METABOLIC SPECIFICITY IN OUTRIGGER CANOE PADDLERS

by

JANE MARIE LABRECHE

B.H.K., University of British Columbia, 1999

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR

THE DEGREE OF MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

SCHOOL OF HUMAN KINETICS

We accept this thesis as conforming to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

October, 2001

~~Department of~~ School of Human Kinetics

The University of British Columbia
Vancouver, Canada

Date Oct 11/01

ABSTRACT

Leg drive is encouraged in paddling to increase power per stroke. When involving additional muscle mass during exercise, it can be expected that the metabolic demand would also increase. Treadmill (TM) and paddling ergometer (PE) with leg drive, (PEL) and with no leg drive (PENL) incremental testing to fatigue was recorded in 22 healthy male subjects. Eleven experienced outrigger canoeists (P) (age=35.64±5.66 yrs, ht=179.16±3.81 cm, wt=84.39±9.23 kg) and eleven matched controls (C) (age=36.45±5.66 yrs, ht=178.85±4.07 cm, wt=83.95±8.32 kg) participated. Metabolic variables were monitored using the COSMED K4b^2 portable metabolic system. Oxygen consumption was significantly increased with the addition of leg drive during maximal exercise on the paddling ergometer (PEL=3.88±0.53, PENL=3.23±0.47 L/min). Paddlers attained a higher percentage (14.58% higher than controls) of treadmill VO_2max when using leg drive. Furthermore, trained individuals (the paddling group) were able to reach higher percentages of treadmill VO_2max during paddling tests both with legs (P=85.05±7.82 vs. C=67.52±4.58) and without legs (P=70.47±5.47 vs. C=61.79±4.16) when compared to the untrained individuals. There was no significant difference between oxyhaemoglobin saturation levels of paddlers and controls across the three testing conditions. Ventilatory thresholds were significantly higher on the TM than on the PE, but were not significantly different between groups. At exercise intensities of 75% and 100% VO_2max during PEL significantly higher breathing frequency (45.57±6.86 vs. 57.71±7.99 br/min respectively), tidal volume (2.20±0.35 vs. 2.57±0.35 L respectively), and minute ventilation (99.44±20.17 vs. 146.84±18.54 L/min respectively) values were recorded in paddlers. In addition, at the same intensities of 75% and 100% VO_2max, stroke rate was significantly correlated with breathing frequency (r=0.833, r=0.693 respectively), indicating entrainment in the paddling group.

Therefore leg drive does appear to affect the energy cost of paddling. These results suggest that the metabolic demand of exercise is sensitive to the specificity of testing conditions.

TABLE OF CONTENTS

Abstract.. ii

Table of Contents... iv

List of Tables.. v

List of Figures... vi

Acknowledgments... vii

Introduction.. 1

Methodology.. 3
- Subjects 3
- Experimental Protocol 3
- Maximal Paddling Ergometer Test 5
- Maximal Treadmill Test 5
- Statistical Analysis 6

Results... 7
- Maximal Exercise Testing 8
- Paddling VO_2max as a Percentage of Treadmill VO_2max 10
- Respiratory Kinetics (PEL Test Only) 12
- Ventilatory Thresholds 16

Discussion.. 17
- Descriptive Data 17
- Maximal Exercise Testing 18
- Respiratory Kinetics 21
- Ventilatory Thresholds 22
- Summary 24

References.. 25

Appendix A: Review of Literature.. 29
- Introduction 29
- Volume of Active Muscle Mass 29
- Central vs. Peripheral Limitations to Exercise 30
- Exercise-Induced Hypoxemia 32
- Ventilatory Thresholds 34
- Summary 34

Appendix B: Photos of subject on adapted Concept II paddling erg....... 35

LIST OF TABLES

Results:

Table 1. Anthropometric data.. 7
Table 2. Maximal treadmill and paddling ergometer data.................. 9
Table 3. Respiratory kinetics data.. 13

LIST OF FIGURES

Results:

Figure 1. Paddling ergometer data as a percentage of treadmill data..... 11
Figure 2. Breathing frequency and stroke rate at 25% VO_2max.......... 14
Figure 3. Breathing frequency and stroke rate at 50% VO_2max.......... 14
Figure 4. Breathing frequency and stroke rate at 75% VO_2max.......... 15
Figure 5. Breathing frequency and stroke rate at 100% VO_2max......... 15

ACKNOWLEDGEMENTS

I would like my family and friends to know how much I appreciated the time they volunteered to participate in one (and sometimes two or three) of the studies I completed during this degree. And I would especially like to thank my advisor and colleagues within the lab for always being approachable and available to point me in the right direction.

INTRODUCTION

Canoeists can be classified according to the type of boat they paddle. Traditional canoeists are in the high-kneel position (C1, C2, C4, C15) while dragonboat and outrigger paddlers (OC1, OC2, OC6) are seated. Dragonboat and traditional canoeists are sprinters competing in flat-water events, only paddling on the preferred side. Outrigger canoeists are mainly endurance based competing in open water, paddling on both the left and right sides. Distance races in outrigger canoes are generally held over 5-42 km.

As paddling sports become more common recreationally as well as competitively, it is necessary to develop protocol and testing procedures specific to their needs. Traditionally, the cycle ergometer and treadmill (TM) have been the preferred assessment equipment for studying the metabolic demands of exercise. In upper body athletes, arm ergometry has been utilized in an attempt to make testing more sport-specific. For paddlers however, an arm crank test is not as specific as a cycle ergometer test is to a cyclist, a treadmill test is to a runner, or a rowing ergometer test is to a rower. For kayakists, the use of the K1 Ergo (wind-braked kayak ergometer) has been reported (Bishop, 2000; van Someren et al., 2000). In terms of canoeists, the literature does indicate the limited employment of paddling ergometry. Early studies cite the use of a "customized" paddling ergometer (Bunc and Heller, 1991; Bunc et al., 1987). More recent work involves the use of an adapted Concept II rowing ergometer known for its reliability and widespread use with the rowing population (Humphries et al., 2000). Within our own lab, this ergometer was found to be a useful tool for race simulation in dragonboat paddlers when comparing it to an on-water race simulation. The paddling ergometer (PE) continues to grow in popularity both as a training tool as well as a research and testing tool. Research indicating that the quantity and trainability of active muscle mass during exercise directly affects metabolic demands and possibly performance has provoked further investigations into the appropriateness of testing in the laboratory situation. Particularly in unique populations, such as in those who paddle, these variables play a distinct and measurable role during exercise. While other paddling disciplines (mostly flatwater sprinters) have been investigated to some extent, data on outrigger canoeists are limited. A recent study by Humphries et al. (2000) was the first of it's kind to examine this population reporting descriptive data using paddling ergometry. Studies involving intervention to address some of the issues facing canoeists have yet to be performed until the present investigation.

Involving additional muscle mass during a stroke has implications for outrigger paddling technique. While most of the force and propulsion in paddling is derived from the arms and trunk, (seated) canoeists are encouraged to utilize leg drive to improve performance. Pushing on the inside of the hull of the canoe with their legs, allows the paddler to both stabilize their body, as well as assisting in the rotation of the torso during the stroke thereby increasing power per stroke. Although this particular technique variation has never been addressed scientifically, it can be assumed that increasing active muscle mass will also increase oxygen consumption. If power and VO_2 significantly increase when the legs are active during paddling, then there is reason to believe that performance can be improved.

The purpose of this study was to investigate the metabolic specificity in outrigger canoe paddlers. The oxygen demand of paddling with and without leg drive was compared to whole-body exercise in trained and untrained individuals. It was hypothesized that by allowing paddlers to utilize their legs during each stroke, overall metabolic demand would be altered.

METHODOLOGY

Subjects

Twenty-two male subjects were recruited. Eleven experienced outrigger paddlers were recruited from False Creek Racing Canoe Club and the Jericho Outrigger Canoe Club. These athletes had competed in the sport for a minimum of 2 years with an average of 10 years for the group. All paddlers were able to complete a 5 km time trial in a solo outrigger canoe in less than 27.5 minutes. Eleven active, non-paddling individuals were recruited to form the control group. This group regularly exercised with a minimum of 30 minutes of moderate exercise 3x/wk. Control subjects were both height and age matched to their respective paddlers. Requirements were to be within 2 inches of height and 2 years of age. All subjects were non-smokers with no allergies and no history of cardiac or respiratory disease. Subjects who satisfied these criteria were included in the study. Prior to any testing, subjects received a verbal description of the experiment, and completed a written consent form. This study was approved by the Clinical Screening Committee for Research and Other Studies Involving Human Subjects of the University of British Columbia.

Experimental Protocol

Subjects were required to report to the laboratory on three separate occasions to perform three maximal tests, one running and two paddling (legs, no legs). There was at least 48 hours between each visit. Subjects were asked to abstain from strenuous exercise for 24 hours and to fast 2 hours (water allowed) prior to testing. Anthropometric data was obtained during the initial session, including age, standing height, sitting height, arm span, and body mass. For all testing, expired gases were collected and analyzed breath-by-breath using a portable metabolic system (COSMED K4b^2 Rome, Italy). This unit has been found to be reliable by McLaughlin et al

(2001) for work rates up to 250 W and within our own lab, compared to the Physio-Dyne metabolic data acquisition system (Physio-Dyne Instrument Corp. Quogue N.Y. 11959) for maximal exercise (VO_2 r=0.972). Oxygen consumption (VO_2), production of carbon dioxide (VCO_2), breathing frequency (Rf), tidal volume (VT), and minute ventilation (VE) were all measured. Prior to testing each testing session, the gas analyzers were calibrated with a known gas and room air. Arterial oxygen saturation levels (SaO_2) were measured with a pulse ear oximeter (Ohmeda Biox 3740, BOC Health Care Inc. Edison, NJ). SaO_2 was recorded at exhaustion. Heart rate was measured using a heart rate monitor interfaced with the $K4b^2$ unit (Polar Vantage XL, Kempele, Finland). Standard indicators for achieving VO_2max were used: volitional fatigue, a plateau in VO_2 with increasing work rate, heart rate $\geq$ 90% of age predicted maximum, and a respiratory exchange ratio $\geq$ 1.15. Given that three of the preceding criteria were met, VO_2max was determined by averaging the 4 highest consecutive 15 second intervals.

Ventilatory thresholds were determined by visual inspection of 15 second plots of minute ventilation versus time by two observers (one of which was blinded to the test condition). The inflection point whereby minute ventilation increased exponentially was the criteria. The observers agreed on 58 of the 66 cases. If the threshold could not be agreed upon, an average of the two were taken. If the threshold could not be determined at all (4 cases), plots of VE/VO_2 versus VE/VCO_2 were used whereby the threshold was determined to be at the intersection point of these two variables.

Respiratory kinetics (Rf, VT, VE) and HR were reviewed at four points during the paddling (with legs) test only. Data from the second minute of each 2-minute stage were averaged and expressed as a percentage of the VO_2max as previously determined. Values closest to 25%, 50%, 75% and 100% were selected.

Maximal Paddling Ergometer Test

Subjects were tested on a paddling ergometer (Concept II Model C Indoor Rower with paddling adapter, Vermont Waterways Inc. East Hardwick VT). The rowing ergometer was fitted with a canoe paddle shaft. The participants sat on a stationary seat located on the central shaft of the ergometer (Appendix B). The Concept II display was used to monitor power output (W) throughout the test. Those not familiar with the apparatus completed an introductory session to the ergometer prior to the initial test.

For testing that included the legs, subjects were allowed to apply pressure with their feet and legs on either the floor, or on the foot pegs attached to the shaft of the ergometer. For testing excluding the legs, subjects were anchored to the seat by a hip strap with their feet resting on a wooden block at the approximate distance of the foot pegs. Subjects were permitted to have some movement through the hips but were asked not to apply pressure with the legs and were monitored visually for this throughout the test. After a 5-minute self-selected warm-up, paddling commenced for 2 minutes at 25 W (paddlers) or 20 W (for controls) increasing 25 W (paddlers) or 20 W (controls) each two minutes until the individual failed to maintain the intensity for that given workload. Subjects regulated intensity by visually monitoring the power output per stroke displayed on the monitor of the paddling ergometer and adjusting to adhere to the requirements listed above. A 30 second stroke side change was maintained throughout the test. Stroke rate was recorded manually for each 2-minute step. Stroke rate was self-selected.

Maximal Treadmill Test

Subjects were tested on a Precor C964i running treadmill (Precor Inc., Bothwell WA). After a 5-minute self-selected warm-up, running began at 6 mph increasing 1 mph every two minutes thereafter until volitional fatigue. All subjects completed the same protocol with two exceptions. Based on the experience of these two subjects, we began one individual at 5mph while the other began at 7 mph in efforts to keep the test within 8-12 minutes in length. The treadmill was kept at a zero degree grade for the duration of the test.

Statistical Analysis

Maximal data and ventilatory threshold data were examined using a 2 (group) by 3 (test) factorial analysis of variance (ANOVA) with repeated measures on the second factor (test). Scheffe's post-hoc procedure was used to identify differences between specific tests. Data for the analysis of respiratory kinetics were examined using a 2 (group) by 4 (test, indicated as percent of maximum: 25%, 50%, 75%, 100%) ANOVA with repeated measures on the second factor. Scheffe's test was used to distinguish differences between tests (percent of maximum). Data expressed as a percentage of the treadmill test were analyzed using a 2 (group) by 2 (test) ANOVA with repeated measures on the second factor (test). Pearson Product Moment Correlations were used to compare breathing frequency to stroke rate at 25%, 50%, 75% and 100% of the PEL test. The level of significance was $p<0.05$ for all statistical comparisons.

RESULTS

Twenty-two healthy males, eleven paddlers and eleven controls, completed the study (Table 1).

Table 1. Anthropometric data for both groups.

	Paddlers (n=11)	Controls (n=11)
Age (years)	35.64±5.66	36.45±5.66
Body Mass (kg)	84.39±9.23	83.95±8.32
Height (cm)	179.16±3.81	178.85±4.07
Sitting Height (cm)	91.75±2.07	91.45±2.48
Arm span (cm)	183.82±6.43	180.68±4.27

Values are means (±SD)

Maximal Exercise Testing

Results from the treadmill and paddling ergometer testing showed a significant group effect for Rf ($p<0.01$), VT ($p<0.05$), VE ($p<0.01$) and VO_2 ($p<0.01$). Post-hoc tests revealed that the difference for Rf and VT between groups was for the PEL test only (Table 2).

VE and VO_2 were significantly different between groups for all tests ($p<0.01$). There was also a significant test main effect for VE and VO_2 ($p<0.01$). Further analysis of VO_2max results showed that for the paddling group, all tests were significantly different from each other. In the control group, the two paddling tests were significantly different from the treadmill test ($p<0.01$) but not from each other ($p=0.295$). For minute ventilation, it was found that in the paddling group, there was no significant difference between any of the tests. In the control group however, the two paddling tests were significantly different from the treadmill test ($p<0.01$) but not from each other ($p=0.839$) (Table 2). These results were also indicated by a significant group x test interaction effect found for VO_2 and VE ($p<0.01$).

There was no significant group main effect for oxyhaemoglobin saturation ($F=0.502$, $df=1/20$, $p=0.487$). A significant test main effect was found ($p<0.01$), however post-hoc tests showed no differences between tests when the groups were separated (Table 2). There was also a significant test effect for HR ($p<0.01$). Post-hoc tests showed that the maximal HR for paddlers was different between TM and PENL only. Maximal HR for both paddling tests was significantly lower than the treadmill tests in the controls ($p<0.01$).

Table 2. Maximal breathing frequency (Rf), and tidal volume (L), oxygen consumption (VO_2), and minute ventilation (VE), heart rate (HR), and oxyhaemoglobin saturation (SaO_2), obtained during maximal treadmill (TM) and paddling ergometer with legs (PEL) and without legs (PENL) testing for paddlers (P) and controls (C).

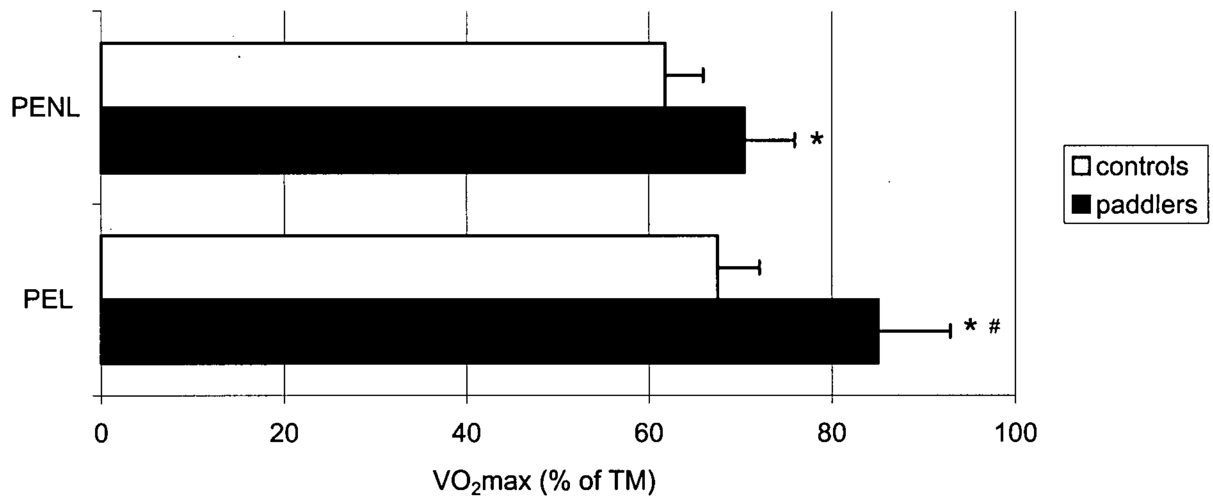
	TM (n=11)	PEL (n=11)	PENL (n=11)
P : Rf (br/min)	55.06(10.20)	62.31(8.07)*	60.44(6.29)
C : Rf (br/min)	63.80(10.72)	57.98(5.00)	58.58(4.34)
P: VT (L)	2.99(0.47)	2.61(0.38)*	2.46(0.41)
C: VT (L)	2.86(0.30)	2.21(0.20)	2.17(0.29)
P: VE (L/min)	149.97(13.90)*	151.91(17.30)*	141.41(20.60)*
C: VE (L/min)	131.43(16.99)	110.18(15.20) #	104.22(14.08) #
P: VO_2 max (L/min)	4.58(0.61)*	3.88(0.53) * #	3.23(0.47) * # ∞
C: VO_2 max (L/min)	3.85(0.41)	2.60(0.36) #	2.38(0.32) #
P: HR (bpm)	183.36(11.38)	175.73(9.39)	171.27(11.46) #
C: HR (bpm)	187.64(12.68)	172.36(13.34) #	173.82(11.12) #
P: SaO_2 (%)	91.73(2.20)	92.73(2.57)	92.82(2.32)
C: SaO_2 (%)	90.64(2.66)	91.73(2.72)	92.73(3.58)

Values are means (±SD)
*significantly different from controls ($p<0.01$)
significantly different from TM ($p<0.01$)
∞ significantly different from PEL ($p<0.01$)

Paddling VO_2max as a Percentage of Treadmill VO_2max

There was a significant group effect, test effect and group x test interaction effect for the two paddling ergometer tests ($p<0.01$). Paddlers reached a higher percentage of the treadmill test for both PEL (Paddlers: 85.05±7.82, Controls: 67.52±4.58) and PENL (Paddlers: 70.47±5.47, Controls: 61.79±4.16) when compared to the controls ($p<0.01$) (Figure 1). Post-hoc tests showed that PEL was significantly higher than PENL for the paddling group, but not for the control group ($p<0.01$).

Figure 1. Maximal oxygen consumption for paddlers and controls during PEL and PENL (expressed as a percentage of TM).



* significantly different from controls (p<0.01)
\# significantly different from PENL (p<0.01)

Respiratory Kinetics (PEL test only)

There was a significant group effect, test (percent of maximum) effect, and group x test interaction effect for Rf ($p<0.05$), VT ($p<0.05$), and VE ($p<0.01$). Post-hoc tests only showed significant differences between the two groups at the higher intensities of 75% and 100% ($p<0.05$) (Table 3).

There was a significant test effect and group x test effect for stroke rate indicating that maximal stroke rate was different between tests for the two groups ($p<0.01$). In addition, stroke rate and breathing frequency were significantly correlated at 75% ($r=0.833$) and 100% ($r=0.693$) for the paddling group only ($p<0.05$) (Table 3, Figures 2, 3, 4, 5).

Table 3. Tidal volume (L), minute ventilation (L/min), breathing frequency (Rf) and stroke rate (SR) at 25%, 50%, 75% and 100% of VO_2max during PEL testing.

	25%	50%	75%	100%
P: VT (L) (n=11)	1.23 (0.18)	1.60 (0.36)	2.20* (0.35)	2.57* (0.35)
C: VT (L) (n=11)	1.08 (0.19)	1.40 (0.32)	1.76 (0.32)	2.16 (0.23)
P: VE (L/min) (n=11)	30.92 (4.91)	55.21 (11.40)	99.44* (20.17)	146.84* (18.54)
C: VE (L/min) (n=11)	29.31 (6.40)	41.21 (6.04)	64.22 (10.99)	103.52 (19.93)
P: Rf (br/min) (n=11)	26.08 (6.47)	36.06 (9.18)	45.57* # (6.86)	57.71* # (7.99)
C: Rf (br/min) (n=11)	27.37 (4.79)	30.54 (7.05)	37.10 (6.19)	47.92 (5.66)
P: SR (spm) (n=11)	34.73 (5.52)	39.00 (6.60)	46.55 (6.62)	57.18 (7.96)
C: SR (spm) (n=11)	35.82 (2.52)	41.36 (4.03)	44.45 (2.91)	51.18 (3.22)

Values are means (±SD)
*significantly different than controls ($p<0.01$)
#significantly correlated with SR at the respective percent maximum for that group ($p<0.05$)

Figure 2. Breathing Frequency vs. Stroke Rate at 25% VO_2max

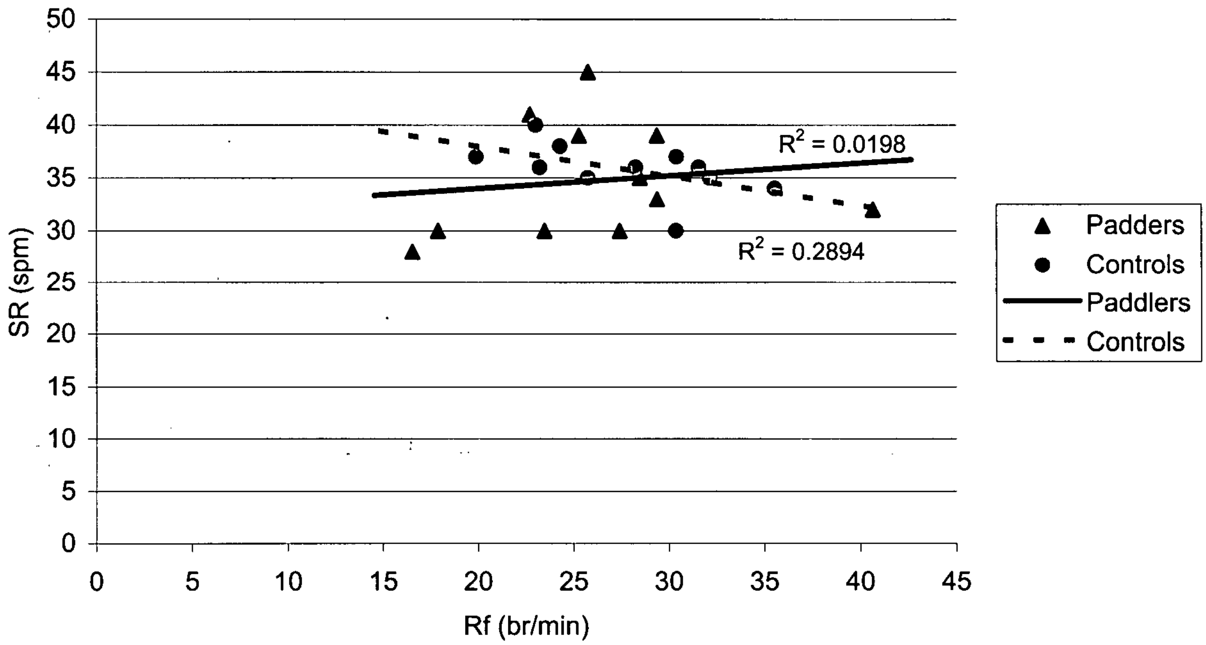


Figure 3. Breathing Frequency vs. Stroke Rate at 50% VO_2max

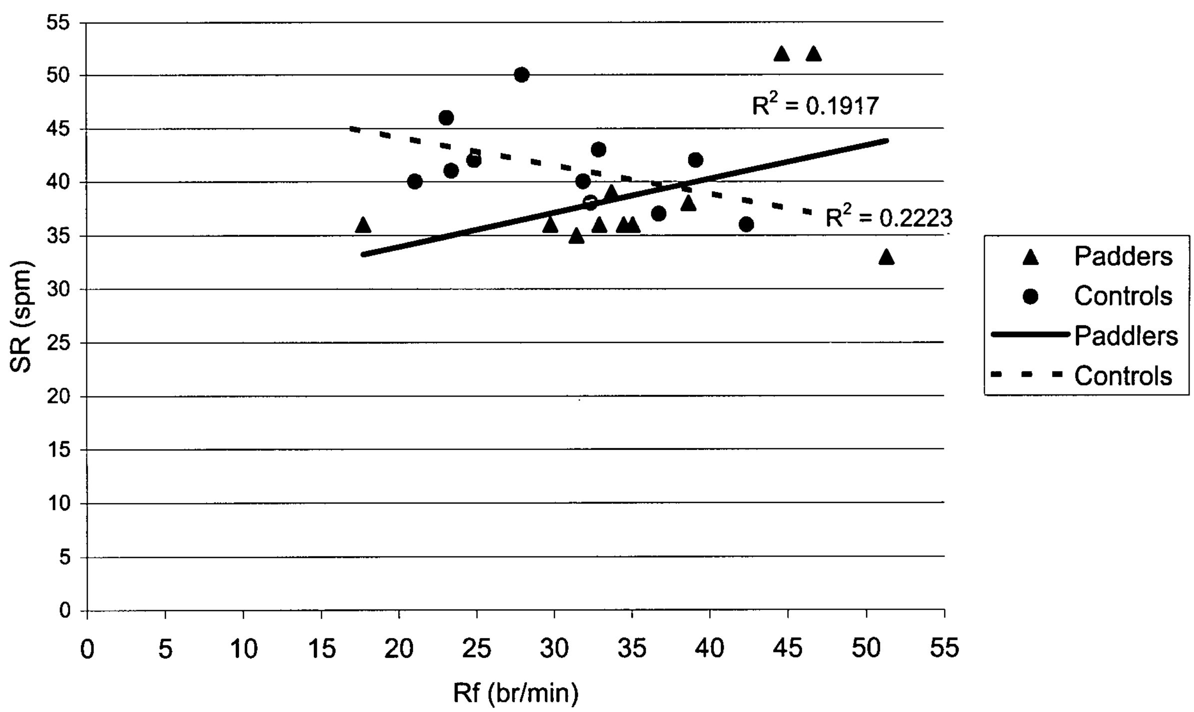


Figure 4. Breathing Frequency vs. Stroke Rate at 75% VO_2max

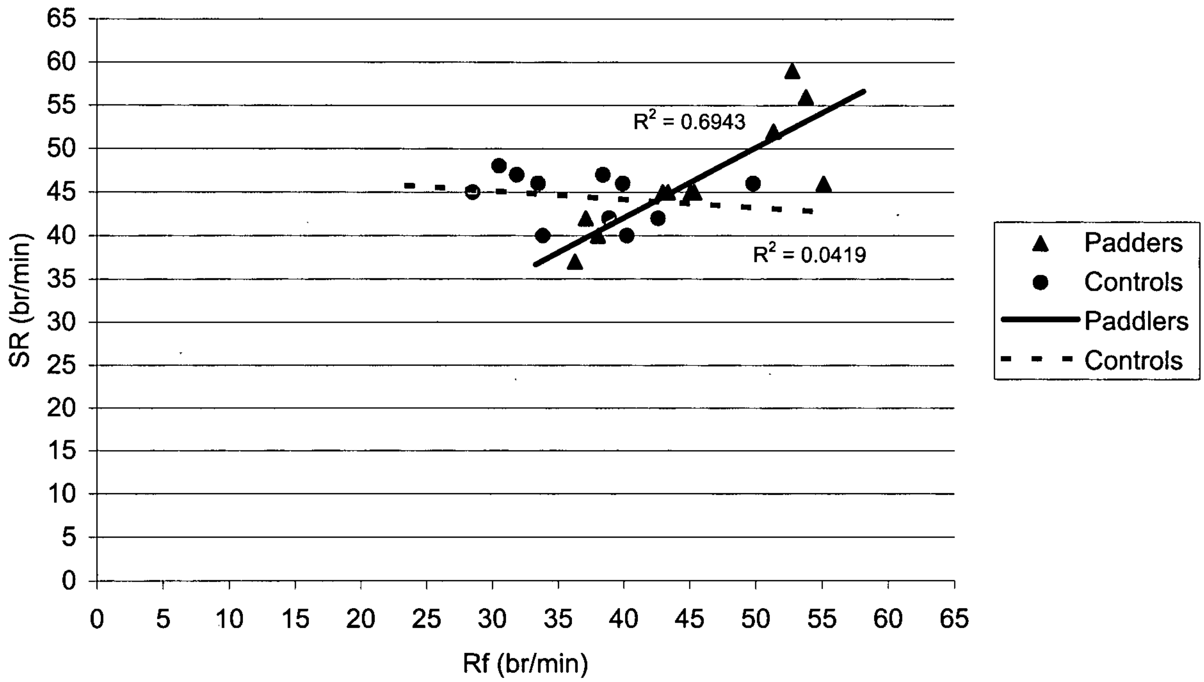
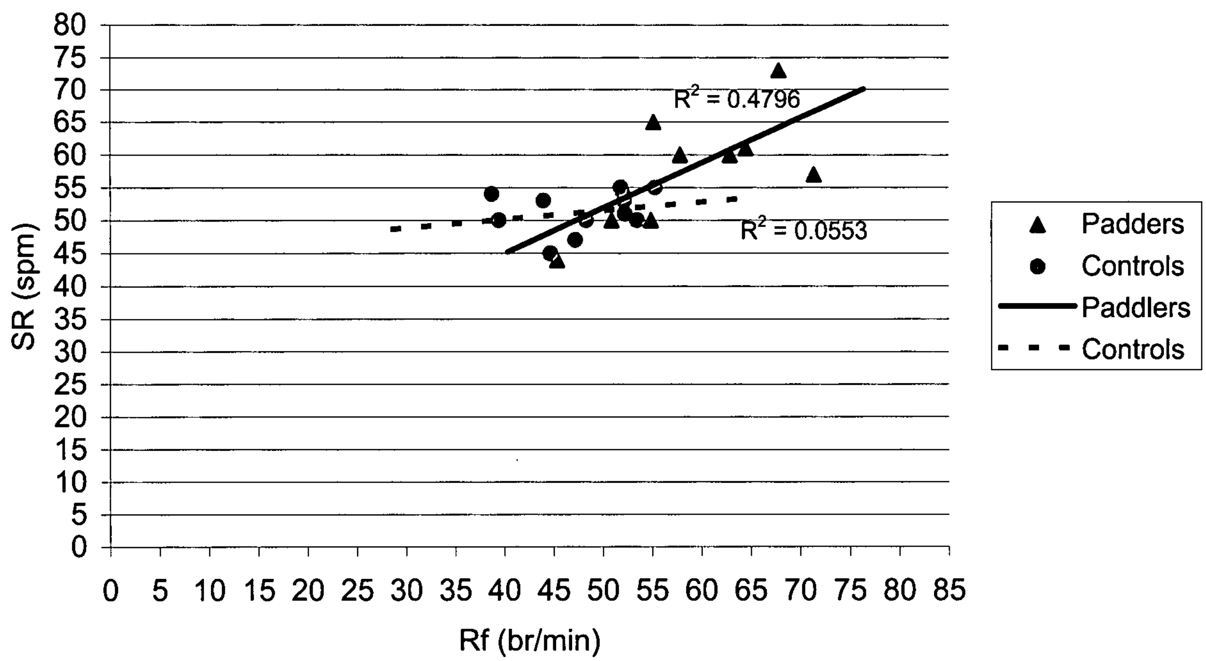


Figure 5. Breathing Frequency vs. Stroke Rate at 100% VO_2max



Ventilatory Thresholds

A significant test effect was found for $\%VO_2max$ at ventilatory threshold ($p<0.01$). Post-hoc tests showed that in the paddling group, TM was significantly later than PEL (TM: 81.55±4.95 $\%VO_2max$, PEL: 70.73±10.34 $\%VO_2max$) ($p<0.05$). In the control group, TM was significantly later than both PEL and PENL (TM: 84.60±5.86 $\%VO_2max$, PEL: 73.35±9.16 $\%VO_2max$, PENL: 67.75±7.04 $\%VO_2max$) ($p<0.05$). Ventilatory thresholds were not significantly different between groups ($F=0.01$, $df=1/20$, $P=0.912$).

DISCUSSION

This study has contributed to the limited descriptive data on outrigger canoe paddlers. In addition, it has confirmed that metabolic results can be affected not only by the specificity of the test implemented, but also by the volume and level of training of the muscle mass actively used during exercise.

Descriptive Data

Anthropometric data acquired are similar to that reported by Humphries et al. (2000) and Labman Hawaii (2001, unpublished) obtained exclusively on male outrigger canoeists. VO_2max was lower in Humphries group of paddlers (n=11) when compared to the VO_2max from the present investigation (3.0±0.4 vs. 3.88±0.53 L/min, respectively), while maximal heart rate was higher (188±8.0 vs. 176±9.39 bpm respectively). Height, body mass, sitting height and arm span were similar between studies. This may suggest that the paddlers in Humphries study were not as well trained as the paddlers who volunteered for this study.

In males, data on other paddling disciplines, particularly flatwater sprint athletes, were higher than outrigger endurance paddlers. VO_2max values of 3.9 - 4.6 L/min during arm or kayak ergometry in elite kayakers have been reported (Misigoj-Durakovic and Heimer, 1992; Tesch et al., 1976; van Someren et al., 2000; Vrijens et al., 1975). In canoeists, available data are similar (4.9 L/min) (Misigoj-Durakovic and Heimer, 1992), whereas dragonboat paddlers tend to produce lower maximal values (2.8 L/min) (Singh et al., 1995). These are quite possibly a function of the demand of physical training that sprint athletes undergo, but may also reflect the fitness and level of competition of the sample of paddlers tested.

Maximal Exercise Testing

In accordance with previous reports, increasing the amount of active muscle mass during testing of the present investigation did indeed increase metabolic demand as shown in VO_2max results (Table 2). This occurred not only in paddlers but also in their control counterparts. Secher et al. (1974) tested for maximal oxygen uptake during arm cranking (A), leg cranking (L) as well as arm plus leg cranking (A+L), and treadmill running and cycling. It was found that A+L exercise yielded similar results to treadmill running. Leg exercise produced higher VO_2max data than arm cranking, and A+L resulted in higher VO_2max data than L alone. Furthermore, the difference in results was more pronounced in arm-trained subjects. Secher et al. (1974) concluded that the trainability of the exercising muscle may limit VO_2max and the importance of task-specific testing was stressed. For paddlers tested in the present study, VO_2max was higher during PEL than PENL, and higher again during TM than PEL showing that additional active muscle mass increased metabolic demand. In controls, the two paddling tests were lower than TM, yet PEL did not generate a higher VO_2max than PENL. Therefore, in paddlers, leg drive appears to significantly affect metabolic demand.

Studies investigating upper versus lower body exercise have shown differences between trained and untrained subjects. Maximal arm ergometry tests expressed as a percentage of maximal leg ergometry tests have been reported to be 60-70% for the untrained and 80-95% in the (arm) trained (Reybrouck et al., 1975; Seals and Mullin, 1982; Swaine, 1997; Vrijens et al., 1975). Consistent with previous data, paddlers in the present study were able to achieve a higher percentage of whole body exercise during both paddling tests suggesting that the trainability of muscle mass may have limited VO_2max in controls. In addition, paddlers were 17.53% higher than controls during PEL and 8.68% higher during PENL (Figure 1). This two-fold difference between groups indicates the value and metabolic specificity of leg drive in canoeists. The degree of conditioning of the legs will most probably determine the extent to which VO_2max is affected.

Ogita et al. (1996) examined well-trained swimmers in a swimming flume during arm stroke only, leg stroke only, and combined whole-body swimming. It was found that arm stroking elicited 78.2% of whole-body swimming at maximal exercise while leg kicking accounted for 91.0% of whole body exercise. In accordance with previous research reviewed, larger amounts of muscle mass produced higher metabolic results in these swimmers. Interestingly, it was not suggested that peripheral factors were necessarily limiting in this case. Studies reporting a sport-specific test with lower values than a whole-body test (treadmill) often conclude that peripheral factors must be limiting. Holmer and Astrand (1972) found that in some individuals, swimming VO_2max and cardiac output were lower during swimming than running. However, it was also shown that in the well-trained individuals, swimming VO_2max was similar to running VO_2max (Holmer and Astrand, 1972). It was proposed that perhaps in the elite athletes, there is an upper limit on the capacity of the heart to meet the demand of the oxygen consuming muscles at exercise.

Trained individuals (paddlers) were able to consume more oxygen at maximal exercise when compared to untrained individuals (controls) during paddling tests with and without legs. Although it was initially thought that paddlers and controls could possibly show little or no difference during the running treadmill test (as it was not specific to their sport), this was not found in the VO_2max data. The significant difference between P and C during TM may be attributed to additional cross-training of the paddling group, as well as the difference in volume and intensity of total exercise per week when compared to the control group. This may also be indicative of the paddling group's central physiological response to training.

Level of training in the paddling group was also indicated by higher maximal VE values across the three testing conditions. As noted, minute ventilation did not change significantly across tests while the maximal oxygen consumption varied. This supports the usefulness of specificity in testing where a more appropriate result in oxygen demand may be attained by adjusting the testing condition. This also suggests the possible role of peripheral factors during maximal exercise. That is, with maximal ventilation remaining relatively constant across tests, VO_2max decreased significantly with tests utilizing a decreased muscle mass. This of course is based upon the assumption that the volume of muscle mass utilized during testing decreases in the following order of tests: 1)TM, 2)PEL, 3)PENL. The volume of muscle mass dictating the extent of metabolic demand could possibly explain these results.

In further support of appropriate testing conditions for athletes, differences between paddlers and controls were evident during the PEL test only for Rf and VT. It appears that breathing mechanics at maximal exercise in paddlers do not show significant differences from untrained individuals during testing unless the most sport-specific exercise test is employed (PEL).

The treadmill elicited the highest values for maximal heart rate as it utilizes the largest volume of muscle mass. For both paddling tests, controls showed lower values. In contrast, paddlers were able to achieve a maximal heart rate during PEL, which was not significantly different from TM, yet were unable to do so for PENL. This not only indicates the specificity of a canoeist's training but also the impact of leg drive on the paddler's exercising heart. That is, without the use of leg drive, paddlers are unable to reach maximum values close to whole-body results. Although the range of motion in the legs is not outstanding when leg drive is employed, there is enough movement to influence cardiac function during paddling.

Maximal oxyhaemaglobin saturation data were not consistent with the majority of the literature on endurance athletes. While normal healthy individuals tend to drop only 2-3% during exercise, it has been suggested that 40 to 50% of elite endurance athletes (cyclists and runners) demonstrate a marked decrease in arterial oxygenation at work rates near VO_2max

displaying what is known as exercise-induced hypoxemia (EIH) (Powers et al., 1993). Under categories outlined by Dempsey and Wagner (1999), the outrigger canoeists desaturated to moderate levels (88-93%) for each of the three tests. These results are consistent with data reported on trained cyclists and runners in various studies (Dempsey et al., 1984; Lawler et al., 1988; Warburton et al., 1999; Warren et al., 1991). However, it must be noted that the control group also desaturated to a moderate level during each test. Although most of the literature on EIH focuses on the elite athletic population, there have been studies reporting control groups (of untrained subjects) who have desaturated to values similar to these results (Martin and O'Kroy, 1992; Rowell et al., 1964; Williams et al., 1986). No difference in saturation between the groups was shown in the present study. Possible mechanisms include inadequate hyperventilatory compensation, venoarterial shunt, ventilation perfusion mismatch resulting in a widening of the alveolar-to-arterial PO_2 difference (A-aDO2), and diffusion limitation across the blood-gas interface possibly due to interstitial edema (Dempsey and Wagner, 1999). The observation of non-elite active individuals displaying EIH should be further investigated with respect to these proposed mechanisms.

Respiratory Kinetics

Ventilatory kinetics have not been explored to a large extent in paddlers. For this reason, Rf, VT, VE and SR were examined during paddling (with legs) as it was the most sport-specific test for outrigger canoe paddlers. Compared to controls, paddlers showed significantly higher breathing frequency, tidal volume, and minute ventilation values at higher exercise intensities only. Matched non-paddlers showed similar breathing patterns to their paddler counterparts during lower intensities despite the exercise type being unfamiliar to them. These results suggest that in this population, respiration during submaximal exercise is not dramatically altered by training. As the exercise intensity increased, the trained individuals have the capacity to facilitate larger breathing frequencies and tidal volumes. In addition, it was noted that while the control subjects had spontaneous breathing patterns, the paddlers tended to breath at a 1:1 ratio (Rf:SR), exhaling upon the catch and pull phase of the stroke. Again, this pattern was only observed at, or near maximal exercise. Entrainment during exercise has been documented particularly in rowers (Mahler et al., 1991; Siegmund et al., 1999). It has been suggested that the ventilatory response is different according to the level of training and rowing experience. Mahler et al. (1991) recorded a 1.5 ratio of Rf:SR in elite rowers but found collegiate and untrained individuals to have various responses. Furthermore, the elite rowers predominantly utilized increases in VT to bring about increases in minute ventilation, whereas collegiate rowers depended on elevated Rf. Both paddlers and controls in this study used increases in Rf and VT to augment VE. However, it must be noted that paddlers were able to reach higher power outputs on the ergometer, compared to controls, which generally necessitates a higher stroke rate. With the occurrence of entrainment, this may account for the elevated Rf at 75% and 100% VO_2max. It is still unclear in the literature whether entrainment can improve the economy of exercise in sport. Shepherd et al. (1989) has suggested that physical training causes VT to increase and Rf to decrease at a given level of VE, which is consistent with Mahler's data. However, in non-rowers tested on rowing ergometers, it has been shown that there was no difference in VO_2 attained using two styles of entrainment as well as spontaneous breathing patterns (Maclennan et al., 1994). Whether paddlers may benefit physiologically from entrainment is yet to be deciphered.

Ventilatory Thresholds

Conflicting results have been documented regarding the influence of the volume of active muscle mass on thresholds at submaximal exercise. During arm work, ventilatory thresholds (VTh) have been found to be lower when compared to that of leg work (Paterson and Morton, 1986). In canoeists, $\%VO_{2max}$ at VTh has been reported to be similar between males (81.3%) and females (82.7%) on a treadmill (Bunc et al., 1987). However, in subjects tested during 1-leg, 2-leg, arm and shoulder, and arm only exercise no significant difference between tests for VTh was found (Shephard et al., 1989). In a study involving arm exercise in active individuals no difference was found between males and females when peak VO_2 was corrected for arm and shoulder size (Washburn and Seals, 1984). Differences between males and females have therefore been reported to be a function of the size of the contracting muscle mass and not due to sex-related differences in oxygen delivery or utilization. Paddling tests in the present study provoked thresholds that were lower than those recorded during treadmill testing in both groups. Although leg drive did not appear to affect VTh between the two paddling tests, the difference between whole-body testing and paddling tests supports the notion that volume of active muscle mass may indeed play a role at submaximal exercise.

VTh results of controls and paddlers in the present study do not reflect those in previous literature. It has been proposed that elite athletes have higher ventilatory thresholds (VTh) allowing them to train at high intensities with less fatigue. VTh, expressed as $\%VO_2max$, has been reported to range from 50-70% in untrained individuals, and 80-90% in trained individuals (Bunc et al., 1987). Bunc and Heller (1991, 1994) collected data from both canoeists (C) and kayakists (K) who were highly trained. It was shown that during cycle ergometry (unspecific exercise load), values in paddlers were close to that of the untrained population (C=72%, K=74%). In the same subjects during paddling ergometry (specific exercise load), $\%VO_2max$ at VTh was typical for elite athletes (C=83%, K=84%). It was concluded that these results were due, in large part, to the trainability of the active muscle mass. This study showed no difference between controls and outrigger paddlers for VTh. In fact, values for both controls and paddlers during treadmill running (unspecific exercise load) and paddling ergometry (specific exercise load) were similar to those of the untrained population collected by Bunc and Heller (1991, 1994). In the present study, failure to find significant differences between controls and paddlers unfortunately does not support the hypothesis that trainability of muscle mass has an effect on ventilatory thresholds in endurance paddlers. Possible explanations are that our sample of paddlers may not have been at as high a level of competition as the canoeists and kayakers in previous studies who produce a marked difference and VTh may not be as reliable a measure of training status as many believe, particularly in the paddling population.

Summary

The results of this study showed that paddlers were able to achieve a high percentage of whole body VO_2max during a sport-specific testing condition (paddling ergometry). The inclusion of leg drive into the paddling gait also increased these results. In this population, this is the first data to address the specificity of testing indicating the metabolic cost of leg drive. It was also demonstrated that endurance paddlers do show moderate exercise-induced hypoxemia, comparable to healthy non-paddlers. Data during the three testing conditions confirm that volume of active muscle mass, and the trainability of that muscle mass will affect metabolic demand during exercise in outrigger paddlers. Limiting factors to VO_2max, either central or peripheral, still remain unclear from these results. However, central limitation in trained athletes and peripheral limitation in the untrained has been alluded to. Specificity in testing and training should be considered when examining the metabolic effect of exercise in paddlers.

REFERENCES

Anderson, G.S., and Rhodes, E.C. (1989). A review of blood lactate and ventilatory methods of detecting transition thresholds. **Sports Med.** 8:43-55.

Bangsbo, J. (2000). Muscle oxygen uptake in humans at onset of and during intense exercise. **Acta Physiol Scand.** 168:457-64.

Bishop, D. (2000). Physiological predictors of flat-water kayak performance in women. **Eur J Appl Physiol.** 82:91-7.

Bunc, V., and Heller, J. (1991). Ventilatory threshold and work efficiency on a bicycle and paddling ergometer in top canoeists. **J Sports Med Phys Fitness.** 31:376-9.

Bunc, V., and Heller, J. (1994). Ventilatory threshold and work efficiency during exercise on cycle and paddling ergometers in young female kayakists. **Eur J Appl Physiol Occup Physiol.** 68:25-9.

Bunc, V., Heller, J., Leso, J., Sprynarova, S., and Zdanowicz, R. (1987). Ventilatory threshold in various groups of highly trained athletes. **Int J Sports Med.** 8:275-80.

Coetzer, P., Noakes, T.D., Sanders, B., Lambert, M.I., Bosch, A.N., Wiggins, T., and Dennis, S.C. (1993). Superior fatigue resistance of elite black South African distance runners. **J Appl Physiol.** 75:1822-7.

Dempsey, J.A. (1986). J.B. Wolffe memorial lecture. Is the lung built for exercise? **Med Sci Sports Exerc.** 18:143-55.

Dempsey, J.A., Hanson, P.G., and Henderson, K.S. (1984). Exercise-induced arterial hypoxaemia in healthy human subjects at sea level. **Journal of Physiology.** 355:161-175.

Dempsey, J.A., and Wagner, P.D. (1999). Exercise-induced arterial hypoxemia. **J Appl Physiol.** 87:1997-2006.

Gleser, M., Horstman, D., and Mello, R. (1973). The effect on VO_2max of adding arm work to maximal leg work. **Medicine and science in sports and exercise.** 6:104-107.

Hill, A.V., and Lupton, H. (1923). Muscular exercise, lactic acid, and the supply and utilization of oxygen. **Quarterly journal of medicine.** 16:135-171.

Holmer, I., and Astrand, P.O. (1972). Swimming training and maximal oxygen uptake. **J Appl Physiol.** 33:510-3.

Hopkins, S.R., and McKenzie, D.C. (1989). Hypoxic ventilatory response and arterial desaturation during heavy work. **J Appl Physiol.** 67:1119-24.

Humphries, B., Abt, G.A., Stanton, R., and Sly, N. (2000). Kinanthropometric and physiological characteristics of outrigger canoe paddlers. **J Sports Sci.** 18:395-9.

Kayser, B., Narici, M., Binzoni, T., Grassi, B., and Cerretelli, P. (1994). Fatigue and exhaustion in chronic hypobaric hypoxia: influence of exercising muscle mass. **J Appl Physiol.** 76:634-40.

Labman Hawaii. (2001). Descriptive data of participants in the Queen Lili'uokalani long distance canoe race (unpublished).

Lawler, J., Powers, S.K., and Thompson, D. (1988). Linear relationship between VO2max and VO2max decrement during exposure to acute hypoxia. **J Appl Physiol.** 64:1486-92.

Maclennan, S.E., Silvestri, G.A., Ward, J., and Mahler, D.A. (1994). Does entrained breathing improve the economy of rowing? **Med Sci Sports Exerc.** 26:610-4.

Mahler, D.A., Shuhart, C.R., Brew, E., and Stukel, T.A. (1991). Ventilatory responses and entrainment of breathing during rowing. **Med Sci Sports Exerc.** 23:186-92.

Martin, D., and O'Kroy, J. (1992). Effects of acute hypoxia on VO_2max of trained and untrained subjects. **Journal of Sport Sciences.** 11:37-42.

McLaughlin, J.E., King, G.A., Howley, E.T., Bassett Jr, D.R., Ainsworth, B.E. (2001). Validation of the COSMED K4 b^2 portable metabolic system. **Int J Sports Med.** 22:280-284.

Misigoj-Durakovic, M., and Heimer, S. (1992). Characteristics of the morphological and functional status of kayakers and canoeists. **J Sports Med Phys Fitness.** 32:45-50.

Noakes, T.D. (1998). Maximal oxygen uptake: "classical" versus "contemporary" viewpoints: a rebuttal. **Med Sci Sports Exerc.** 30:1381-98.

Ogita, F., Hara, M., and Tabata, I. (1996). Anaerobic capacity and maximal oxygen uptake during arm stroke, leg kicking and whole body swimming. **Acta Physiol Scand.** 157:435-41.

Owles, W.H. (1930). Alterations in the lactic acid content of the blood as a result of light exercise, and associated changes in CO_2 combining power of the blood and into alveolar CO_2 pressure. **Journal of Physiology.** 69:214-237.

Paterson, D.J., and Morton, A.R. (1986). Maximal aerobic power, ventilatory and respiratory compensation thresholds during arm cranking and bicycle ergometry. **Australian journal of science and medicine in sport.** 18:11-15.

Pendergast, D., Cerretelli, P., and Rennie, D.W. (1979). Aerobic and glycolytic metabolism in arm exercise. **J Appl Physiol.** 47:754-60.

Pivarnik, J.M., Grafner, T.R., and Elkins, E.S. (1988). Metabolic, thermoregulatory, and psychophysiological responses during arm and leg exercise. **Med Sci Sports Exerc.** 20:1-5.

Powers, S., Lawler, J., Dempsey, J., Dodd, S., and Landry, G. (1989). Effects of incomplete pulmonary gas exchange on VO_2max. **Journal of Applied Physiology.** 66:2491-2495.

Powers, S., Martin, D., and Dodd, S. (1993). Exercise-induced hypoxemia in elite endurance athletes: incidence, causes and impact on VO_2max. **Sports Medicine.** 16:14-22.

Powers, S.K., Dodd, S., Lawler, J., Landry, G., Kirtley, M., McKnight, T., and Grinton, S. (1988). Incidence of exercise induced hypoxemia in endurance trained athletes at sea level. **European Journal of Applied Physiology and Occupational Physiology.** 58:298-302.

Powers, S.K., Martin, D., Cicale, M., Collop, N., Huang, D., and Criswell, D. (1992). Exercise induced hypoxemia in athletes: role of inadequate hyperventilation. **European Journal of Applied Physiology and Occupational Physiology.** 65:37-42.

Reybrouck, T., Heigenhauser, G.F., and Faulkner, J.A. (1975). Limitations to maximum oxygen uptake in arms, leg, and combined arm-leg ergometry. **J Appl Physiol.** 38:774-9.

Rowell, L.B., Taylor, H.L., Wang, L., and Carlson, W.S. (1964). Saturation of arterial blood with oxygen during maximal exercise. **Journal of Applied Physiology.** 19:284-286.

Saltin, B. (1985). Hemodynamic adaptations to exercise. **Am J Cardiol.** 55:42D-47D.

Seals, D.R., and Mullin, J.P. (1982). VO2 max in variable type exercise among well-trained upper body athletes. **Res Q Exerc Sport.** 53:58-63.

Secher, N.H., Ruberg-Larsen, N., Binkhorst, R.A., and Bonde-Petersen, F. (1974). Maximal oxygen uptake during arm cranking and combined arm plus leg exercise. **J Appl Physiol.** 36:515-8.

Shephard, R.J., Bouhlel, E., Vandewalle, H., and Monod, H. (1989). Anaerobic threshold, muscle volume and hypoxia. **Eur J Appl Physiol Occup Physiol.** 58:826-32.

Siegmund, G.P., Edwards, M.R., Moore, K.S., Tiessen, D.A., Sanderson, D.J., and McKenzie, D.C. (1999). Ventilation and locomotion coupling in varsity male rowers. **J Appl Physiol.** 87:233-42.

Singh, R., Singh, H.J., and Sirisinghe, R.G. (1995). Physical and physiological profiles of Malaysian dragon boat rowers. **Br J Sports Med.** 29:13-5.

Speechley, D.P., Taylor, S.R., and Rogers, G.G. (1996). Differences in ultra-endurance exercise in performance-matched male and female runners. **Medicine and science in sports and exercise.** 28:359-365.

Sutton, J.R., Reeves, J.T., Wagner, P.D., Groves, B.M., Cymerman, A., Malconian, M.K., Rock, P.B., Young, P.M., Walter, S.D. et al. (1988). Operation Everest II: oxygen transport during exercise at extreme simulated altitude. **J Appl Physiol.** 64:1309-21.

Swaine, I.L. (1997). Cardiopulmonary responses to exercise in swimmer using a swim bench and a leg-kicking ergometer. **Int J Sports Med.** 18:359-62.

Tesch, P., Piehl, K., Wilson, G., and Karlsson, J. (1976). Physiological investigations of Swedish elite canoe competitors. **Med Sci Sports.** 8:214-8.

Toner, M.M., Glickman, E.L., and McArdle, W.D. (1990). Cardiovascular adjustments to exercise distributed between the upper and lower body. **Med Sci Sports Exerc.** 22:773-8.

van Someren, K.A., Phillips, G.R., and Palmer, G.S. (2000). Comparison of physiological responses to open water kayaking and kayak ergometry. **Int J Sports Med.** 21:200-4.

Vrijens, J., Hoekstra, P., Bouckaert, J., and Van Uytvanck, P. (1975). Effects of training on maximal working capacity and haemodynamic response during arm and leg-exercise in a group of paddlers. **Eur J Appl Physiol Occup Physiol.** 34:113-9.

Warburton, D.E.R., Gledhill, N., Jamnik, V., Krip, B., and Card, N. (1999). Induced hypervolemia, cardiac function, VO_2max and performance of elite cyclists. **Medicine and Science in Sports and Exercise.** 31:800-808.

Warren, G.L., Cureton, K.J., Middendorf, W.F., Ray, C.A., and Warren, J.A. (1991). Red blood cell pulmonary capillary transit time during exercise in athletes. **Med Sci Sports Exerc.** 23:1353-61.

Washburn, R.A., and Seals, D.R. (1984). Peak oxygen uptake during arm cranking for men and women. **J Appl Physiol.** 56:954-7.

Wasserman, K., Whipp, B.J., Koyl, S.N., and Beaver, W.L. (1973). Anaerobic threshold and respiratory gas exchange during exercise. **J Appl Physiol.** 35:236-43.

Williams, J.H., Powers, S.K., and Stuart, M.K. (1986). Hemoglobin desaturation in highly trained athletes during heavy exercise. **Med Sci Sports Exerc.** 18:168-73.

APPENDIX A

REVIEW OF LITERATURE

Introduction

The energy cost of paddling is a function of many factors including velocity and hull design of the craft, the design of the paddle, the environmental conditions present, and the technical and physiological capabilities of the canoeist themselves. Sports that predominantly involve upper body musculature present unique demands on their athletes. As exercise physiologists, we strive to gain insight to those factors which influence performance. VO_2max testing is widely used to give us some insight to the metabolic cost of exercise. While the laboratory allows us to control for many conditions eliminating confounding variables in testing, it is also limited by those very circumstances that make it unspecific to actual competition. The more specific the testing tool and condition, the more closely the results resemble the actual metabolic demand during a sporting event.

The following literature review will concentrate on the effects of volume and trainability of active muscle mass on exercise, the debate of central vs. peripheral limitations to VO_2max results, and the implications of exercise-induced hypoxemia and ventilatory thresholds in athletes.

Volume of active muscle mass

In the literature where arm and leg exercise is compared, it is well known that increasing amount of active muscle mass will increase VO_2max (Secher et al., 1974). High oxygen consumption, recruiting the largest amount of muscle mass, relative to an individual, is most often found by running on a treadmill. In trying to encorporate specificity in testing, and for convenience, upper-body athletes are most often tested during maximal exercise on arm ergometers. For canoeists, the paddling ergometer can be utilized as a specific tool for measuring metabolic cost and power contributed to their respective discipline.

Studies have shown that VO_2max during arm cranking is lower than that achieved during a cycle ergometer test in both trained and untrained individuals (Paterson and Morton, 1986; Pivarnik et al., 1988; Reybrouck et al., 1975; Secher et al., 1974; Toner et al., 1990). However the degree to which this difference occurs depends on the type and level of training of that individual. An upper body athlete will exhibit higher VO_2max values on an arm ergometer and leg ergometer than an untrained individual. Furthermore, the arm crank test will elicit a higher percentage of leg VO_2max in trained (upper body) individuals compared to the untrained (Pendergast et al., 1979; Seals and Mullin, 1982; Vrijens et al., 1975). While non-athletes can attain 60-70% of their leg VO_2max during an arm crank test, well-trained upper body athletes can reach 80-95% of their leg VO_2max. In paddlers specifically, Vrijens et al (1975) measured the ratio of arm to leg exercise and compared it to a control group. It was reported that the paddlers achieved values during arm exercise (as a percentage of leg VO_{2max}) that were 7.4% higher compared to their control counterparts.

Central vs. Peripheral Limitations to VO_2max

There is great deal of debate within the literature as to whether whole body oxygen uptake is limited by oxygen delivery to (central factors), or oxygen utilization (local factors) of the exercising muscle. A majority of the available data tends to support the classical viewpoint that central factors such as maximal cardiac output, associated with heart volume and blood volume, and maximal ventilation and exchange of oxygen over the lung membranes will limit VO_2max. Early work by Hill and Lupton (1923) proposed an upper limit of VO_2max. Since a plateau could be observed during maximal exercise testing, it was thought that the circulatory and respiratory systems were at their maximum, and were thus limiting further increases in oxygen consumption. Hill and Lupton (1923) termed this "the governor" which terminated exercise before myocardial ischemia. Furthermore, he suggested that at intensities beyond this limit, requirements of the body for oxygen could not be met and lactic acid accumulation, increasing oxygen debt, and fatigue and exhaustion incur. Studies examining the effects of varying volumes of active muscle mass on VO_2max support the central-limiting theory. Arm work has been shown to elicit 65-75% of VO_2max values collected during leg work (Reybrouck et al., 1975). It was expected that when combining arm and leg exercise, that VO_2max values would significantly exceed that of maximal leg work. A number of studies failing to show this difference supported the classical view (Gleser et al., 1973; Reybrouck et al., 1975; Secher et al., 1974). An additional argument for this theory is that the capacity of the central system to deliver oxygen is exceeded by the maximal respiratory rate of skeletal muscle. It has been determined that the maximal oxygen uptake of an isolated muscle working (during knee extensor exercise), is around 300 mL/min/kg in active untrained subjects (Saltin, 1985). Based on the assumption that these subjects obtain a VO_2max of 3.6 L/min, the active muscle mass would need to be 12 kg. This is much less than that required during involvement in cycling or running exercise (Bangsbo, 2000).

Yet another factor influencing the transport and utilization of oxygen is exercise-induced hypoxemia. As convincing evidence for the central limiting theory, it has been shown that in athletes displaying EIH, the breathing of hyperoxic mixtures (26%) increased hemoglobin saturation and VO_2max (Dempsey, 1986; Powers et al., 1989). This suggested that in those with high cardiac outputs (highly trained athletes), maximal oxygen uptake is constrained by a pulmonary diffusion limitation.

Although the traditional, central-limiting view has had much support, it has also been challenged. For some researchers, the very fact that in a number of individuals, a plateau cannot be observed during maximal exercise testing is the basis of the argument that the central system does not necessarily limit VO_2max (Noakes, 1998). Furthermore, some researchers persist that the traditional theory cannot explain why elite South African distance runners are able to perform significantly better (at distances larger than 5km) than a group of middle distance runners whose VO_2max values are the same (Coetzer et al., 1993). Nor can it explain, in their opinion, why women with lower VO_2max values are able to outperform men in races over 56km (Speechley et al., 1996). However, these arguments are based on the assumption that VO_2max is highly correlated with performance in these athletes.

Many authors believe that skeletal muscle function is regulated to prevent damage to the central system, especially the heart. In subjects climbing Mount Everest, it was found that at any work rate, CO was the same at higher altitudes and at sea level (Sutton et al., 1988). Since CO was not increased to compensate for the reduced arterial oxygen content, it was thought that the body was making no attempt to maximize oxygen delivery to the active tissues at altitude. Thus, it was believed that the demands of skeletal muscle must be regulated through reduced recruitment and lower blood and muscle lactate concentrations, to protect the heart from hypoxia (Kayser et al., 1994).

For these reasons, among others, the debate continues within the literature as to what system limits exercise, in what population, and under what conditions.

Exercise-Induced Hypoxemia

VO_2 can be influenced by oxygen saturation of the blood. Normal healthy individuals (at sea level) have an oxyhaemoglobin arterial saturation (SaO_2) of 98% decreasing 2-3% during exercise. However, in highly trained individuals, a drop in saturation to 85% has been documented with maximal exercise (Powers et al., 1988). The incidence of this exercise induced arterial hypoxemia (EIAH) is believed to be as high as 50% in elite athletes both male and female (Powers et al., 1993). Dempsey and Wagner (1999) recently categorized EIAH into mild

(93-95% saturation), moderate (88-93% saturation), and severe (<88% saturation) levels. In testing the athletic population it is important to note that, assuming an increase in active muscle mass will increase VO_2max in a given individual, an athlete with EIAH, could display a greater desaturation during a treadmill test versus an upper body test. In terms of application to sport, desaturation, especially in severe cases, has been linked to decreases in performance (Powers et al., 1989).

Possible mechanisms for hypoxemia include hypoventilation, venoarterial shunt, ventilation perfusion (V_A/Q) mismatch, and diffusion limitation across the blood-gas interface. Venoarterial shunt is thought to be negligible as both Dempsey et al (1984) and Powers et al (1992) have demonstrated that breathing a hyperoxic gas mixture increased PaO_2 back to normal levels in hypoxemic athletes exercising near VO_2max. As PaO_2 levels have been reported to decrease during heavy exercise, hypoventilation is not considered to be a major determinant of EIH (Powers et al., 1992). Generally in the healthy lung, ventilation and perfusion are well matched during rest. With exercise, we see a widening of the alveolar-to-arterial PO_2 difference ($A\text{-}aDO_2$). V_A/Q inequality accounts for most of this difference at rest however, during exercise it is unclear as the whether the regional V_A/Q equality improves, or whether it increases accounting for a widening of $A\text{-}aDO_2$. And finally, decreases in both partial pressure of oxygen in mixed venous blood (due to high O_2 extraction by the muscle), and the red blood cell transit time (due to increased cardiac output), contribute to a diffusion limitation resulting in incomplete pulmonary gas exchange. Athletes with EIH tested during a 5-minute treadmill test at 100% VO_2max were found to maintain P_AO_2 levels while PaO_2 decreased thus relating to A-aDO2 (Hopkins and McKenzie, 1989). The authors suggested diffusion limitation to be a likely etiology.

Ventilatory Thresholds

Trained and untrained individuals will show physiological differences with submaximal exercise. For elite athletes, many sports require not only a strong maximal exercise performance, but also an ability to perform at high levels during submaximal exercise. Non-invasive measures of submaximal thresholds have been developed helping to indicate adaptation to a given physical workload. Ventilatory threshold (VTh) can be described as a disproportional increase in ventilation relative to oxygen consumed. This break point has been linked to increasing blood lactate accumulation (Wasserman et al., 1973). An early study by Owles (1930) recognized that expired volume (VE) and volume of expired CO_2 (VCO_2) increased disproportionately above an intensity where plasma lactate began to rise. The increased CO_2 production, associated fall in blood bicarbonate, and a rise in arterial pH have been identified as prime stimulators of ventilation (Anderson and Rhodes, 1989).

Summary

Increasing volume of active muscle mass during exercise is thought to increase metabolic demand and therefore VO_2max. Those that are trained are able to consume more oxygen than untrained individuals during similar workloads.

Arguments for both the contemporary or peripheral-limiting theory, and the classical or central-limiting theory are substantiated in the literature. Although a great deal of the research supports that of the latter, it is clear that under various conditions, each individual and/or population cannot be easily categorized under one of the two theorems.

And finally, the occurrence of exercise-induced hypoxemia has been well documented and should be considered whenever the maximal testing of athletes is undertaken. During submaximal exercise, ventilatory thresholds can help provide us with information at given exercise intensities.

APPENDIX B

Photos of subject on paddling ergometer