output relationship compared to on-water training and performance. Thus, the actual incremental protocol could potentially be exacerbating the physiological differences between ergometer and on-

water rowing beyond those resulting from biomechanical and movement pattern variations. Stroke rate-power output relationships and physiological responses should therefore be compared between situations where rowing workloads are prescribed using submaximal power outputs and by target stroke rates only (whereby power output is self-selected), to establish if the results are consistent between conditions.

Future research may also evaluate ways to better replicate on-water rowing in the controlled laboratory environment. It has previously been suggested that the ‘floating foot-stretcher’ Rowperfect ergometer (Elliott *et al.* 2002), or an ergometer placed on rollers (Martindale and Robertson 1984), better replicates the movement patterns of on-water sculling. However, Kleshnev (2005) cautions that there are still biomechanical differences between rowing performed on the Rowperfect ergometer and in single sculls. Nevertheless, further work to better match the gearing and resistance characteristics of the ergometer flywheel to the actual on-water condition may improve rowing simulations provided by the Rowperfect ergometer, or the Concept2 when used with slides that permit the entire ergometer to move. This could possibly be achieved by simultaneously examining physiological responses and biomechanical factors across a range of ergometer resistance settings, and attempting to find the setting that best reproduces the biomechanics and physiology of the on-water criterion. In the case of the Concept2 ergometer, resistance characteristics can be adjusted by modulating the degree of flywheel damping, which can be controlled using the ‘drag factor’. It may therefore be possible to improve rowing simulations on the Concept2 by adopting a more suitable drag factor setting during laboratory tests. Moreover, as the ‘gearing’ and resistance characteristics of on-water rowing will differ between boat classes (i.e. single scull and coxed eight), Concept2 dragfactor settings could possibly be adjusted to simulate any of these classes. Thus, further research that critically evaluates laboratory-based rowing tests, and that attempts to improve ergometer-based rowing simulations, may eventually enable valid on-water training recommendations to be prescribed from laboratory-based rowing tests. Such an outcome would also avoid the logistical difficulties and limitations associated with conducting incremental rowing tests in the field.

REFERENCES

1. Affeld, K., Schichl, K. and Ziemann, A. (1993). "Assessment of rowing efficiency." *International Journal of Sports Medicine*, 14 (Suppl 1): S39-41.
2. Aitchison, D. and Grey, A. (2002). *A rowing gate based force sensor for the accurate assessment of propulsive force development*. International Conference on the Engineering of Sport, Kyoto, Japan, Blackwell Publishing.
3. Altenburg, D. (1992). "Planning and organizing general fitness training for rowers." *FISA Coach*, 3 (1): 5-8.
4. Armstrong, L. and Costill, D. (1985). "Variability of respiration and metabolism: responses to submaximal cycling and running." *Research Quarterly for Exercise and Sport*, 56: 93-96.
5. Åstrand, P.-O., Rodahl, K., Dahl, H. and Strømme, S. (2003). *Textbook of Work Physiology: Physiological Bases of Exercise*. 4th edition. Human Kinetics, Champaign.
6. Atkinson, G., Davison, R. and Nevill, A. (2005). "Performance characteristics of gas analysis systems: what we know and what we need to know." *International Journal of Sports Medicine*, 26 (Suppl 1): S2-10.
7. Barrett, R. and Manning, J. (2004). "Relationships between rigging set-up, anthropometry, physical capacity, rowing kinematics and rowing performance." *Sports Biomechanics*, 3 (2): 221-235.
8. Batterham, A. and Hopkins, W. (2006). "Making meaningful inferences about magnitudes." *International Journal of Sports Physiology and Performance*, 1: 50-57.
9. Beneke, R. (1995). "Anaerobic threshold, individual anaerobic threshold, and maximal lactate steady state in rowing." *Medicine and Science in Sports and Exercise*, 27 (6): 863-867.
10. Bishop, D., Jenkins, D. and Mackinnon, L. (1998). "The relationship between plasma lactate parameters, Wpeak and 1-h cycling performance in women." *Medicine and Science in Sports and Exercise*, 30 (8): 1270-1275.
11. Bland, J. and Altman, D. (1986). "Statistical methods for assessing agreement between two methods of clinical measurement." *Lancet*, 1: 307-310.
12. Bloomfield, J. and Roberts, A. (1972). "A correlational and trend analysis of strength and aerobic power scores in prediction of rowing performance." *Australian Journal of Sports Medicine*, 4: 25-36.
13. Bompa, T. (1980). "Technique and muscle force." *Canadian Journal of Applied Sport Sciences*, 5 (4): 245-249.

14. Bompa, T., Hebbelinck, M. and Van Gheluwe, B. (1985). "Force analysis of the rowing stroke employing two differing oar grips." *Canadian Journal of Applied Sport Sciences*, 10 (2): 64-67.
15. Borg, G. (1973). "Perceived exertion: a note on "history" and methods." *Medicine and Science in Sports and Exercise*, 5: 90-93.
16. Bourdin, M., Messonnier, L., Hager, J. and Lacour, J. (2004). "Peak power output predicts rowing ergometer performance in elite male rowers." *International Journal of Sports Medicine*, 25: 368-373.
17. Bourdon, P. (2000). "Blood lactate transition thresholds: concepts and controversies." In *Physiological tests for elite athletes*. Edited by C. Gore. Human Kinetics, Champaign, IL.
18. Bourdon, P., David, A. and Buckley, J. (2009). "A single exercise test for assessing physiological and performance parameters in elite rowers: the 2-in-1 test." *Journal of Science and Medicine in Sport*, 12: 205-211.
19. Boyas, S., Nordez, A., Cornu, C. and Guevel, A. (2006). "Power responses of a rowing ergometer: mechanical sensors vs. Concept2 measurement system." *International Journal of Sports Medicine*, 27 (10): 830-833.
20. Brooks, G. (1985). "Anaerobic threshold: review of the concept and directions for future research." *Medicine and Science in Sports and Exercise*, 17 (1): 22-34.
21. Bruce, C., Anderson, M., Fraser, S., Stepto, N., Klein, R., Hopkins, W. and Hawley, J. (2000). "Enhancement of 2000-m rowing performance after caffeine ingestion." *Medicine and Science in Sports and Exercise*, 32 (11): 1958-1963.
22. Buckley, J., Bourdon, P. and Woolford, S. (2003). "Effect of measuring blood lactate concentrations using different automated lactate analysers on blood lactate transition thresholds." *Journal of Science and Medicine in Sport*, 6 (4): 408-421.
23. Bunc, V., Heller, J., Moravec, P. and Sprynarova, S. (1989). "Ventilatory threshold and mechanical efficiency in endurance runners." *European Journal of Applied Physiology*, 58: 693-698.
24. Celentano, F., Cortili, G., Di Prampero, P. and Cerretelli, P. (1974). "Mechanical aspects of rowing." *Journal of Applied Physiology*, 36 (6): 642-647.
25. Chènier, D. and Leger, L. (1991). "Measurement of VO₂max with two rowing ergometers on the water in a skiff." *Canadian Journal of Applied Sport Sciences*, 16 (4): 258-263.
26. Chirtel, S., Barbee, R. and Stainsby, W. (1984). "Net O₂, CO₂, lactate, and acid exchange by muscle during progressive working contractions." *Journal of Applied Physiology*, 56 (1): 161-165.

27. Clausen, J. (1976). "Circulatory adjustments to dynamic exercise and effect of physical training in normal subjects and in patients with coronary artery disease." *Progress in Cardiovascular Diseases*, 18 (6): 459-495.
28. Clifford, P., Hanel, B. and Secher, N. (1994). "Arterial blood pressure response to rowing." *Medicine and Science in Sports and Exercise*, 26 (6): 715-719.
29. Coen, B., Urhausen, A. and Kindermann, W. (2003). "Sport specific performance diagnosis in rowing: an incremental graded exercise test in coxless pairs." *International Journal of Sports Medicine*, 24 (6): 428-432.
30. Cohen, J. (1988). *Statistical power analysis for the behavioral sciences*. 2nd edition. Laurence Erlbaum Associates, New Jersey: 567.
31. Cohen, J. (1990). "Things I have learned (so far)." *American Psychologist*, 45 (12): 1304-1312.
32. Connett, R., Gayeski, T. and Honig, C. (1984). "Lactate accumulation in fully aerobic, working, dog gracilis muscle." *American Journal of Physiology*, 246 (1): H120-128.
33. Cosgrove, M., Wilson, J., Watt, D. and Grant, S. (1999). "The relationship between selected physiological variables of rowers and rowing performance as determined by a 2000 m ergometer test." *Journal Sports Sciences*, 17 (11): 845-852.
34. Coyle, E., Martin, W., Ehsani, A., Hagberg, J., Bloomfield, S., Sinacore, D. and Holloszy, J. (1983). "Blood lactate threshold in some well-trained ischemic heart disease patients." *Journal of Applied Physiology*, 54 (1): 18-23.
35. Crouter, S., Antczak, A., Hudak, J., DellaValle, D. and Haas, J. (2006). "Accuracy and reliability of the ParvoMedics TrueOne 2400 and MedGraphics VO2000 metabolic systems." *European Journal of Applied Physiology*, 98 (2): 139-151.
36. Crouter, S., Foster, C., Esten, P., Brice, G. and Porcari, J. (2001). "Comparison of incremental treadmill exercise and free range running." *Medicine and Science in Sports and Exercise*, 33: 644-647.
37. Davis, J. (1985). "Anaerobic threshold: review of the concept and directions for future research." *Medicine and Science in Sports and Exercise*, 17 (1): 6-21.
38. Dawson, R., Lockwood, R., Wilson, J. and Freeman, G. (1998). "The rowing cycle: sources of variance and invariance in ergometer and on-the-water performance." *Journal of Motor Behaviour*, 30 (1): 33-43.
39. Di Prampero, P., Cortili, G., Celentano, F. and Cerretelli, P. (1971). "Physiological aspects of rowing." *Journal of Applied Physiology*, 31 (6): 853-857.

40. Donovan, C. and Brooks, G. (1983). "Endurance training affects lactate clearance, not lactate production." *American Journal of Physiology*, 244 (1): E83-92.
41. Douglas, C. (1911). "A method for determining the total respiratory exchange in man." *Journal of Physiology*, 42: 17-18.
42. Driller, M., Fell, J., Gregory, J., Shing, C. and Williams, A. (2009). "The effects of high-intensity interval training in well-trained rowers." *International Journal of Sports Physiology and Performance*, 4 (1): 110-121.
43. Droghetti, P., Jensen, K. and Nilsen, T. (1991). "The total estimated metabolic cost of rowing." *FISA coach*, 2 (2): 1-4.
44. Duffield, R., Dawson, B., Pinnington, H. and Wong, P. (2004). "Accuracy and reliability of a Cosmed K4b² portable gas analysis system." *Journal of Science and Medicine in Sport*, 7 (1): 11-22.
45. Eisenmann, J., Brisko, N., Shadrack, D. and Welsh, S. (2003). "Comparative analysis of the Cosmed Quark b² and K4b² gas analysis systems during submaximal exercise." *Journal of Sports Medicine and Physical Fitness*, 43: 150-155.
46. Elliott, B., Lyttle, A. and Birkett, O. (2002). "The RowPerfect ergometer: a training aid for on-water single scull rowing." *Sports Biomechanics*, 1 (2): 123-134.
47. Forsyth, J. and Reilly, T. (2003). "Reliability of lactate threshold assessment during rowing." *Journal Sports Sciences*, 21 (4): 272.
48. Fukunaga, T., Matsuo, A., Yamamoto, K. and Asami, T. (1986). "Mechanical efficiency in rowing." *European Journal of Applied Physiology and Occupational Physiology*, 55 (5): 471-475.
49. Godfrey, R. and Whyte, G. (2006). "Life at the top: how are elite rowers tested and monitored?" *Peak Performance*, 240: 5-8.
50. Gore, C., Catcheside, P., French, S., Bennett, J. and Laforgia, J. (1997). "Automated VO₂max calibrator for open-circuit indirect calorimetry systems." *Medicine and Science in Sports and Exercise*, 29 (8): 1095-1103.
51. Gore, C., Hopkins, W. and Burge, C. (2005). "Errors of measurement for blood volume parameters: a meta-analysis." *Journal of Applied Physiology*, 99 (November): 1745-1758.
52. Green, H., Hughson, R., Orr, G. and Ranney, D. (1983). "Anaerobic threshold, blood lactate, and muscle metabolites in progressive exercise." *Journal of Applied Physiology*, 54 (4): 1032-1038.
53. Gullstrand, L. (1996). "Physiological responses to short-duration high-intensity intermittent rowing." *Canadian Journal of Applied Physiology*, 21 (3): 197-208.

54. Hagberg, J. (1984). "Physiological implications of the lactate threshold." *International Journal of Sports Medicine*, 5 (Suppl 1): S106-109.
55. Hagberg, J. and Coyle, E. (1983). "Physiological determinants of endurance performance as studied in competitive racewalkers." *Medicine and Science in Sports and Exercise*, 15 (4): 287-289.
56. Hagberg, J., Coyle, E., Carroll, J., Miller, J., Martin, W. and Brooke, M. (1982). "Exercise hyperventilation in patients with McArdle's disease." *Journal of Applied Physiology*, 52 (4): 991-994.
57. Hagerman, F. (1984). "Applied physiology of rowing." *Sports Medicine*, 1: 303-326.
58. Hagerman, F. (2000). "Physiology of competitive rowing". In *Exercise and Sport Science*. Edited by W. E. J. Garrett and D. T. Kirkendall. Lippincott Williams & Wilkins, Philadelphia, PA: 843-873.
59. Hagerman, F., Addington, W. and Gaensler, E. (1972). "A comparison of selected physiological variables among outstanding competitive oarsmen." *Journal of Sports Medicine and Physical Fitness*, 12 (1): 12-22.
60. Hagerman, F., Connors, M., Gault, J., Hagerman, G. and Polinski, W. (1978). "Energy expenditure during simulated rowing." *Journal of Applied Physiology*, 45 (1): 87-93.
61. Hagerman, F., Hagerman, G. and Mickelson, T. (1979). "Physiological profiles of elite rowers." *Physician and Sportsmedicine*, 7 (7): 74-77.
62. Hagerman, F. and Lee, W. (1971). "Measurement of oxygen consumption, heart rate, and work output during rowing." *Medicine and Science in Sports*, 3 (4): 155-160.
63. Hagerman, F. and Staron, R. (1983). "Seasonal variation among physiological variables in elite oarsmen." *Canadian Journal of Applied Sport Sciences*, 8 (3): 143-148.
64. Hahn, A. (1990). "Identification and selection of talent in Australian rowing." *Excel*, 6 (3): 5-11.
65. Hahn, A., Bourdon, P. and Tanner, R. (2000). "Protocols for the physiological assessment of rowers". In *Physiological tests for elite athletes*. Edited by C. Gore. Human Kinetics, Champaign, IL: 311-326.
66. Hahn, A., Tumilty, D., Shakespear, P., Rowe, P. and Telford, R. (1988). "Physiological testing of oarswomen on Gjessing and Concept II rowing ergometers." *Excel*, 5 (1): 19-22.
67. Hartmann, U., Mader, A., Wasser, K. and Klauer, I. (1993). "Peak force, velocity, and power during five and ten maximal rowing ergometer strokes by world class female and male rowers." *International Journal of Sports Medicine*, 14 (Suppl 1): S42-45.

68. Hausswirth, C., Bigard, A. and Le Chevalier, J. (1997). "The Cosmed K4 telemetry system as an accurate device for oxygen uptake measurements during exercise." *International Journal of Sports Medicine*, 18: 449-453.
69. Heck, H., Mader, A., Hess, G., Mucke, S., Muller, R. and Hollmann, W. (1985). "Justification of the 4-mmol/l lactate threshold." *International Journal of Sports Medicine*, 6 (3): 117-130.
70. Henry, J., Clark, R., McCabe, R. and Vanderby, R., Jr. (1995). "An evaluation of instrumented tank rowing for objective assessment of rowing performance." *Journal Sports Sciences*, 13 (3): 199-206.
71. Holm, S. (1979). "A simple sequentially rejective multiple test procedure." *Scandinavian Journal of Statistics*, 6: 65-70.
72. Hopkins, W. (2000a). "Measures of reliability in sports medicine and science." *Sports Medicine*, 30: 1-15.
73. Hopkins, W. (2000b) "A new view of statistics." Internet Society for Sport Science: <http://www.sportsci.org/resource/stats/>.
74. Hopkins, W. (2002) "Probabilities of clinical or practical significance." *Sportscience*, 6.
75. Hopkins, W. (2003) "A spreadsheet for analysis of straightforward controlled trials." *Sportscience*, 7.
76. Hopkins, W. (2007) "A spreadsheet for deriving a confidence interval, mechanistic inference and clinical inference from a P value." *Sportscience*, 11.
77. Hopkins, W., Hawley, J. and Burke, L. (1999). "Design and analysis of research on sport performance enhancement." *Medicine and Science in Sports and Exercise*, 31 (3): 472-485.
78. Hopkins, W., Marshall, S., Batterham, A. and Hanin, J. (2009). "Progressive statistics for studies in sports medicine and exercise science." *Medicine and Science in Sports and Exercise*, 41 (1): 3-13.
79. Hughes, E., Turner, S. and Brooks, G. (1982). "Effects of glycogen depletion and pedaling speed on "anaerobic threshold"." *Journal of Applied Physiology*, 52 (6): 1598-1607.
80. Ingham, S., Carter, H. and Doust, J. (2002a). "Methods of determining oxygen uptake kinetics during heavy exercise in rowing." *Journal of Sports Sciences*, 20 (1): 51-52.
81. Ingham, S., Whyte, G., Jones, K. and Nevill, A. (2002b). "Determinants of 2,000 m rowing ergometer performance in elite rowers." *European Journal of Applied Physiology*, 88 (3): 243-246.

82. Jackson, R. and Secher, N. (1976). "The aerobic demands of rowing in two Olympic rowers." *Medicine and Science in Sports*, 8 (3): 168-170.
83. Jacobs, I. (1986). "Blood lactate, implications for training and sports performance." *Sports Medicine*, 3: 10-25.
84. Jürimäe, J. and Jürimäe, T. (2001). "Responses of blood hormones to the maximal rowing ergometer test in college rowers." *Journal of Sports Medicine and Physical Fitness*, 41 (1): 73-77.
85. Jürimäe, J., Mäestu, J. and Jürimäe, T. (2002a). "The relationship between different physiological variables of rowers and rowing performance as determined by a maximal rowing ergometer test." *Journal of Human Movement Studies*, 42 (5): 367-382.
86. Jürimäe, J., Mäestu, J., Jürimäe, T. and Pihl, E. (1999). "Relationship between rowing performance and different metabolic parameters in male rowers." *Medicina Dello Sport*, 52 (2): 119-126.
87. Jürimäe, J., Mäestu, J., Jürimäe, T. and Pihl, E. (2000). "Prediction of rowing performance on single sculls from metabolic and anthropometric variables." *Journal of Human Movement Studies*, 38: 123-136.
88. Jürimäe, J., Purge, P., Mäestu, J. and Jürimäe, T. (2002b). "Physiological responses to successive days of intense training in competitive rowers." *Hungarian Review of Sports Medicine*, 43 (1): 11-19.
89. Kane, D., Jensen, R., Williams, S. and Watts, P. (2008). "Effects of drag factor on physiological aspects of rowing." *International Journal of Sports Medicine*, 29 (5): 390-394.
90. Katch, V., Weltman, A., Sady, S. and Freedson, P. (1978). "Validity of the relative percent concept for equating training intensity." *European Journal of Applied Physiology*, 39: 219-227.
91. Kautza, B., Castello, G. and Sothmann, M. (2004). "Validation of MedGraphics' VO2000 portable metabolic analyzer and a modified pneumotachometer." *Medicine and Science in Sports and Exercise*, 36 (5): s222.
92. Kawakami, Y., Nozaki, D., Matsuo, A. and Fukunaga, T. (1992). "Reliability of measurement of oxygen uptake by a portable telemetric system." *European Journal of Applied Physiology and Occupational Physiology*, 65 (5): 409-414.
93. Kindermann, W., Simon, G. and Keul, J. (1979). "The significance of the aerobic-anaerobic transition for the determination of work load intensities during endurance training." *European Journal of Applied Physiology and Occupational Physiology*, 42 (1): 25-34.

94. Kleshnev, V. (2000). *Power in rowing*. 18th International Symposium on Biomechanics in Sport, Hong Kong, China, International Society of Biomechanics in Sports.
95. Kleshnev, V. (2005). *Comparison of on-water rowing with its simulation on Concept2 and Rowperfect machines*. 23rd International Symposium on Biomechanics in Sport, Beijing, China, International Society of Biomechanics in Sports.
96. Klusiewicz, A., Faff, J. and Zdanowicz, R. (1999). "Diagnostic value of indices derived from specific laboratory tests for rowers." *Biology of Sport*, 16 (1): 39-50.
97. Klusiewicz, A., Sitkowski, D., Bienko, A., Furdal, S. and Skwarczynski, T. (1991). "Optimizing the selection of indices for assessing the work capacity of rowers." *Biology of Sport*, 8 (4): 167-175.
98. Koutedakis, Y. (1989). "The role of physiological assessment in team selection with special reference to rowing." *British Journal of Sports Medicine*, 23 (1): 51-52.
99. Kramer, J., Leger, A., Paterson, D. and Morrow, A. (1994). "Rowing performance and selected descriptive, field, and laboratory variables." *Canadian Journal of Applied Physiology*, 19 (2): 174-184.
100. LaFontaine, T., Londeree, B. and Spath, W. (1981). "The maximal steady state versus selected running events." *Medicine and Science in Sports and Exercise*, 13 (3): 190-193.
101. Lamb, D. H. (1989). "A kinematic comparison of ergometer and on-water rowing." *American Journal of Sports Medicine*, 17 (3): 367-373.
102. Larsson, L. and Forsberg, A. (1980). "Morphological muscle characteristics in rowers." *Canadian Journal of Applied Sport Sciences*, 5 (4): 239-244.
103. Larsson, P., Wadell, K., Jakobsson, E., Burlin, L. and Henriksson-Larsén, K. (2004). "Validation of the MetaMax II portable metabolic measurement system." *International Journal of Sports Medicine*, 25: 115-123.
104. Lormes, W., Buckwitz, R., Rehbein, H. and Steinacker, J. (1993). "Performance and blood lactate on Gjessing and Concept II rowing ergometers." *International Journal of Sports Medicine*, 14 (Suppl 1): S29-31.
105. Lucía, A., Hoyos, J., Carvajal, A. and Chicharro, J. (1999). "Heart rate responses to professional road cycling: The Tour de France." *International Journal of Sports Medicine*, 20: 167-172.
106. Lucía, A., Hoyos, J., Perez, M. and Chicharro, J. (2000). "Heart rate and performance parameters in elite cyclists: a longitudinal study." *Medicine and Science in Sports and Exercise*, 32: 1777-1782.

107. Lucía, A., Pardo, J., Durantez, A., Hoyos, J. and Chicharro, J. (1998). "Physiological differences between professional and elite road cyclists." *International Journal of Sports Medicine*, 19: 342-348.
108. MacRae, H., Hise, K. and Allen, P. (2000). "Effects of front and dual suspension mountain bike systems on uphill cycling performance." *Medicine and Science in Sports and Exercise*, 32 (7): 1276-1280.
109. Mäestu, J. and Jürimäe, J. (2000). "Anthropometrical and physiological factors of rowing performance: a review." *Acta Kinesiologiae Universitatis Tartuensis*, 5: 130-150.
110. Mäestu, J., Jürimäe, J. and Jürimäe, T. (2000). "Prediction of rowing performance from selected physiological variables." *Medicina Dello Sport*, 53 (3): 247-254.
111. Mahler, D., Nelson, W. and Hagerman, F. (1984). "Mechanical and physiological evaluation of exercise performance in elite national rowers." *Journal of the American Medical Association*, 252 (4): 496-499.
112. Mahler, D., Parker, H. and Andresen, D. (1985). "Physiologic changes in rowing performance associated with training in collegiate women rowers." *International Journal of Sports Medicine*, 6 (4): 229-233.
113. Mahony, N., Donne, B. and O'Brien, M. (1999). "A comparison of physiological responses to rowing on friction-loaded and air-braked ergometers." *Journal of Sports Sciences*, 17 (2): 143-149.
114. Martin, T. and Bernfield, J. (1980). "Effect of stroke rate on velocity of a rowing shell." *Medicine and Science in Sports and Exercise*, 12 (4): 250-256.
115. Martindale, W. and Robertson, D. (1984). "Mechanical energy in sculling and in rowing an ergometer." *Canadian Journal of Applied Sport Sciences*, 9 (3): 153-163.
116. McKenzie, D. and Rhodes, E. (1982). "Cardiorespiratory and metabolic responses to exercise on a rowing ergometer." *Australian Journal of Sports Medicine*, 14 (1): 21-23.
117. McLaughlin, J., King, G., Howley, E., Bassett, D. J. and Ainsworth, B. (2001). "Validation of the COSMED K4 b² portable metabolic system." *International Journal of Sports Medicine*, 22: 280-284.
118. McLellan, T. and Jacobs, I. (1993). "Reliability, reproducibility and validity of the individual anaerobic threshold." *European Journal of Applied Physiology and Occupational Physiology*, 67 (2): 125-131.
119. McLellan, T. and Skinner, J. (1981). "The use of the aerobic threshold as a basis for training." *Canadian Journal of Applied Sport Sciences*, 6 (4): 197-201.

120. Meyer, T., Davidson, R. and Kindermann, W. (2005a). "Ambulatory gas exchange measurements - current status and future options." *International Journal of Sports Medicine*, 26 (Suppl 1): S19-27.
121. Meyer, T., Gabriel, H. and Kindermann, W. (1999). "Is determination of exercise intensities as percentages of VO_2max or HRmax adequate?" *Medicine and Science in Sports and Exercise*, 31 (9): 1342-1345.
122. Meyer, T., Georg, T., Becker, C. and Kindermann, W. (2001). "Reliability of gas exchange measurements from two different spirometry systems." *International Journal of Sports Medicine*, 22: 593-597.
123. Meyer, T., Lucia, A., Earnest, C. and Kindermann, W. (2005b). "A conceptual framework for performance diagnosis and training prescription from submaximal gas exchange parameters - theory and application." *International Journal of Sports Medicine*, 26 (Suppl 1): S38-48.
124. Mickelson, T. and Hagerman, F. (1982). "Anaerobic threshold measurements of elite oarsmen." *Medicine and Science in Sports and Exercise*, 14 (6): 440-444.
125. Mikulić, P., Ruzić, L. and G., O. (2007). "What distinguishes the Olympic level heavyweight rowers from other internationally successful rowers?" *Collegium Antropologicum*, 31 (3): 811-816.
126. Millet, G., Tronche, C., Fuster, N. and Candau, R. (2002). "Level ground and uphill cycling efficiency in seated and standing positions." *Medicine and Science in Sports and Exercise*, 34 (10): 1645-1652.
127. Payne, W., Smith, R., Galloway, M. and Hull, T. (1995). *How valid is ergometer testing for measuring blood lactate profiles: summary report*. National Sports Research Centre, Belconnen, A.C.T.
128. Payne, W., Smith, R., Galloway, M. and Hull, T. (1996). *The validity of ergometer testing in rowing*. National Sports Research Centre, Australian Sports Commission, Belconnen, A.C.T.
129. Petibois, C., Cazorla, G. and Deleris, G. (2003). "The biological and metabolic adaptations to 12 months training in elite rowers." *International Journal of Sports Medicine*, 24 (1): 36-42.
130. Pinnington, H., Wong, P., Tay, J., Green, D. and Dawson, B. (2001). "The level of accuracy and agreement in measures of $F_{E\text{O}_2}$, $F_{E\text{CO}_2}$ and V_E between the Cosmed K4b² portable, respiratory gas analysis system and a metabolic cart." *Journal of Science and Medicine in Sport*, 4 (3): 324-335.
131. Prieur, F., Castells, J. and Denis, C. (2003). "A methodology to assess the accuracy of a portable metabolic system ($V_{\text{maxST}}^{\text{TM}}$)." *Medicine and Science in Sports and Exercise*, 35 (5): 879-885.

132. Pripstein, L., Rhodes, E., McKenzie, D. and Coutts, K. (1999). "Aerobic and anaerobic energy during a 2-km race simulation in female rowers." *European Journal of Applied Physiology and Occupational Physiology*, 79 (6): 491-494.
133. Robertson, E., Pyne, D., Hopkins, W. and Anson, J. (2009). "Analysis of lap times in international swimming competitions." *Journal of Sports Sciences*, 27 (4): 387-395.
134. Romer, L., Davies, P., Godfrey, R., Humphrey, S., McCarthy, P. and Ramsay, R. (1999). "Anaerobic and aerobic contributions to intense exercise in elite rowers: effects of sex and weight category." *Journal of Sports Sciences*, 17: 43-44.
135. Roth, W., Schwanitz, P., Pas, P. and Bauer, P. (1993). "Force-time characteristics of the rowing stroke and corresponding physiological muscle adaptations." *International Journal of Sports Medicine*, 14 (Suppl 1): S32-34.
136. Russell, A., le Rossignol, P. and Sparrow, W. (1998). "Prediction of elite schoolboy 2000 m rowing ergometer performance from metabolic, anthropometric and strength variables." *Journal of Sports Sciences*, 16: 749-754.
137. Russell, G., Gore, C., Ashenden, M., Parisotto, R. and Hahn, A. (2002). "Effects of prolonged low doses of recombinant human erythropoietin during submaximal and maximal exercise." *European Journal of Applied Physiology*, 86 (5): 442-449.
138. Ryan-Tanner, R., Hahn, A., Lawton, E., Bellenger, S. and Kearns, A. (1999a). *A comparison of "performance" during on-water racing and ergometer rowing*. Fifth IOC World Congress on Sport Sciences; Australian Conference of Science and Medicine in Sport Sydney, Sports Medicine Australia, Canberra.
139. Ryan-Tanner, R., Hahn, A., Lawton, E., Bellenger, S. and Kearns, A. (1999b). *A comparison of physiological responses to ergometer and on-water rowing*. Fifth IOC World Congress on Sport Sciences; Australian Conference of Science and Medicine in Sport Sydney, Sports Medicine Australia, Canberra.
140. Saltin, B. and Astrand, P. (1967). "Maximal oxygen uptake in athletes." *Journal of Applied Physiology*, 23 (3): 353-358.
141. Sanderson, B. and Martindale, W. (1986). "Towards optimizing rowing technique." *Medicine and Science in Sports and Exercise*, 18 (4): 454-468.
142. Schabort, E., Hawley, J., Hopkins, W. and Blum, H. (1999). "High reliability of performance of well-trained rowers on a rowing ergometer." *Journal of Sports Sciences*, 17 (8): 627-632.

143. Schulz, H., Helle, S. and Heck, H. (1997). "The validity of the telemetric system CORTEX X1 in the ventilatory and gas exchange measurement during exercise." *International Journal of Sports Medicine*, 18: 454-457.
144. Secher, N. (1983). "The physiology of rowing." *Journal of Sports Sciences*, 1 (1): 23-53.
145. Secher, N. (1990). "Rowing". In *Physiology of Sports*. Edited by T. Reilly. E. & F. N. Spon, London: 259-285.
146. Secher, N. (1993). "Physiological and biomechanical aspects of rowing. Implications for training." *Sports Medicine*, 15 (1): 24-42.
147. Secher, N., Espersen, M., Binkhorst, R., Andersen, P. and Rube, N. (1982a). "Aerobic power at the onset of maximal exercise." *Scandinavian Journal of Sports Sciences*, 4 (1): 12-16.
148. Secher, N., Ruberg-Larsen, N., Binkhorst, R. and Bonde-Petersen, F. (1974). "Maximal oxygen uptake during arm cranking and combined arm plus leg exercise." *Journal of Applied Physiology*, 36 (5): 515-518.
149. Secher, N. and Vaage, O. (1983). "Rowing performance, a mathematical model based on analysis of body dimensions as exemplified by body weight." *European Journal of Applied Physiology and Occupational Physiology*, 52 (1): 88-93.
150. Secher, N., Vaage, O. and Jackson, R. (1982b). "Rowing performance and maximal aerobic power of oarsmen." *Scandinavian Journal of Sports Sciences*, 4 (1): 9-11.
151. Secher, N., Vaage, O., Jensen, K. and Jackson, R. (1983). "Maximal aerobic power in oarsmen." *European Journal of Applied Physiology and Occupational Physiology*, 51 (2): 155-162.
152. Shephard, R. (1998). "Science and medicine of rowing: a review " *Journal of Sports Sciences*, 16 (7): 603-620.
153. Sjodin, B., Jacobs, I. and Svedenhag, J. (1982). "Changes in onset of blood lactate accumulation (OBLA) and muscle enzymes after training at OBLA." *European Journal of Applied Physiology and Occupational Physiology*, 49 (1): 45-57.
154. Skinner, J. and McLellan, T. (1980). "The transition from aerobic to anaerobic metabolism." *Research Quarterly for Exercise and Sport*, 51 (1): 234-248.
155. Smith, R., Galloway, M., Patton, R. and Spinks, W. (1993). "Ergometer based prediction of on-water rowing performance." *Sports Coach*, 16 (2): 24-26.
156. Smith, R., Galloway, M., Patton, R. and Spinks, W. (1994). "Analysing on-water rowing performance." *Sports Coach*, 17: 37-40.

157. Smith, R. and Loschner, C. (2002). "Biomechanics feedback for rowing." *Journal of Sports Sciences*, 20: 783-791.
158. Soper, C. and Hume, P. (2004). "Reliability of power output during rowing changes with ergometer type and race distance." *Sports Biomechanics*, 3 (2): 237-248.
159. Stegmann, H. and Kindermann, W. (1982). "Comparison of prolonged exercise tests at the individual anaerobic threshold and the fixed anaerobic threshold of 4 mmol.l⁻¹ lactate." *International Journal of Sports Medicine*, 3 (2): 105-110.
160. Steinacker, J. (1993). "Physiological aspects of training in rowing." *International Journal of Sports Medicine*, 14 (Suppl 1): S3-10.
161. Steinacker, J., Both, M. and Whipp, B. (1993a). "Pulmonary mechanics and entrainment of respiration and stroke rate during rowing." *International Journal of Sports Medicine*, 14 (Suppl 1): S15-19.
162. Steinacker, J., Laske, R., Hetzel, W., Lormes, W., Liu, Y. and Stauch, M. (1993b). "Metabolic and hormonal reactions during training in junior oarsmen." *International Journal of Sports Medicine*, 14 (Suppl 1): S24-28.
163. Steinacker, J., Marx, T. and Theil, U. (1982). *A rowing ergometer test with stepwise increased workloads*. World Congress of Sports Medicine, Vienna, Urban and Schwarzenberg.
164. Steinacker, J., Michalsky, R., Grünert-Fuchs, M. and Lormes, W. (1987). "Field tests in rowing (English translation of Feldtests im rudern)." *Deutsche Zeitschrift Für Sportmedizin*, 38: 19-26.
165. Sterne, J. and Davey Smith, G. (2001). "Sifting the evidence-what's wrong with significance tests?" *British Medical Journal*, 322: 226-231.
166. Stuart, M., Howley, E., Gladden, L. and Cox, R. (1981). "Efficiency of trained subjects differing in maximal oxygen uptake and type of training." *Journal of Applied Physiology*, 50: 444-449.
167. Urhausen, A., Coen, B., Weiler, B. and Kindermann, W. (1993a). "Individual anaerobic threshold and maximum lactate steady state." *International Journal of Sports Medicine*, 14 (3): 134-139.
168. Urhausen, A., Weiler, B. and Kindermann, W. (1993b). "Heart rate, blood lactate, and catecholamines during ergometer and on water rowing." *International Journal of Sports Medicine*, 14 (Suppl 1): S20-23.
169. Vaage, O. (1977). "Table 16-2". In *Textbook of Work Physiology*. 2nd edition. Edited by P.-O. Åstrand and K. Rodahl. McGraw-Hill, New York.
170. Vermulst, L., Vervoorn, C., Boelens-Quist, A., Koppeschaar, H., Erich, W., Thijssen, J. and de Vries, W. (1991). "Analysis of seasonal training volume and working capacity in elite female rowers." *International Journal of Sports Medicine*, 12 (6): 567-572.

171. Vogler, A., Lindh, A. and Rice, A. (2008). Accuracy and reliability of MinimaxX GPS technology in rowing (Abstract). *13th Annual Congress of the European College of Sport Science*. Editorial do Ministério da Educação, Estoril, Portugal: 693-694.
172. Vogler, A., Rice, A. and Withers, R. (2007). "Physiological responses to exercise on different models of Concept II rowing ergometer." *International Journal of Sports Physiology and Performance*, 2 (December): 360-370.
173. Wasserman, K. and McIlroy, M. (1964). "Detecting the threshold of anaerobic metabolism in cardiac patients during exercise." *American Journal of Cardiology*, 14: 844-852.
174. Withers, R., Gore, C., Gass, G. and Hahn, A. (2000). "Determination of maximal oxygen consumption (VO_2 max) or maximal aerobic power". In *Physiological Tests For Elite Athletes*. Edited by C. Gore. Human Kinetics, Champaign, IL: 114-127.
175. Womack, C., Davis, S., Wood, C., Sauer, K., Alvarez, J., Weltman, A. and Gaesser, G. (1996). "Effects of training on physiological correlates of rowing ergometry performance." *Journal of Strength and Conditioning Research*, 10 (4): 234-238.
176. Woolford, S. and Gore, C. J. (2004). " Interpreting skinfold sums. Use of absolute or relative typical error?" *American Journal of Human Biology*, 16 (1): 87-90.
177. Yoshiga, C. and Higuchi, M. (2003). "Rowing performance of female and male rowers." *Scandinavian Journal of Medicine and Science in Sports*, 13 (5): 317-321.

APPENDIX

PUBLICATIONS

CHAPTER 3: VALIDATION OF THE CONCEPT2 MODEL D ROWING ERGOMETER

Vogler, A., Rice, A. and Withers, R. (2007). "Physiological responses to exercise on different models of the Concept II rowing ergometer." *International Journal of Sports Physiology and Performance*, 2 (4): 360-370.

Physiological responses to exercise on different models of Concept II rowing ergometer

Original Investigation

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Purpose: The Concept II Model C (IIC) rowing ergometer was replaced by the Concept II Model D (IID), but the design modifications of the updated ergometer may alter resistance characteristics and rowing technique thereby potentially influencing ergometer test results. This study evaluated the physiological response to rowing on the IIC and IID ergometers during a sub-maximal progressive incremental test and maximal performance time trial. **Methods:** Eight national level rowers completed sub-maximal and maximal tests on the IIC and IID ergometers separated by 48-72 h. Physiological responses and calculated blood lactate thresholds (LT₁ and LT₂) were compared between ergometer models (IIC vs. IID) using standardised drag factor settings. **Results:** Power output, oxygen consumption, rowing economy (mLO₂·min⁻¹·W⁻¹), heart rate, blood lactate concentration, stroke rate and rating of perceived exertion all displayed similar responses regardless of ergometer model. Calculated physiological values equivalent to LT₁ and LT₂ were also similar between models, except for blood lactate concentration at LT₁ which displayed a small but statistically significant difference (P=0.02) of 0.2 mmol·L⁻¹. **Conclusions:** The physiological response when rowing on IIC and IID ergometers is nearly identical and testing may therefore be carried out on either ergometer and the results directly compared.

Key Words: rowing, ergometer, oxygen consumption, blood lactate, rowing economy

CHAPTER 4: VALIDITY OF THE METAMAX3B PORTABLE METABOLIC SYSTEM

Vogler, A., Rice, A. and Gore, C. (2010). "Validity and reliability of the Cortex MetaMax3B portable metabolic system." Accepted in *Journal of Sports Sciences*.

Validity and reliability of the Cortex MetaMax3B portable metabolic system

Original Investigation

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Abstract

Portable indirect calorimetry systems offer the advantage of field-based measurements, but manufacturers rarely provide data about either validity or reliability. This investigation evaluated the validity and reliability of the Cortex MetaMax3B portable metabolic system. Validity was determined by comparing MetaMax3B results against those from a first-principles metabolic calibrator and an automated Douglas bag system. Reliability was obtained from duplicate exercise tests completed by eight athletes. Participants completed three identical incremental rowing tests on a Concept2 ergometer; two tests used the MetaMax3B and one test used the Douglas bag system. Compared to the metabolic calibrator, MetaMax3B results were within 0.20 L.min⁻¹ (7.8%) and 6.15 L.min⁻¹ (4.0%) for $\dot{V}O_2$ and $\dot{V}E$, respectively. During exercise, MetaMax3B results were within 0.16 L.min⁻¹ (4.1%; $\dot{V}O_2$), 0.32 L.min⁻¹ (7.7%; $\dot{V}CO_2$) and 3.22 L.min⁻¹ (4.9%; $\dot{V}E$) compared to the Douglas bag system. MetaMax3B results were significantly higher for submaximal $\dot{V}O_2$ ($p=0.03$) and $\dot{V}CO_2$ ($p<0.001$). Typical error from duplicate exercise tests using the MetaMax3B ranged from 2.0% ($\dot{V}O_2$) to 3.6% ($\dot{V}E$). Our results show that the MetaMax3B provides reliable measurements of metabolic demand with adequate validity for field-based measurements.

Keywords: Indirect calorimetry, oxygen consumption, carbon dioxide production, Douglas bag

CHAPTER 5: COMPARISON OF ERGOMETER AND ON-WATER INCREMENTAL ROWING TESTS

Vogler, A., Rice, A. and Gore, C. (2010). "Physiological responses to ergometer and on-water incremental rowing tests." Accepted in *International Journal of Sports Physiology and Performance*.

Physiological responses to ergometer and on-water incremental rowing tests

Original Investigation

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Purpose: This study evaluated the validity of ergometer tests against the criterion of on-water rowing and determined the reliability of field measurements by comparing results between ergometer (ERG) and on-water (OW) tests. **Methods:** Seven male rowers completed incremental tests on a Concept2 rowing ergometer and in a single scull. Average power output, oxygen consumption ($\dot{V}O_2$), heart rate (HR), blood lactate concentration (BLa) and distance completed were measured during each ERG and OW workload. **Data treatment:** Linear regression between power output and HR, BLa and distance allowed submaximal results to be compared between ERG and OW tests at equivalent intensities based on five standard power outputs. Submaximal results were analyzed using repeated measure factorial ANOVAs and maximal data used dependent *t*-tests ($P < 0.05$), the magnitude of differences were also classified using effect size analyses. The reliability of repeated measurements was established using Typical Error. **Results:** Differences between ERG and OW submaximal results were not statistically significant for power output HR, BLa, and $\dot{V}O_2$, but distance completed ($P < 0.001$) was higher during the ERG test. However, the magnitude of physiological response differences between the ERG and OW tests varied between individuals. Mean HR at anaerobic threshold showed good agreement between both tests ($r = 0.81$), but the standard error of the estimate was 9 $\text{beat}\cdot\text{min}^{-1}$. **Conclusions:** Individual variation in physiological response differences between ERG and OW tests meant that training intensity recommendations from the ERG test were not applicable to on-water training for some rowers, but provided appropriate prescriptions for most athletes.

Key Words: Oxygen consumption, heart rate, blood lactate threshold, training prescription, Concept2