

EXPERIMENTAL STUDIES PREDICTING MAXIMUM OXYGEN CONSUMPTION
IN SWIMMING USING SWIM BENCH ERGOMETRY

by

ASHLEY I. MEERLOO

B.A., University of Cardiff, 1982

A THESIS SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENT FOR THE DEGREE OF

MASTER OF ARTS

in the school

of

Physical Education

ACCEPTED

FACULTY OF GRADUATE STUDIES

DEAN

DATE

March 24, 86

We accept this thesis as conforming
to the required standard

Supervisor: Dr. M.L. Collis

Dr. H.A. Wenger

Dr. T.W. Pearson

Dr. R. Backus

© ASHLEY I. MEERLOO, 1985

UNIVERSITY OF VICTORIA

June 1985

*All rights reserved. This thesis may not be reproduced
in whole or in part, by mimeograph or other means,
without the permission of the author.*

ABSTRACT

Three studies were undertaken to assess the use of the Biokinetic swim bench in predicting maximum oxygen consumption ($\dot{V}_{O_2\max}$) in swimming. The purpose of the first study was to determine whether a continuous (SBC) or discontinuous (SBD) swim bench protocol would elicit a higher $\dot{V}_{O_2\max}$ in competent swimmers. No differences were found for $\dot{V}_{O_2\max}$ when tested with either SBC or SBD. It was concluded that, from an administrative viewpoint, SBC should be used as testing time was greatly reduced. Study 2 compared SBC with tethered swimming (TS). A higher ($p < 0.001$) $\dot{V}_{O_2\max}$ was elicited by the swimmers during TS compared with SBC. A prediction equation was produced: $TS \dot{V}_{O_2\max} = (0.595 SBC \dot{V}_{O_2\max}) + 35.8$ ($s_{x,y} = 4.74$). These results suggested that SBC $\dot{V}_{O_2\max}$ was not a valid measure of TS $\dot{V}_{O_2\max}$, and that SBC $\dot{V}_{O_2\max}$ was a poor predictor of TS $\dot{V}_{O_2\max}$ in elite swimmers. The final study compared arms only tethered swimming (TSA) with TS, and TSA with SBC. TS $\dot{V}_{O_2\max}$ was higher than TSA $\dot{V}_{O_2\max}$ ($p < 0.01$). No differences were found in submaximal \dot{V}_{O_2} scores between TSA and SBC. A higher $\dot{V}_{O_2\max}$ was found for TSA compared with SBC ($p < 0.005$). The results suggested that the absence of leg kick reduced the active muscle mass during TSA. In addition, the inability of the swimmer to perform correct stroke mechanics reduced the active muscle mass during SBC. The reductions in muscle mass resulted in lower $\dot{V}_{O_2\max}$ scores.

Examiners :

[REDACTED]

Supervisor: Dr. M. L. Collis

[REDACTED]

Dr. H. A. Wenger

[REDACTED]

Dr. T. W. Pearson

[REDACTED]

Dr. R. Backus

Supervisor : Dr. Martin L. Collis

PREFACE

Preparation for many competitive sports involves a component that specifically stresses the cardio-respiratory capacity of an athlete. This stress is maximal in some forms of endurance exercise during which the energy for contraction is supplied primarily through aerobic metabolism (Holloszy, 1973; Fox and Mathews, 1981). Circulatory adaptations in response to exercise of prolonged duration result in increased capacity to take-up, transport and deliver oxygen to the working muscles. Maximum oxygen consumption ($\dot{V}_{O_2\max}$), has been established as the most effective physiological variable for measuring the uptake, transport and utilisation of oxygen (Åstrand and Rodahl, 1977).

The importance of $\dot{V}_{O_2\max}$ has been discussed in detail by Wenger (1981). A high $\dot{V}_{O_2\max}$ reflects an ability to resist fatigue, recover from exercise more rapidly and the capability to work at high rates for short periods of time, i.e., a gross measure of fitness. When monitoring training progress or performance potential for endurance (aerobic) competition, $\dot{V}_{O_2\max}$ is the most commonly used criterion.

An elite swimmer is concerned with stroke technique, speed and tolerance to fatigue (training and competition). Other measures may be more useful, such as a speed performance test, or anaerobic threshold determination. Therefore aerobic capacity (which is specific to a given situation and can be expressed as a % $\dot{V}_{O_2\max}$) is probably more useful than aerobic power ($\dot{V}_{O_2\max}$). However, at present, $\dot{V}_{O_2\max}$ is used in monitoring the fitness progress of athletes (MacDougall et al., 1982) and is used by organisations such as the Canadian Swimming Association. In order to facilitate comparisons between the swimmers

of the present study with others, and to develop an inexpensive and convenient test protocol, $\dot{V}_{O_2\max}$ was chosen as the test standard.

Adaptations to training can be evaluated using ergometry. The most extensively used ergometers are the treadmill and cycle. The treadmill has been shown to simulate running, and the cycle has been shown to simulate bicycling (Roberts and Alspaugh, 1972; Pechar et al., 1974). Therefore, when assessing physiological changes due to a particular mode of exercise, the ergometer specific to that exercise mode should be selected to impose the load.

In order to obtain the highest $\dot{V}_{O_2\max}$ values, the largest muscle mass must be used throughout the test (Cardus, 1979). Treadmill running employs a greater active muscle mass, therefore, it is the most valid means for eliciting whole body $\dot{V}_{O_2\max}$ (McArdle et al., 1973; Corry and Powers, 1982). However, if a mode specific adaptation is to be studied, other protocols may be more useful. Rowers, for example, can be tested on an ergometer specially designed to simulate the actual rowing motion (Martindale and Robertson, 1984).

The most commonly used apparatus to determine $\dot{V}_{O_2\max}$ in swimmers is the tethered swimming device. It allows the swimmer to swim in water without any forward movement. Instruments can be attached to the swimmer and physiological data collected at the poolside during the swimming exercise. However, setting up this equipment can cause many technical problems (e.g., moving expensive and fragile machinery on to the pool deck), therefore a dry-land method would be advantageous.

Dry-land testing equipment has not been able to simulate the specific stroke mechanics utilised by a swimmer in water (Schleihauf, 1982). The use of arm crank ergometry to test swimmers is questionable, as the muscle contractions do

not adequately mimic swimming.

It would appear that if the oxygen consumption of a swimmer is to be measured accurately by an ergometer, then the device must be designed specifically to reproduce the joint actions, muscle mass employed and the power of the stroke in water. A machine known as the Biokinetic Swim Bench (Isokinetics, Inc.) has been recently developed as a dry-land training device, and has been purported to simulate the type of muscle contraction used by a swimmer in water (Flavell and Counsilman, 1981).

If the Biokinetic swim bench (Figure 1) could be used as an ergometer, it would allow all the testing to be carried out in a controlled laboratory setting. However, exercise on the swim bench uses only arm actions, which depress $\dot{V}_{O_2\max}$ due to the absence of leg action (M. Plyley and D. Smith, personal communications, October 1984). The work of both Holmer (1974c), which showed that the addition of leg kick to arm work produced high values for $\dot{V}_{O_2\max}$ compared with whole stroke, and Watkins and Gordon (1983) which highlighted the importance of leg kick in stabilising and streamlining the body during swimming, suggests that the swim bench may be inadequate as an ergometer for testing swimming specific $\dot{V}_{O_2\max}$.

Recent studies using a type of swim bench have found $\dot{V}_{O_2\max}$ scores which were lower than when using tethered or flume swimming (Holmer, 1974c; Swaine and Reilly, 1983; Gergley et al., 1984). In these studies the Biokinetic swim bench was not used as the testing device. Furthermore, it has been suggested that a discontinuous protocol should be used when testing activities involving a small muscle mass (Cardus, 1979; MacDougall et al., 1982). At present there is no consistency in the use of swim bench protocols, and differences in $\dot{V}_{O_2\max}$ obtained when using a continuous versus a discontinuous swim bench

protocol have not been evaluated.

Therefore, the purpose of the present studies were :

1) to determine whether a continuous or a discontinuous swim bench protocol would elicit the greater $\dot{V}_{O_2\max}$ value.

2) to determine if the Biokinetic swim bench could be used as a valid measure of tethered swimming $\dot{V}_{O_2\max}$ in elite swimmers, and to determine if the swim bench $\dot{V}_{O_2\max}$ of a swimmer could predict tethered swimming $\dot{V}_{O_2\max}$.

3) to determine the sources of error in prediction of tethered swimming $\dot{V}_{O_2\max}$ from swim bench $\dot{V}_{O_2\max}$.

TABLE OF CONTENTS

ABSTRACT	ii
PREFACE	iii
TABLE OF CONTENTS	vii
LIST OF TABLES	ix
LIST OF FIGURES	x
ACKNOWLEDGEMENTS	xii
CHAPTER I. Determination of $\dot{V}_{O_2\max}$ in competent swimmers when using a continuous versus a discontinuous swim bench protocol	1
Abstract	2
Introduction	3
Methods	4
Results	5
Discussion	5
References	8
CHAPTER II. A comparison of $\dot{V}_{O_2\max}$ attained by elite swimmers using the biokinetic swim bench and tethered swimming	15
Abstract	16
Introduction	17
Methods	18
Results	20
Discussion	20
References	24
CHAPTER III. A comparison of the $\dot{V}_{O_2\max}$ attained by elite swimmers during tethered swimming with the legs immobilised, tethered swimming whole stroke and	

swim bench ergometry	41
Abstract	42
Introduction	43
Methods	44
Results	45
Discussion	46
References	50
SUMMARY	67
FURTHER RESEARCH	68
RECOMMENDATIONS	68
APPENDIX A	70
Informed consent form	70
APPENDIX B	73
Par-Q Form	73
APPENDIX C	75
Review of Literature	75
References	89

LIST OF TABLES

Table 1. Swim bench load progressions	12
Table 2. Mean age, weight (Wt), height (Ht), total body fat (TBF) and lean body mass (LBM) of the subjects	13
Table 3. $\dot{V}_{O_2\max}$, HR_{\max} , \dot{V}_E/\dot{V}_{O_2} ratio and R_{\max} results for swim bench discontinuous (SBD) and swim bench continuous (SBC) ergometry (n=7)	14
Table 4. An example of a tethered swimming load progression	31
Table 5. Swim bench load progressions	34
Table 6. Mean age, weight (Wt), height (Ht), total body fat (TBF) and lean body mass (LBM) of the swimmers	35
Table 7. $\dot{V}_{O_2\max}$, HR_{\max} , \dot{V}_E/\dot{V}_{O_2} ratio and R_{\max} results for tethered swimming (TS) and swim bench continuous (SBC) ergometry (n=13)	36
Table 8. An example of a tethered swimming load progression	56
Table 9. Swim bench load progressions	59
Table 10. Mean age, weight (Wt), height (Ht), total body fat (TBF) and lean body mass (LBM) of the swimmers	60
Table 11. $\dot{V}_{O_2\max}$, HR_{\max} , \dot{V}_E/\dot{V}_{O_2} ratio and R_{\max} results for tethered swimming (TS) and tethered swimming arms only (TSA)(n=13)	61
Table 12. $\dot{V}_{O_2\max}$, HR_{\max} , \dot{V}_E/\dot{V}_{O_2} ratio and R_{\max} results for tethered swimming arms only (TSA) and swim bench continuous (SBC) ergometry (n=13)	62

LIST OF FIGURES

Figure 1. Side view of the experimental setup for the Biokinetic swim bench protocol.	10
Figure 2a. Side view of the experimental setup for the tethered swimming protocol.	27
Figure 2b. Overhead view of the experimental setup for the tethered swimming protocol.	29
Figure 3. Side view of the experimental setup for the Biokinetic swim bench protocol.	32
Figure 4. Diagrammatic representation of the changes in ventilatory equivalent (\dot{V}_E/\dot{V}_{O_2}) during tethered swimming (TS) and swim bench ergometry (SBC).	37
Figure 5. Diagrammatic representation of the changes in oxygen consumption (\dot{V}_{O_2}) and ventilation (\dot{V}_E) during tethered swimming (TS) and swim bench ergometry (SBC).	39
Figure 6a. Side view of the experimental setup for the tethered swimming protocol.	52
Figure 6b. Overhead view of the experimental setup for the tethered swimming protocol.	54
Figure 7. Side view of the experimental setup for the Biokinetic swim bench protocol.	57
Figure 8. Submaximal \dot{V}_{O_2} ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) responses during tethered swimming arms only (TSA) and swim bench ergometry (SBC), expressed at a given submaximal HR ($\text{b}\cdot\text{min}^{-1}$) range.	63
Figure 9. Diagrammatic representation of the changes in ventilatory equivalent (\dot{V}_E/\dot{V}_{O_2}) during tethered swimming arms only	

(TSA) and swim bench ergometry (SBC). 65

ACKNOWLEDGEMENTS

I would like to thank my supervisor, Professor Martin L. Collis for his encouragement over the last two years. I would like to thank Dr. Terry W. Pearson for his assistance as a member of my supervisory committee; his comments during testing and at the final stages of writing were of great help. Thanks are also extended to Dr. Richard Backus, the external examiner.

A special thank you is extended to Professor Howard A. Wenger, a member of my supervisory committee. I am more than grateful for the help offered in the form of critical analyses and excellent suggestions when writing this thesis. I was encouraged to look at exercise physiology from a varying perspective, and most importantly, to put the knowledge gained into practice.

This study was not possible without the help of others. A big thank you to Dawn and her work-study people for helping with the testing. To Cindy, thank you for the diagrams; thank you Beverly for graphics. To the often neglected computer people, Ise for her help with the statistical programmes and Eugene, for help with the graph plots. I am indebted to Mike and Laura for introducing me to the world of word processing.

Thanks are extended to the triathletes Sue, Karen, Bonnie, Pat, Bob, Chad and the 'old man'; and swimmers Connie, Shelley, Tanya, Patty, Nancy, Kevin, Wayne, Rod, Jon, Fin, John, Phil, Glen and Dr. Vizsolyi (coach). Their suffering was most appreciated. A special thank you to my fellow graduate students for their support over the last three years.

To a friend and colleague, Pat Neary, thanks are not enough.

CHAPTER I

DETERMINATION OF $\dot{V}_{O_2\text{MAX}}$ IN COMPETENT SWIMMERS WHEN USING A
CONTINUOUS VERSUS A DISCONTINUOUS SWIM BENCH PROTOCOL

Abstract

Maximum oxygen consumption ($\dot{V}_{O_2\max}$) and maximum heart rate (HR_{\max}) were determined in seven competent swimmers using a continuous swim bench protocol (SBC) and a discontinuous swim bench protocol (SBD). In both SBC and SBD the load was raised by increasing the resistance on the swim bench, with a 15 minute rest before the final load. During SBD, the work-rest ratio was 4:3 (minutes). Expired gases were measured every 30s using a Beckman Metabolic Measurement Cart (MMC). No differences were found between SBD and SBC in $\dot{V}_{O_2\max}$ and HR_{\max} . High correlations ($p < 0.01$) were found between SBC and SBD for $\dot{V}_{O_2\max}$ and HR_{\max} . These results suggested that either SBC or SBD exercise protocols can be used to determine $\dot{V}_{O_2\max}$ in the swimmers of the present study. However, from an administrative standpoint, SBC is preferable when testing groups.

Introduction

Tests predicting maximum oxygen consumption ($\dot{V}_{O_2\max}$) have been found to be specific to the exercise mode (Roberts and Alspaugh, 1972; Pechar et al., 1974). The test can be either continuous or discontinuous, with a variety of loading progressions (Cardus, 1979). The results of physiological measurements can be affected in the testing situation by combinations of arm plus leg work (Reybrouck et al., 1975; Bergh et al., 1976), test duration (McArdle et al., 1973; Pimental et al., 1984) and the rate at which the test is performed, for example, bicycle pedal frequency or stroke rate (Sawka et al., 1983; Swaine and Reilly, 1983). Thus, certain test procedures are more appropriate than others for a given situation.

It has been suggested that when performing a $\dot{V}_{O_2\max}$ test, a discontinuous protocol should be used with untrained subjects and where small (easily fatigued) muscle masses are utilised, whereas a continuous test should be used for trained individuals (Cardus, 1979; MacDougall et al., 1982). But both continuous and discontinuous protocols are equally reliable in predicting $\dot{V}_{O_2\max}$ when testing trained subjects on a treadmill and cycle (McArdle et al., 1973). However, comparisons between continuous and discontinuous arm protocols to predict $\dot{V}_{O_2\max}$ during a swimming mode of exercise have not been evaluated.

Therefore, the purpose of the present study was to determine whether a continuous or discontinuous swim bench protocol would elicit greater $\dot{V}_{O_2\max}$ values in competent swimmers.

Methods

Seven trained swimmers (male=4, female=3), signed informed consent forms and were familiarised with the testing procedures. The subjects performed two separate tests to determine $\dot{V}_{O_2\max}$: 1) Biokinetic swim bench ergometry continuous test (SBC), and, 2) Biokinetic swim bench ergometry discontinuous test (SBD).

During SBC and SBD, the subjects were strapped to the swim bench to limit body movements, and hand gloves were worn for protection (Figure 1). Stroke rate (SR) was set by a metronome at 72 strokes per minute ($_{spm}$), but dropped to 64 $_{spm}$ at the higher resistance settings. The SR was based on the mean SR obtained from a tethered swim performed by the swimmers in a preliminary test. SBC consisted of a 2 minute warm-up at setting 7 (low tension) followed by a setting increase every 2 minutes until setting 4 (high tension) was reached. A 15 minute rest was taken to reduce the effects of fatigue (MacDougall et al., 1982), followed by a final load at setting 3 (Table 1). The same load progression was used for SBD, except work periods were of 4 minutes duration with a 3 minute rest after each work period (4:3 work-rest ratio). An alternate arm pulling action was used during the swim bench tests, with an under-arm recovery.

During the exercise tests, the subjects breathed through a low resistance respiratory valve. Oxygen (O_2) and carbon dioxide (CO_2) were collected and analysed by a Beckman Metabolic Measurement Cart (MMC) previously calibrated with gases of known concentrations. Physiological measures, including volume of expired air (\dot{V}_E), oxygen consumption (\dot{V}_{O_2}), respiratory exchange ratio (R) and heart rate (HR), were recorded every 30s. Prior to testing, body fat estimations

were performed according to procedures by Yuhasz (Carter, 1982).

A correlated 't' test was employed to determine whether significant differences existed between SBC and SBD for $\dot{V}_{O_2\max}$ and HR_{\max} when testing trained swimmers. In addition, correlation coefficients were computed for $\dot{V}_{O_2\max}$ and HR_{\max} .

Results

The physical characteristics of the subjects are shown in Table 2. The mean values (means \pm S.E.) for $\dot{V}_{O_2\max}$ and HR_{\max} and levels of significance are presented in Table 3. The SBD $\dot{V}_{O_2\max}$ was $0.02 \text{ l}\cdot\text{min}^{-1}$ or $2.8 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ higher than SBC $\dot{V}_{O_2\max}$. In addition, the mean HR_{\max} for SBD was $2 \text{ b}\cdot\text{min}^{-1}$ higher than SBC HR_{\max} . No statistically significant differences were found between the two protocols. The correlation coefficients were $r=0.92$ ($p=0.001$), $r=0.84$ ($p=0.008$) and $r=0.93$ ($p=0.001$) for $\dot{V}_{O_2\max} (\text{l}\cdot\text{min}^{-1})$, $\dot{V}_{O_2\max} (\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1})$ and HR_{\max} respectively.

The mean maximal respiratory exchange ratios (R_{\max}) were 1.00 (SBD) and 1.12 (SBC), indicating maximal effort by the subjects (MacDougall et al., 1982). The ventilatory equivalents (\dot{V}_E/\dot{V}_{O_2}) at $\dot{V}_{O_2\max}$ were 40.0 and 43.7 for SBD and SBC respectively.

Discussion

The purpose of this study was to determine whether a difference existed in

$\dot{V}_{O_2\max}$ as measured during either a continuous (SBC) or discontinuous (SBD) swim bench protocol. Both SBD and SBC $\dot{V}_{O_2\max}$ were comparable to previous data obtained from swimmers using swim bench ergometry (Armstrong and Davies, 1981). The difference in $\dot{V}_{O_2\max}$ measured during SBC versus SBD were found to be non-significant. This result offers evidence contrary to the suggested theory that $\dot{V}_{O_2\max}$ values may be depressed due to local muscle fatigue when using a continuous test (Cardus, 1979; MacDougall et al., 1982). Sawka and co-workers (1983) have also shown no significant differences in $\dot{V}_{O_2\max}$ when using both a continuous and discontinuous arm test protocol.

The difference in HR_{\max} was found to be non-significant between SBC and SBD, and is in agreement with previous studies involving continuous and discontinuous protocols (McArdle et al., 1973; Sawka et al., 1983) The mean swim bench values for HR_{\max} in this study (SBC=162 $b \cdot \min^{-1}$ and SBD=164 $b \cdot \min^{-1}$) were lower than the 171 $b \cdot \min^{-1}$ found by Gergley et al. (1984), when testing college male swimmers using a discontinuous protocol. However, in the latter study, the load was imposed by attaching weights to an arm pulley system. It is suggested that during arm recovery in the Gergley study, the muscles contracted in an eccentric manner, which increased muscle activity. The additional eccentric work may have raised HR, resulting in the 10 $b \cdot \min^{-1}$ difference found at HR_{\max} between this study and that of Gergley.

The correlation coefficients were significantly positive ($p < 0.01$). The results showed that over 90% of the variance in SBC was associated with SBD. Both protocols, therefore, were reliable when predicting $\dot{V}_{O_2\max}$ and HR_{\max} .

The \dot{V}_E/\dot{V}_{O_2} ratio indicated that ventilatory efficiency for O_2 was approximately equal in both SBC and SBD. The limitation on $\dot{V}_{O_2\max}$ imposed by \dot{V}_E , therefore, would be minimal between the protocols (Brooks and Fahey, 1984).

The 0.12 difference between SBC R_{\max} and SBD R_{\max} was non-significant. However, the observed values were characteristic of intermittent exercise. In a recent study (Neary and Wenger, 1985), a significantly higher lactate production was found during the continuous test compared with the discontinuous test. This suggested a greater contribution of anaerobic metabolism to the exercise (Essen, 1978). The increased anaerobic work would result in a higher R_{\max} during SBD, whereas the recovery period during SBD allowed the lactic acid to be buffered and removed more readily, thereby lowering R_{\max} . This was indicated in the present study and by others (Åstrand and Rodahl, 1977). Observation of both SBC and SBD during testing indicated that both tests were extremely demanding. The subjects stated that the SR of 72_{spm} at the initial power output (PO) levels did not produce a stressful demand. However, at the high tension settings, the demand and subjective feeling of strain was too high to maintain the 72_{spm} SR. For future work with elite swimmers, the SR and the initial tension should be higher. Furthermore, the more highly trained arm musculature in elite swimmers may alleviate the feeling of strain at the high PO levels.

When swim bench continuous (SBC) protocol and swim bench discontinuous (SBD) protocol were compared, no differences in $\dot{V}_{O_2\max}$ and HR_{\max} were found in the swimmers of the present study. From a time saving standpoint, therefore, SBC is recommended when testing groups of individuals on a swim bench ergometer.

References

- Armstrong, N and Davies, B. (1981). An ergometric analysis of age group swimmers. **British Journal of Sports Medicine** 15 (1):20-26.
- Åstrand, P-O. and Rodahl, K. (1977). **Textbook of Work Physiology**. McGraw-Hill, New York.
- Bergh, U., Kanstrup, I-L. and Ekblom, B. (1976). Maximal oxygen uptake during exercise with various combinations of arm and leg work. **Journal of Applied Physiology** 41 (2):191-196.
- Brooks, G.A. and Fahey, T.D. (1984). **Exercise Physiology : Human Bioenergetics and its Applications**. John Wiley and Sons, New York.
- Cardus, D. (1979). Exercise testing : Methods and uses. **Exercise and Sports Science Review** 6:59-103.
- Carter, J.E.L. (1982). Body composition of Montreal Olympic athletes. **Medicine in Sport** 16:107-116.
- Essen, B. (1978). Studies on the regulation of metabolism in human skeletal muscle using intermittent exercise as an experimental model. **Acta Physiologica Scandinavica**. Suppl. 454.
- Gergley, T.J., McArdle, W.D., DeJesus, P., Toner, M.M., Jacobowitz, S., and Spina, R. (1984). Specificity of arm training on aerobic power during swimming and running. **Medicine and Science in Sports and Exercise** 16 (4):349-354.
- MacDougall, J.D., Wenger, H.A. and Green, H.J. (1982) **Physiological Testing of the Elite Athlete**. Canadian Association of Sports Sciences. Mutual Press Limited, Toronto.
- McArdle, W.D., Katch, F.I. and Pecher, G.S. (1973). Comparison of continuous and discontinuous treadmill and bicycle tests for max \dot{V}_{O_2} . **Medicine and Science in Sports and Exercise** 5 (3):156-160.
- Neary, P.J. and Wenger, H.A. (1985). The effects of continuous versus discontinuous cycling on lactate and ventilation thresholds. **Journal of Human Movement Studies** 11:151-157.
- Pecher, G.S., McArdle, W.D., Katch, F.I., Magel, J.R. and Delucia, J. (1974). Specificity of cardiorespiratory adaptation to bicycle and treadmill running. **Journal of Applied Physiology** 36 (6):753-756.
- Pimental, N.A., Sawka, M.N., Billings, D.S. and Trad, L.A. (1984). Physiological responses to prolonged upper-body exercise. **Medicine and Science in Sports and Exercise** 16 (4):360-365.
- Reybrouck, T., Heigenhauser, G.F. and Faulkner, J.A. (1975). Limitations to maximum oxygen uptake in arm, leg, and combined arm-leg ergometry.

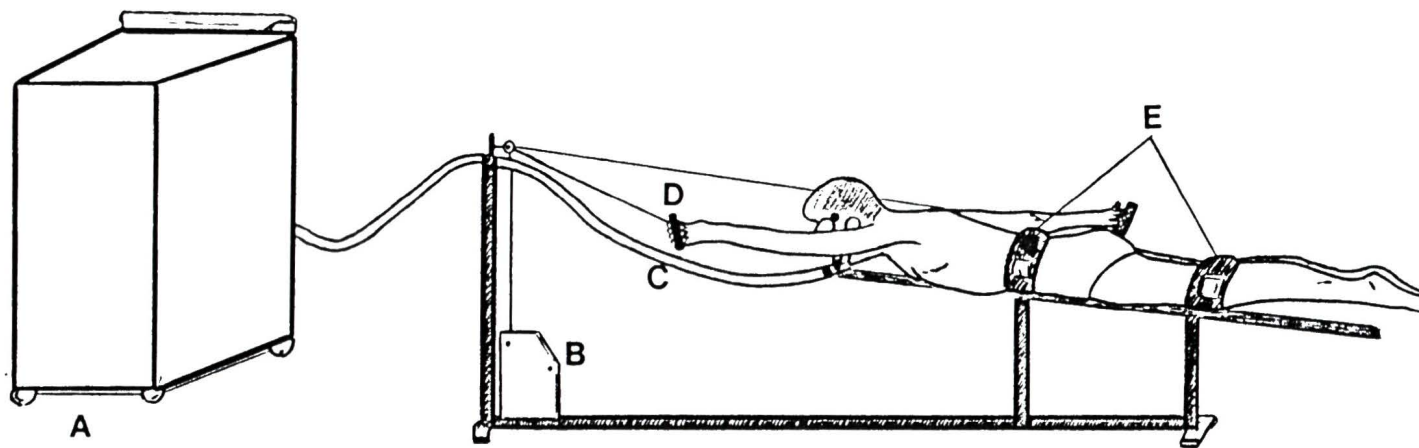
Journal of Applied Physiology 38 (5):774-779.

Roberts, J. A. and Alspaugh, J. W. (1972). Specificity of training effects resulting from programmes of treadmill running and bicycle ergometer riding. **Medicine and Science in Sports and Exercise** 4 (1):6-10.

Sawka, M.N., Foley, M.E., Pimental, N.A., Toner, M.M. and Pandolf, K.B. (1983). Determination of maximal aerobic power during upper-body exercise. **Journal of Applied Physiology** 54 (1):113-117.

Swaine, I. and Reilly, T. (1983). The freely-chosen swimming stroke rate in a maximal swim and on a biokinetic swim bench. **Medicine and Science in Sports and Exercise** 15 (5):370-375.

Figure 1. Side view of the experimental setup for the Biokinetic swim bench protocol.



- A = BECKMAN METABOLIC MEASUREMENT CART
- B = TENSION SETTING
- C = GAS ANALYSIS HOSE
- D = HAND PADDLE ATTACHMENT
- E = STRAPPING

TABLE 1

SWIM BENCH LOAD PROGRESSIONS

Swim Bench Setting	Time (min)
7	2
6	2
5	2
4	2
Rest	15
3	2

TABLE 2
MEAN AGE, WEIGHT (Wt), HEIGHT (Ht), TOTAL BODY FAT (TBF)
AND LEAN BODY MASS (LBM) OF THE SUBJECTS

	Age (yrs)	Wt (kg)	Ht (cm)	TBF (%)	LBM (kg)
Women (n=3)	21 (0.6)	58.7 (0.8)	168.0 (2.1)	13.0 (1.3)	50.6 (0.8)
Men (n=4)	25 (1.3)	72.8 (3.3)	176.4 (1.2)	8.1 (0.8)	67.0 (2.7)
Group (n=7)	23 (1.1)	66.8 (3.3)	172.8 (2.3)	10.2 (1.2)	59.9 (3.6)

Note :

Standard errors shown in parentheses

TABLE 3
 $\dot{V}_{O_2\text{MAX}}$, HR_{MAX}, \dot{V}_E/\dot{V}_{O_2} RATIO AND R_{MAX}
 RESULTS FOR SWIM BENCH DISCONTINUOUS (SBD) AND
 SWIM BENCH CONTINUOUS (SBC) ERGOMETRY (n=7)

	SBD	SBC	p
$\dot{V}_{O_2\text{max}}$ (l·min ⁻¹)	2·32 (0·2)	2·30 (0·2)	NS
$\dot{V}_{O_2\text{max}}$ (ml·kg ⁻¹ ·min ⁻¹)	31·8 (1·8)	34·6 (1·9)	NS
HR _{max} (b·min ⁻¹)	164 (8)	162 (6)	NS
\dot{V}_E/\dot{V}_{O_2}	40·0 (2·0)	43·7 (2·3)	NS
R _{max}	1·00 (·05)	1·12 (·04)	NS

Note :

Group means shown

Standard error in parentheses

'p' indicates significance of 't' test (p<0·05)

CHAPTER II

A COMPARISON OF $\dot{V}_{O_2\text{MAX}}$ ATTAINED BY ELITE SWIMMERS USING THE BIOKINETIC SWIM BENCH AND TETHERED SWIMMING

Abstract

The purpose of this study was to develop a regression equation for predicting the maximum oxygen consumption ($\dot{V}_{O_2\max}$) of an elite swimmer during tethered swimming from the $\dot{V}_{O_2\max}$ attained on a Biokinetic Swim Bench. Thirteen national and varsity swimmers volunteered to perform tethered swimming (TS) and continuous swim bench (SBC) tests to obtain $\dot{V}_{O_2\max}$. A stepwise load increase every two minutes was used in both TS (by adding weights) and SBC (by increasing tension). Expired gases were measured every 30s using the Beckman Metabolic Measurement Cart (MMC). $\dot{V}_{O_2\max}$ and HR_{\max} were higher in TS than SBC ($p<0.001$ and $p<0.005$ respectively). The \dot{V}_E/\dot{V}_{O_2} ratio at $\dot{V}_{O_2\max}$ was lower in TS compared with SBC ($p<0.01$). There was no difference in R_{\max} for the two tests. These data suggest that SBC $\dot{V}_{O_2\max}$ was not a valid measure of TS $\dot{V}_{O_2\max}$. A positive correlation ($r=0.59$, $p=0.017$) was found between TS $\dot{V}_{O_2\max}$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) and SBC $\dot{V}_{O_2\max}$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$). A stepwise regression analysis yielded the following prediction equation ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$): $\text{TS } \dot{V}_{O_2\max} = 0.595 \text{ SBC } \dot{V}_{O_2\max} + 35.8$ ($s_{x,y}=4.74$). Although the prediction equation was statistically significant, the correlation coefficient accounted for only 35% ($r^2=0.35$) of the common variance. Therefore, SBC $\dot{V}_{O_2\max}$ was a poor predictor of TS $\dot{V}_{O_2\max}$ in elite swimmers.

Introduction

Maximum oxygen consumption or maximum aerobic power ($\dot{V}_{O_2\max}$) is the most widely used indicator of the endurance potential of an individual (Cardus, 1979; Shephard, 1984). Physiologically, $\dot{V}_{O_2\max}$ reflects the efficiency of the body to transport oxygen via the circulatory system (central component) and the efficiency of the muscle to utilise that oxygen in the ATP resynthesis process (peripheral component) (Holloszy, 1975; McCafferty and Horvath, 1977; McKenzie et al., 1978).

$\dot{V}_{O_2\max}$ has been shown to be specific to the mode of exercise performed (Roberts and Alspaugh, 1972; Magel et al., 1975; Pate et al., 1978). The more specific the test to the actual exercise, the more accurate the measure of $\dot{V}_{O_2\max}$ (Bonen et al., 1980; Magel et al., 1975). Tethered swimming (TS) is one such test procedure that has been shown to be both specific to swim trained individuals (Magel and Faulkner, 1967; Magel, 1970), and valid when compared to flume or free swimming (Bonen et al., 1980). However, technical problems can impede data collection in the water environment. It may be advantageous, therefore, to have a dry-land testing device that could be used in a controlled laboratory setting.

The Biokinetic swim bench (Isokinetics, Inc.) was developed as a dry-land training machine for swimmers. The use of this swim bench as a testing device is prevalent in the literature, and has been used to monitor fatigue (Thornton and Flavell, 1981), power output (Costill et al., 1980; 1985), or for prediction of performance, especially in sprint swimming (Sharp et al., 1982). Armstrong and Davies (1981) used the Biokinetic swim bench to predict $\dot{V}_{O_2\max}$ in age-group swimmers, but no validation was made with TS.

The purpose of this study, therefore, was two-fold: 1) to determine whether swim bench $\dot{V}_{O_2\max}$ was a valid measure of tethered swimming $\dot{V}_{O_2\max}$, and, 2) to determine whether $\dot{V}_{O_2\max}$ elicited by a swimmer when using the Biokinetic swim bench could be used to predict the $\dot{V}_{O_2\max}$ in a tethered swimming test.

Methods

Thirteen elite swimmers (male=8, female=5), signed informed consent forms and were familiarised with the testing procedures. The subjects performed two separate tests to determine $\dot{V}_{O_2\max}$: 1) tethered swimming (TS), and, 2) Biokinetic swim bench ergometry continuous test (SBC).

The TS test required a pulley system allowing the swimmer to remain in a stationary position, yet work in a swimming mode at maximum rate (Figure 2a). During TS, a marker was placed on the pool floor, over which the subjects were required to swim, and remain in a stationary position. A metal framework was used to hang hoses from the Beckman Metabolic Measurement Cart (MMC) to the mouth piece on the swimmer (Figure 2b).

The TS procedure required two separate swims. The first was to determine the maximum tether load (TL_{\max}), where weights (in kilogrammes) were rapidly added to the bucket until the subject was pulled back from the mark. Following a ten minute rest, the subject performed a progressive maximum test until exhaustion (i.e., until the weight bucket touched the base of the TS apparatus). The load progressions were based on the TL_{\max} of each swimmer, and increments were made every two minutes (Table 4). The TL_{\max} was divided into six load progressions. The warm-up load was approximately $1/3$ of TL_{\max} ($1/3TL_{\max}$),

followed by increments of $1/6 TL_{max}$ (load 2 and 3), $1/8 TL_{max}$ (load 4 and 5), and a final load increment of $1/12 TL_{max}$. The freestyle swimming stroke was performed by the swimmers during TS.

During SBC, subjects were strapped to the swim bench to limit body movements, and hand gloves were worn for protection (Figure 3). Stroke rate (SR) was set by a metronome at 76 strokes per minute (spm), but dropped at the higher resistance settings. The SBC SR was based on the mean swimming SR of the swimmers from four varsity swim meets. SBC consisted of a 2 minute warm-up at setting 6 (low tension) followed by a setting increase every 2 minutes until setting 3 (high tension) was reached. A 15 minute rest was taken to reduce the effects of fatigue (MacDougall et al., 1982), followed by a final load at setting 2 (Table 5). An alternate arm pulling action, with an under-arm recovery, was used during SBC.

During the exercise tests, subjects breathed through a low resistance respiratory valve. Oxygen (O_2) and carbon dioxide (CO_2) were collected and analysed by the MMC, previously calibrated with gases of known concentrations. Physiological measures, including volume of expired air (\dot{V}_E), oxygen consumption (\dot{V}_{O_2}), respiratory exchange ratio (R) and heart rate (HR), were recorded every 30s. Prior to testing, body fat estimations were performed according to procedures by Yuhasz (Carter, 1982).

A correlated 't' test was employed to determine whether any significant differences in mean scores existed between the two tests for \dot{V}_{O_2max} and HR_{max} , ventilatory equivalent (\dot{V}_E/\dot{V}_{O_2}) at \dot{V}_{O_2max} and maximum respiratory exchange ratio (R_{max}). In addition, a stepwise regression analysis was performed to determine whether SBC \dot{V}_{O_2max} could predict TS \dot{V}_{O_2max} .

Results

The physical characteristics of the subjects (means \pm SE) are shown in Table 6. Presented in Table 7 are the mean TS and SBC scores (\pm SE) and the 't' test probabilities for $\dot{V}_{O_2\max}$, HR_{\max} , \dot{V}_E/\dot{V}_{O_2} ratio and R_{\max} . The mean TS $\dot{V}_{O_2\max}$ was $1.35 \text{ l}\cdot\text{min}^{-1}$ or $19.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ higher than the mean SBC $\dot{V}_{O_2\max}$ ($p < 0.001$).

The mean HR_{\max} was $12 \text{ b}\cdot\text{min}^{-1}$ lower in SBC than TS ($p < 0.005$). The 0.04 higher mean R_{\max} for TS compared to SBC was non-significant, but indicated maximal effort by the swimmers (MacDougall et al., 1982) in both tests. The SBC \dot{V}_E/\dot{V}_{O_2} ratio at $\dot{V}_{O_2\max}$ was 6.5 higher than the TS \dot{V}_E/\dot{V}_{O_2} ratio ($p < 0.01$).

At the lower submaximal loads, as the exercise intensity increased, the TS \dot{V}_E/\dot{V}_{O_2} ratio decreased, but then increased at higher submaximal intensities (Figure 4). An opposite trend occurred during SBC, but the observed ratio did not fluctuate to the same extent as the TS ratio.

The stepwise regression analysis indicated a positive correlation between TS and SBC $\dot{V}_{O_2\max}$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) ($r=0.59$, $p=0.017$). The regression equation was $\text{TS } \dot{V}_{O_2\max} (\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}) = (0.595 \text{ SBC } \dot{V}_{O_2\max} \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}) + 35.8$ ($s_{x,y}=4.74$).

Discussion

Maximum Oxygen Consumption. The mean TS $\dot{V}_{O_2\max}$ score in the present study was in agreement with some previous TS studies (Magel and Faulkner, 1967; Magel, 1970; 1971), but lower than in other studies (Holmer, 1974b) involving elite swimmers. When expressed as an absolute value, the mean SBC $\dot{V}_{O_2\max}$ was

higher than previous work (Armstrong and Davies, 1981; Gergley et al., 1984). However, when expressed relative to body weight, SBC $\dot{V}_{O_2\max}$ was lower than other studies (Armstrong and Davies, 1981). In the latter study, the mean weight of the subjects was 55.5 kg (± 13.4), lower than the swimmers in the present study.

The $\dot{V}_{O_2\max}$ for SBC was significantly lower than for TS. During SBC, increased resistance and hence increased muscular tension (motor unit recruitment) elevated the load, whereas in TS, the load was elevated by SR and speed of contraction. The isokinetic muscle contraction that occurred during SBC resulted in a longer contractile period (especially at high tension, slow speed settings), as indicated by SR. However, during TS, contraction time became shorter as the load was increased. Furthermore, in accordance with stroke mechanic theories (Counsilman, 1971; Barthels, 1978; Counsilman, 1981), the application of the hand of the swimmer in a sculling motion at a given velocity results in an exponential increase in force (f^2). Under these conditions, as the TS test progressed, small increases in motor unit recruitment were adequate to hold the swimmer in a stationary position.

Clausen (1971) states that the optimum ratio of muscle contraction-relaxation (C-R) to facilitate a muscle pump action is 1:0.3. Once this value has been surpassed, blood pressure and local vascular occlusion reduce muscle blood flow (MBF). The reduction in MBF ultimately inhibits $\dot{V}_{O_2\max}$ (Matsui et al., 1978). In the present study, a high C-R during SBC probably impaired MBF, whereas the muscle pump action during TS would have enhanced it. Thus increasing TS $\dot{V}_{O_2\max}$.

Maximum Heart Rate. TS HR_{\max} was significantly higher than SBC HR_{\max} ($p < 0.001$), and mean scores were representative of other trained swimmers (Magel, 1971; Holmer, 1974b; Gergley et al., 1984). According to Rowell (1980), the

circulatory response to exercise is proportional to the motor unit recruitment. Greater HR_{max} scores have been demonstrated in arm-leg work compared with arm work (Bergh et al., 1976; Millerhagen et al., 1983), and during full-stroke compared with legs or arms only freestyle swimming (Holmer 1974a). Therefore, in the present study, the maximal circulatory capacity may have not been met during SBC (Saltin, 1971), resulting in a lower HR_{max} compared with TS.

Ventilatory Equivalent. The \dot{V}_E/\dot{V}_{O_2} ratio is an index of the efficiency of ventilation (Bhambhani and Singh, 1985). The ability of \dot{V}_E to increase is proportionally greater than \dot{V}_{O_2} during exercise, primarily due to an increase in anaerobic metabolism (Whipp, 1978; Brooks and Fahey, 1984). Hence it is unlikely that \dot{V}_E limits \dot{V}_{O_2max} . The \dot{V}_E/\dot{V}_{O_2} ratio for SBC decreased until a deflection point (Figure 4), where it showed a slight increase until maximal levels were reached. This was opposite to the TS \dot{V}_E/\dot{V}_{O_2} and to the data of Bhambhani and Singh (1985). It has been demonstrated that breathing frequency is synchronised with SR or arm revolutions (Holmer, 1974b; Vokac et al., 1975). The SBC SR began at 76_{spm} at a low \dot{V}_{O_2} , then remained at 76_{spm} or dropped towards the end of the test, as the increments in \dot{V}_E fell during periods of high \dot{V}_{O_2} . Moreover, the mean TS SR increased from 54_{spm} to 102_{spm}, with \dot{V}_{O_2} rising from 0.4 l·min⁻¹ to 5.0 l·min⁻¹ (Figure 5). The deflection point during TS coincided with the dramatic increase in SR, hence \dot{V}_E would have increased at a proportionally higher rate than \dot{V}_{O_2} , thereby reducing the \dot{V}_E/\dot{V}_{O_2} ratio. In the present study, therefore, SBC SR imposed a restriction on \dot{V}_E which increased the SBC \dot{V}_E/\dot{V}_{O_2} at \dot{V}_{O_2max} , whereas the higher \dot{V}_E during TS may have enhanced TS \dot{V}_{O_2max} (Figure 5).

Prediction of TS \dot{V}_{O_2max} . The stepwise regression analysis revealed a positive correlation ($r=0.59$, $p=0.017$) between TS \dot{V}_{O_2max} and SBC \dot{V}_{O_2max} , when expressed

relative to body weight. It should be stated that the correlation coefficient ($r=0.59$) represented only 35% ($r^2=0.35$) of the common variance. in TS. The data from the swimmers in the present study produced the following prediction equation :

$$\text{TS } \dot{V}_{O_2\text{max}} \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1} = (0.595 \text{ SBC } \dot{V}_{O_2\text{max}} \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}) + 35.8 (s_{x\cdot y}=4.74)$$

From a practical viewpoint, the standard error of prediction for the equation was too high to be of use for monitoring training progress, due to the low r^2 value.

The above evidence suggested that SBC $\dot{V}_{O_2\text{max}}$ was not a valid measure of TS $\dot{V}_{O_2\text{max}}$, this being the result of restrictions imposed by the circulatory and ventilatory systems. In addition, SBC $\dot{V}_{O_2\text{max}}$ was not a useful predictor of TS $\dot{V}_{O_2\text{max}}$ in swimmers, and where possible, the TS protocol should be used.

References

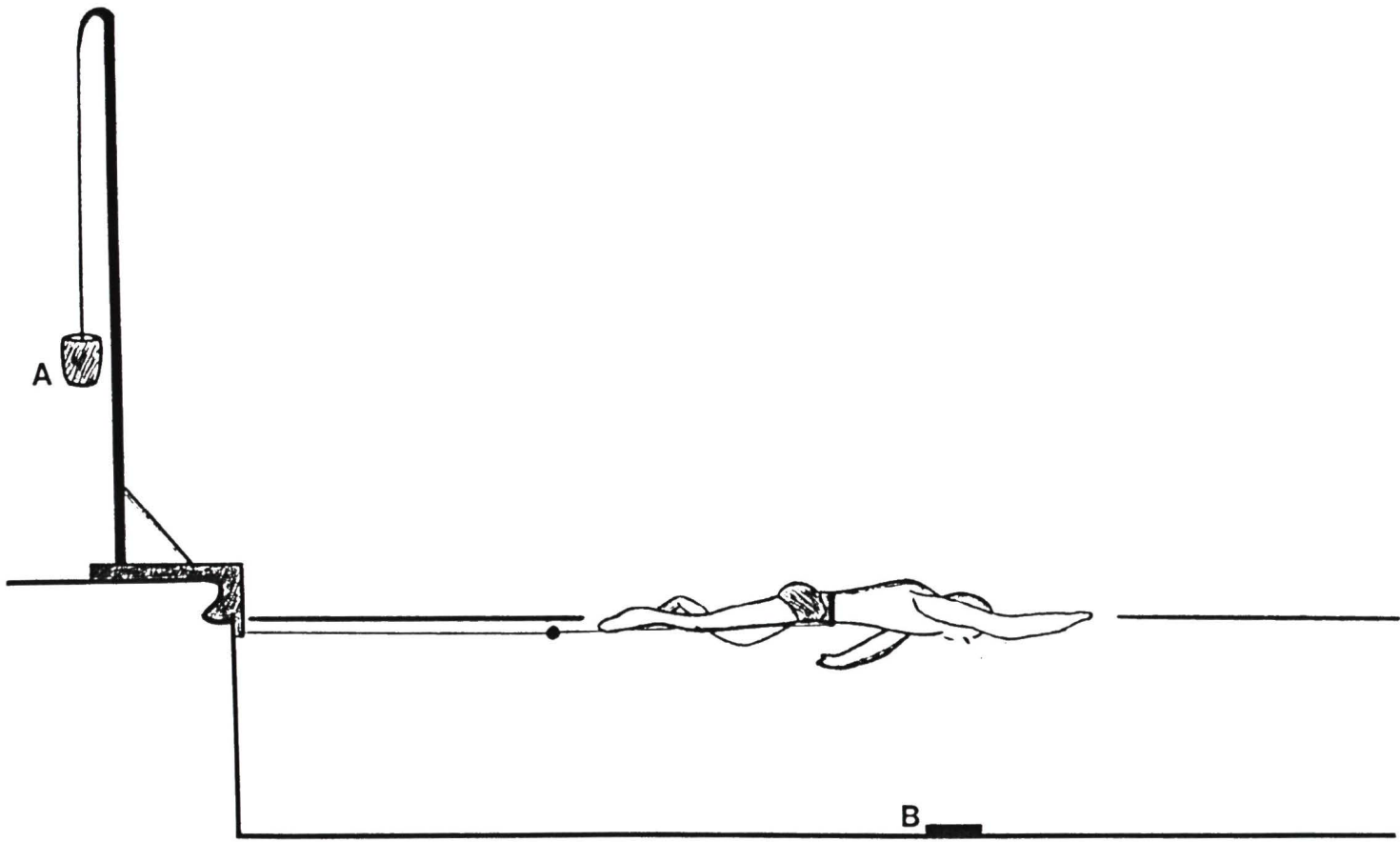
- Armstrong, N. and Davies, B. (1981). An ergometric analysis of age group swimmers. **British Journal of Sports Medicine** 15 (1):20-26.
- Barthels, K.M. (1978). The mechanism for body propulsion in swimming. In J. Terauds and F.W. Bedingford (Eds). **Swimming III**. International Series on Sports 8:45-54. University Park Press, Baltimore.
- Bergh, U., Kanstrup, I-L. and Ekblom, B. (1976). Maximal oxygen uptake during exercise with various combinations of arm and leg work. **Journal of Applied Physiology** 41 (2):191-196.
- Bhambhani, Y. and Singh, M. (1985). The effects of three training intensities on $\dot{V}_{O_2\max}$ and \dot{V}_E/\dot{V}_{O_2} ratio. **Canadian Journal of Applied Sports Sciences** 10 (1):44-51.
- Bonen, A., Wilson, B.A., Yarkony, M. and Belcastro, A.N. (1980). Maximal oxygen uptake during free, tethered, and flume swimming. **Journal of Applied Physiology** 48 (2):232-235.
- Brooks, G.A. and Fahey, T.D. (1984). **Exercise Physiology: Human Bioenergetics and its Applications**. John Wiley and Sons, New York.
- Cardus, D. (1979). Exercise testing : Methods and uses. **Exercise and Sports Science Review** 6:59-103.
- Carter, J.E.L. (1982). Body composition of Montreal Olympic athletes. **Medicine in Sport** 16:107-116.
- Clausen, J.P. (1971). Muscle blood flow during exercise and its significance for maximal performance. In J.Keul (Ed) **Limiting Factors in Physical Performance** :253-266. Georg Thieme Publishers, Stuttgart.
- Costill, D., Sharp, R. and Troup, J. (1980). Muscle strength: Contributions to sprint swimming. **Swimming World** 21 (2):29-34.
- Costill, D.L., King, D.S., Thomas, R. and Hargreaves, M. (1985). Effects of reduced training on muscular power in swimmers. **The Physician and Sportsmedicine** 13 (2):94-101.
- Counsilman, J.E. (1971). The application of Bernoulli's Principle to human propulsion in water. In L. Lewillie and J.P. Clarys (Eds). **First International Symposium on Biomechanics in Swimming**. University Libre de Bruxelles, Brussels, 59-71.
- Counsilman, J.E. (1981). Hand speed and acceleration. **Swimming Technique** May:22-26.
- Gergley, T.J., McArdle, W.D., DeJesus, P., Toner, M.M., Jacobowitz, S., and Spina, R. (1984). Specificity of arm training on aerobic power during swimming and running. **Medicine and Science in Sports and Exercise** 16

(4):349-354.

- Holloszy, J.O. (1975). Adaptation of skeletal muscle to endurance exercise. **Medicine and Science in Sports and Exercise** (7) 3:155-164.
- Holmer, I. (1974a). Energy cost of arm stroke, leg kick, and the whole stroke in competitive swimming styles. **European Journal of Applied Physiology** 33:105-118.
- Holmer, I. (1974b). Physiology of swimming man. **Acta Physiologica Scandinavica** Suppl. 407.
- MacDougall, J.D., Wenger, H.A. and Green, H.J. (1982) **Physiological Testing of the Elite Athlete**. Canadian Association of Sports Sciences. Mutual Press Limited, Toronto.
- Magel, J.R. (1970). Propelling force measured during tethered swimming in the four competitive swimming styles. **Research Quarterly** 41 (1):68-74.
- Magel, J.R. (1971). Comparison of the physiologic response to varying intensities of submaximal work in tethered swimming and treadmill running. **Journal of Sports Medicine** 11:203-212.
- Magel, J.R. and Faulkner, J.A. (1967). Maximum oxygen uptakes of college swimmers. **Journal of Applied Physiology** 22 (5):929-938.
- Magel, J.R., Foglia, G.F., McArdle, W.D., Gutin, B., Pecher, G.S and Katch, F.I. (1975). Specificity of swim training on maximum oxygen uptake. **Journal of Applied Physiology** 38 (1):151-155.
- Matsui, H., Kitamura, K. and Miyamura, M. (1978). Oxygen uptake and blood flow of the lower limb in maximal treadmill and bicycle exercise. **European Journal of Applied Physiology** 40 (1):57-62.
- McCafferty, W.B. and Horvath, S.M. (1977). Specificity of exercise and specificity of training: a subcellular review. **Research Quarterly** 48 (2):358-371.
- McKenzie, D.C., Fox, E.L. and Cohen, K. (1978). Specificity of metabolic and circulatory responses to arm or leg interval training. **European Journal of Applied Physiology** 39 (4):241-248.
- Millerhagen, J.O., Kelly, J.M. and Murphy, R.J. (1983). A study of combined arm and leg exercise with application to Nordic skiing. **Canadian Journal of Applied Sports Science** 8 (2):92-97.
- Pate, R.R., Hughes, R.D., Chandler, J.V. and Ratliffe, J.L. (1978). Effects of arm training on retention of training effects derived from leg training. **Medicine and Science in Sports and Exercise** 10 (2):71-74.
- Roberts, J.A. and Alspaugh, J.W. (1972). Specificity of training effects resulting from programmes of treadmill running and bicycle ergometer riding. **Medicine and Science in Sports and Exercise** 4 (1):6-10.

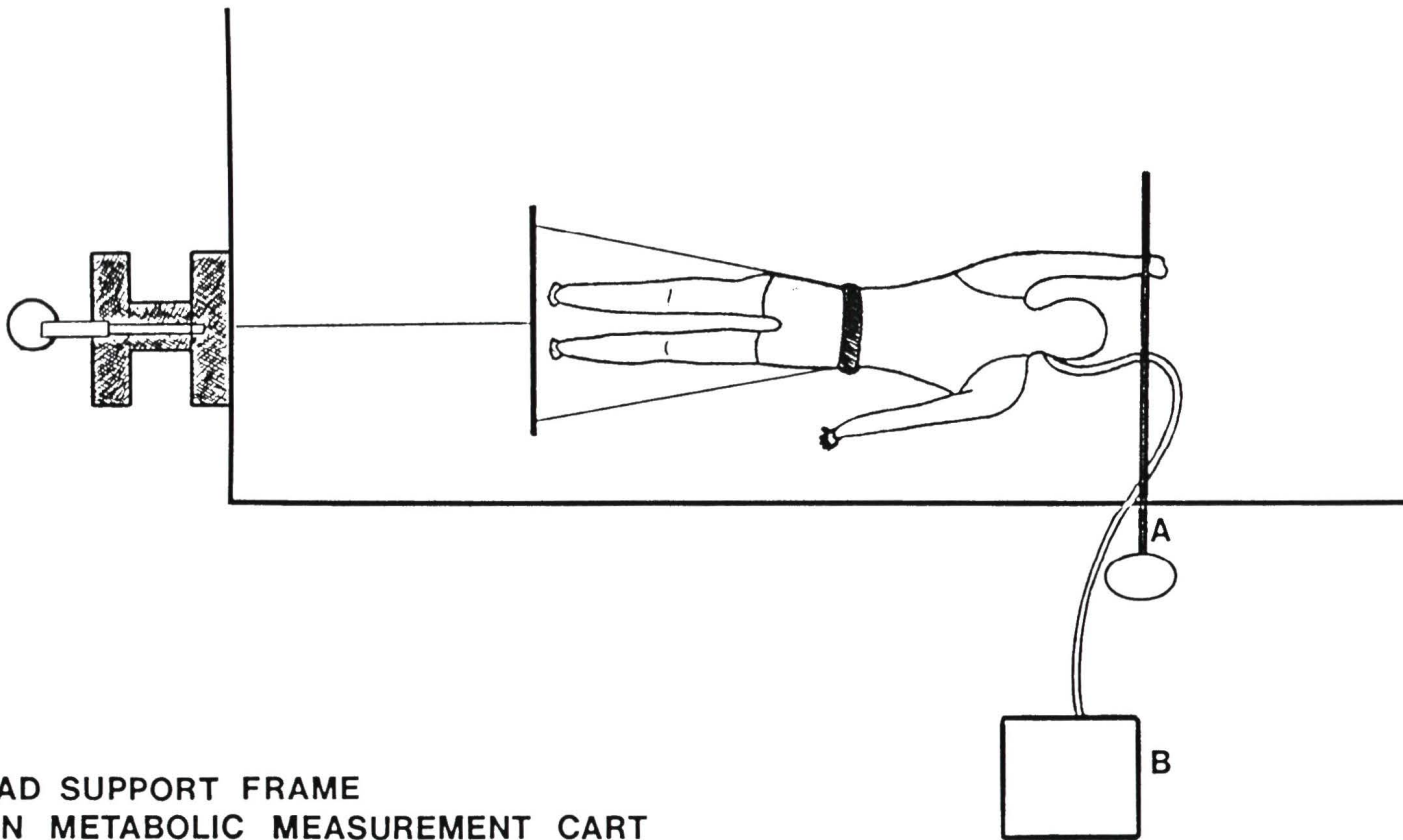
- Rowell, L.B. (1980). What signals govern the cardiovascular responses to exercise? **Medicine and Science in Sports and Exercise** 12 (5):307-315.
- Saltin, B. (1971). Oxygen transport by the circulatory system during exercise in man. In J.Keul (Ed) **Limiting Factors of Physical Performance** :235-252. Georg Thieme Publishers, Stuttgart.
- Sharp, R.L., Troup, J.P. and Costill, D.L. (1982). Relationship between power and sprint freestyle swimming. **Medicine and Science in Sports and Exercise** 14 (1):53-56.
- Shephard, R.J. (1984). Tests of maximum oxygen intake, a critical review. **Sports Medicine** 1:99-124.
- Thornton, N. and Flavell, E.R. (1981). Electronic assisted dryland stroke analysis. In E.R. Flavell (Ed) **Biokinetic Strength Training** 1:59-64. Isokinetics, Inc., Albany.
- Vokac, Z., Bell, H., Bautz-Holter, E., Rodahl, K. (1975). Oxygen intake/heart rate relationship in leg and arm exercise, sitting or standing. **Journal of Applied Physiology** 39 (1):54-59.
- Whipp, B.J. (1978). The hyperpnea of dynamic muscular exercise. **Exercise and Science in Sport** 5:295-311.

Figure 2a. Side view of the experimental setup for the tethered swimming protocol.



A = BUCKET
B = MARKER

Figure 2b. Overhead view of the experimental setup for the tethered swimming protocol.



A = OVERHEAD SUPPORT FRAME
B = BECKMAN METABOLIC MEASUREMENT CART

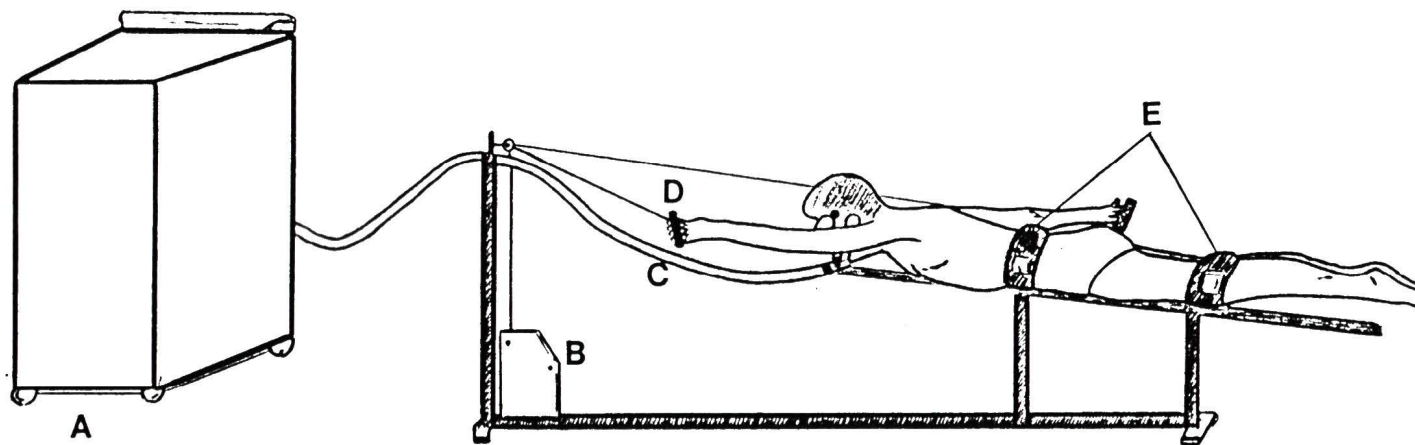
TABLE 4

AN EXAMPLE OF A TETHERED SWIMMING LOAD PROGRESSION

Maximum tether load (TL_{max}) = 12.00 kg

Weight Added (kg)	Accumulated Weight (kg)	Accumulated Time (min)
4.00	4.00	0.0
2.00	6.00	2.0
2.00	8.00	4.0
1.50	9.50	6.0
1.50	11.00	8.0
1.00	12.00	10.0

Figure 3. Side view of the experimental setup for the Biokinetic swim bench protocol.



- A = BECKMAN METABOLIC MEASUREMENT CART
- B = TENSION SETTING
- C = GAS ANALYSIS HOSE
- D = HAND PADDLE ATTACHMENT
- E = STRAPPING

TABLE 5

SWIM BENCH LOAD PROGRESSIONS

Swim Bench Setting	Time (min)
6	2
5	2
4	2
3	2
Rest	15
2	2

TABLE 6
MEAN AGE, WEIGHT (Wt), HEIGHT (Ht), TOTAL BODY FAT (TBF)
AND LEAN BODY MASS (LBM) OF THE SWIMMERS

	Age (yrs)	Wt (kg)	Ht (cm)	TBF (%)	LBM (kg)
Women (n=5)	18.6 (0.6)	64.4 (5.1)	172.4 (3.6)	15.1 (1.6)	54.1 (3.2)
Men (n=8)	19.0 (0.6)	73.1 (1.1)	177.9 (1.8)	7.4 (0.5)	67.7 (1.1)
Group (n=13)	18.8 (0.4)	69.7 (2.3)	175.7 (1.8)	10.3 (1.3)	62.5 (2.3)

Note :

Standard errors shown in parentheses

TABLE 7

$\dot{V}_{O_2\text{MAX}}$, HR_{MAX} , \dot{V}_E/\dot{V}_{O_2} RATIO AND R_{MAX}
RESULTS FOR TETHERED SWIMMING (TS) AND
SWIM BENCH CONTINUOUS (SBC) ERGOMETRY (n=13)

	TS	SBC	p
$\dot{V}_{O_2\text{max}}$ ($l \cdot \text{min}^{-1}$)	4.14 (0.6)	2.79 (0.6)	.001
$\dot{V}_{O_2\text{max}}$ ($\text{ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$)	59.4 (0.6)	39.8 (0.6)	.001
HR_{max} ($b \cdot \text{min}^{-1}$)	184 (2)	172 (2)	.005
\dot{V}_E/\dot{V}_{O_2}	29.1 (1.1)	35.6 (1.4)	.01
R_{max}	1.16 (.04)	1.10 (.02)	NS

Note :

Group means shown

Standard error in parentheses

'p' indicates significance of 't' test

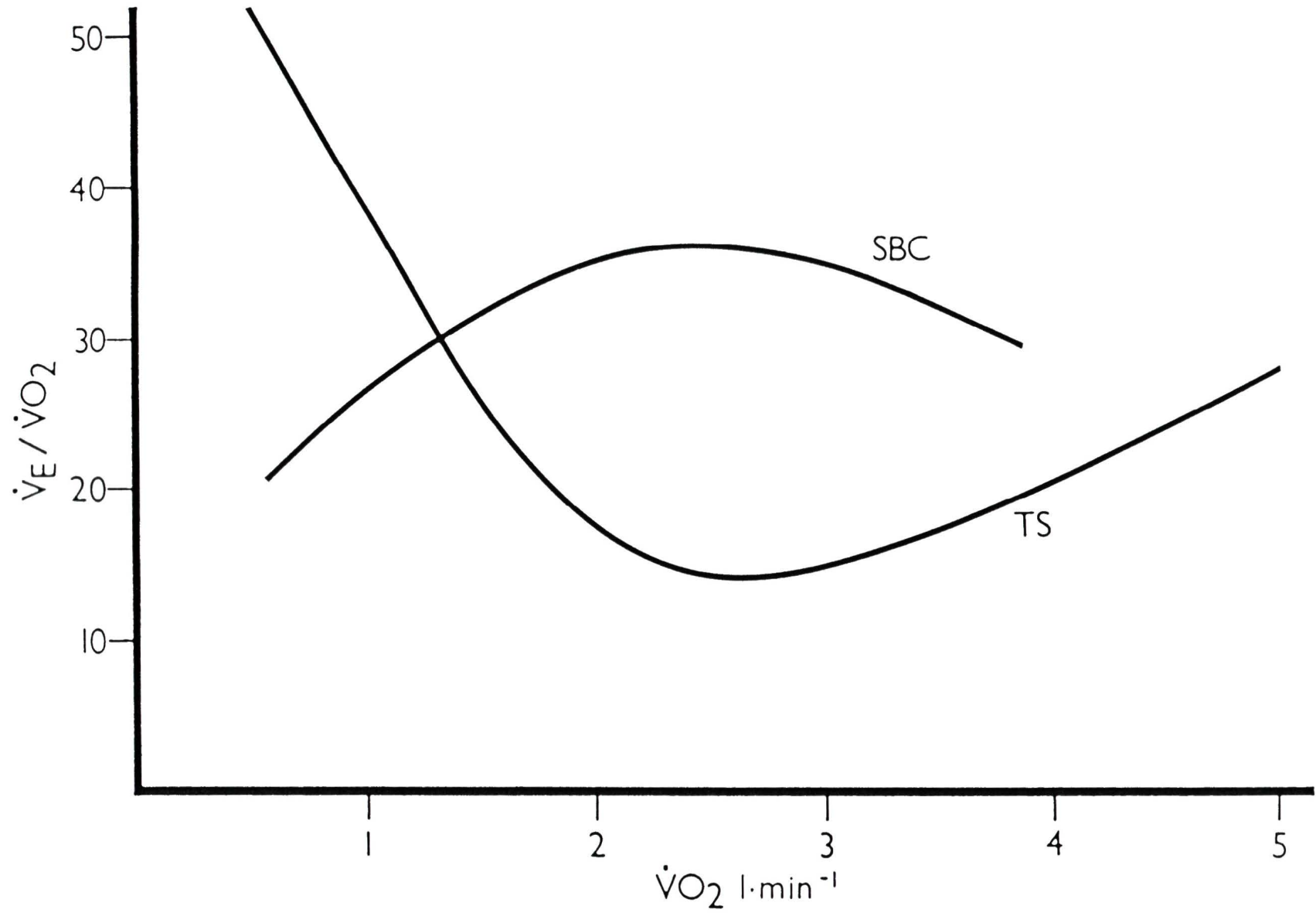
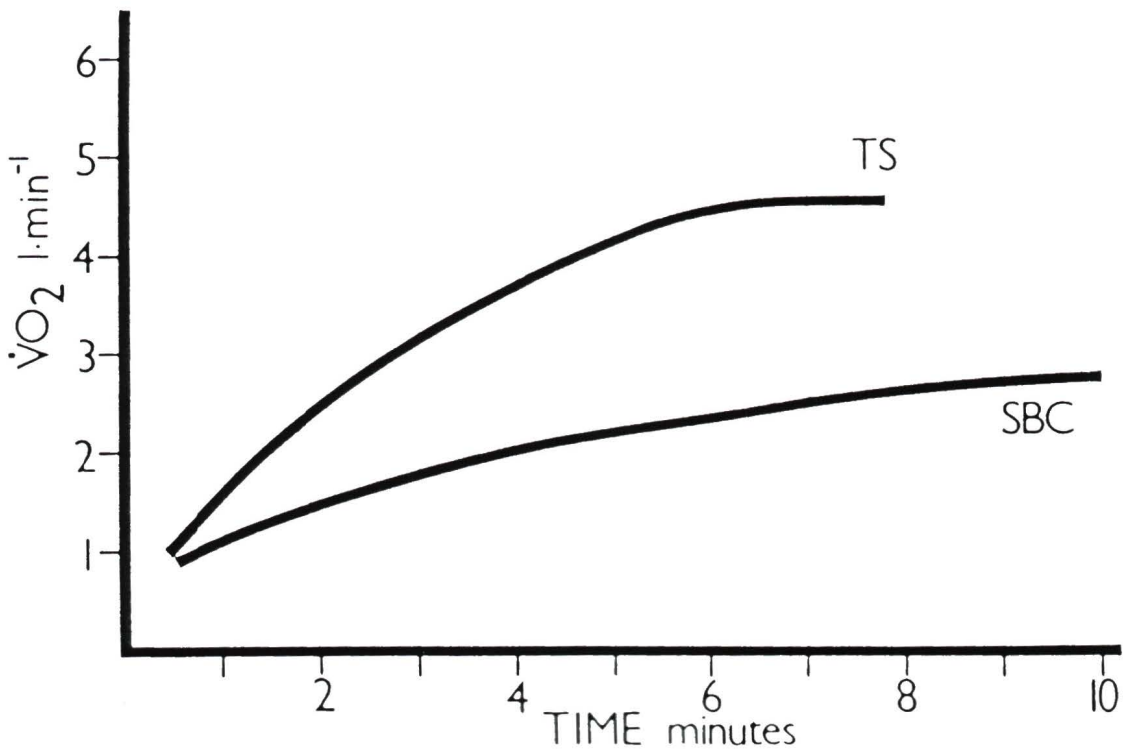
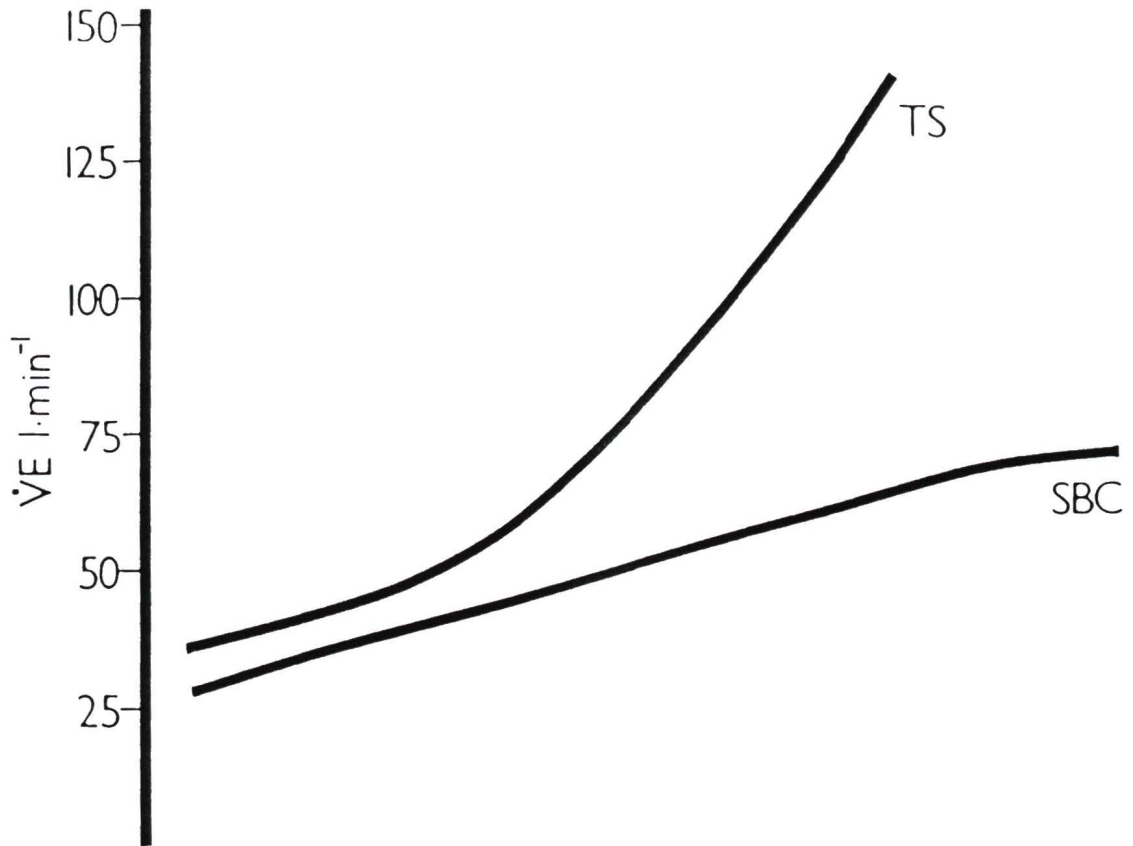


Figure 5. Diagrammatic representation of the changes in oxygen consumption (\dot{V}_{O_2}) and ventilation (\dot{V}_E) during tethered swimming (TS) and swim bench ergometry (SBC).



CHAPTER III

A COMPARISON OF THE $\dot{V}_{O_2\text{MAX}}$ ATTAINED BY ELITE SWIMMERS
DURING TETHERED SWIMMING WITH THE LEGS IMMOBILISED,
TETHERED SWIMMING WHOLE STROKE AND SWIM BENCH ERGOMETRY

Abstract

In order to assess the physiological relationship between tethered swimming arms only (TSA), tethered swimming whole stroke (TS) and swim bench ergometry (SBC), thirteen elite swimmers were studied. Subjects performed a $\dot{V}_{O_2\max}$ test using a continuous test protocol, with load increases every two minutes. SBC was performed on a Biokinetic swim bench (Isokinetics, Inc.). TS and TSA were performed in the water, with the legs immobilised during TSA. Expired gases were measured every 30s using the Beckman Metabolic Measurement Cart (MMC). The swimmers elicited higher scores during TS compared with TSA for $\dot{V}_{O_2\max}$ ($p < 0.01$) and HR_{\max} ($p < 0.001$). No differences were found for R_{\max} and the \dot{V}_E/\dot{V}_{O_2} ratio between the two protocols. Higher $\dot{V}_{O_2\max}$ and \dot{V}_E/\dot{V}_{O_2} ratio scores were found for TSA compared with SBC ($p < 0.005$ and $p < 0.05$ respectively). No differences existed between TSA and SBC for R_{\max} and HR_{\max} . In addition, no differences in submaximal \dot{V}_{O_2} were elicited during TSA and SBC at the low and medium HR ranges. At the high HR range, TSA \dot{V}_{O_2} was higher than SBC \dot{V}_{O_2} ($p < 0.005$). The results suggested that the leg activity of the swimmers during TS compared to TSA significantly increased $\dot{V}_{O_2\max}$. When TSA and SBC were compared, the swimmers elicited similar submaximal \dot{V}_{O_2} scores, which suggested that the size of active muscle mass was comparable in both tests. However, at maximal intensity, TSA $\dot{V}_{O_2\max}$ was significantly higher than SBC $\dot{V}_{O_2\max}$. It was observed that muscle activity, primarily from arm recovery and trunk muscles, increased at maximum exercise levels during TSA in order to maintain correct stroke mechanics. It was concluded that the Biokinetic swim bench fails to reproduce tethered swimming $\dot{V}_{O_2\max}$ values in elite swimmers because of a reduced active muscle mass caused by the absence of leg kick and a difference in stroke mechanics of the arms.

Introduction

Specificity of testing has become increasingly important in sports science. Studies determining maximum oxygen consumption ($\dot{V}_{O_2\max}$) have clearly indicated that the mode of exercise should be specific to the sport discipline of the individual tested (Roberts and Alspaugh, 1972; Magel et al., 1975; Corry and Powers, 1982). In a study involving arm, leg and combined arm-leg protocols, Secher and co-workers (1974) found significantly higher $\dot{V}_{O_2\max}$ scores in the combined test. This suggested that an increased active muscle mass was responsible for the higher $\dot{V}_{O_2\max}$, a result supported by others (Bergh et al., 1976; Secher et al., 1977; Millerhagen et al., 1983).

In the previous study (Chapter II) a significantly higher $\dot{V}_{O_2\max}$ was found during tethered swimming (TS) compared with swim bench ergometry (SBC). It has been hypothesised that the reduction in active muscle, due to the absence of leg action during swim bench ergometry, will depress $\dot{V}_{O_2\max}$ scores (M. Plyley and D. Smith, personal communications, October 1984).

No published studies have determined the contribution of arm work $\dot{V}_{O_2\max}$ during TS and made a direct comparison to arms only tethered swimming (TSA). Furthermore, no studies have compared TSA and SBC to assess whether factors, other than the absence of leg kick, reduce $\dot{V}_{O_2\max}$ scores. Therefore, the purpose of this study was to determine whether differences existed in $\dot{V}_{O_2\max}$ when swimmers exercised using TSA compared with TS. In addition, a second purpose was to determine if differences existed in submaximal oxygen consumption (\dot{V}_{O_2}) between TSA and SBC.

Methods

Thirteen elite swimmers (male=8, female=5), signed informed consent forms and were familiarised with the testing procedures. The subjects performed three separate tests to determine maximum oxygen consumption : 1) Tethered swimming arms only (TSA), 2) Biokinetic swim bench ergometry continuous test (SBC), and 3) tethered swimming whole stroke (TS).

Both TS and TSA required a pulley system allowing the swimmer to remain in a stationary position, yet work in a swimming mode at maximum rate (Figure 6a). A marker was placed on the pool floor, over which the subjects were required to swim, and remain in a stationary position. A metal framework was used to hang hoses from the Beckman Metabolic Measurement Cart (MMC) to the mouth piece on the swimmer (Figure 6b). During TSA the legs were immobilised with two rubber straps, secured at the ankle and knee levels. In addition, floats were held in place by the swimmer, at the calf and thigh levels.

The TSA and TS procedures required two separate swims. The first was to determine the maximum tether load (TL_{max}), where weights (in kilogrammes) were rapidly added to the bucket until the subject was pulled back from the mark. Following a ten minute rest, the subject performed a progressive maximum test until exhaustion (i.e., until the weight bucket touched the base of the TS-TSA apparatus). The load progressions were based on the TL_{max} , and increments were made every two minutes (Table 8). The TL_{max} was divided into six load progressions. The warm-up was approximately $1/3$ of TL_{max} ($1/3TL_{max}$), followed by increments of $1/6TL_{max}$ (loads 2 and 3), $1/8TL_{max}$ (loads 4 and 5) and a final load increment of $1/12TL_{max}$. The freestyle swimming stroke was used during TSA and TS.

During SBC, subjects were strapped to the swim bench to limit body movements, and hand gloves were worn for protection (Figure 7). Stroke rate (SR) was set by a metronome at 76 strokes per minute (s_{pm}), but dropped at the higher resistance settings. SBC SR was based on the mean swimming SR obtained from four varsity swim meets. SBC consisted of a 2 minute warm-up at setting 6 (low tension) followed by a setting increase every 2 minutes until setting 3 (high tension) was reached. A 15 minute rest was taken to reduce the effects of fatigue (MacDougall et al., 1982), followed by a final load at setting 2 (Table 9). An alternate arm pulling motion, with an under-arm recovery, was performed by the swimmers during SBC.

During the exercise tests, subjects breathed through a low resistance respiratory valve. Oxygen (O_2) and carbon dioxide (CO_2) were collected and analysed by the MMC, previously calibrated with gases of known concentrations. Physiological measures, including volume of expired air (\dot{V}_E), oxygen consumption (\dot{V}_{O_2}), respiratory exchange ratio (R) and heart rate (HR), were recorded every 30s. Prior to testing, body fat estimations were performed according to procedures by Yuhasz (Carter, 1982).

A correlated 't' test was employed to determine whether any significant differences in mean scores existed between TSA versus TS, and TSA versus SBC for tests for \dot{V}_{O_2max} and HR_{max} , R_{max} and ventilatory equivalent (\dot{V}_E/\dot{V}_{O_2}) at \dot{V}_{O_2max} . In addition, maximal and submaximal \dot{V}_{O_2} data for TSA and SBC were compared using a 't' test procedure.

Results

The physical characteristics of the swimmers (means \pm SE) are shown in Table 10. Presented in Table 11 (TSA versus TS) and Table 12 (TSA and SBC) are the results for the correlated 't' tests and mean scores (\pm SE) for $\dot{V}_{O_2\max}$, HR_{\max} , R_{\max} and \dot{V}_E/\dot{V}_{O_2} ratio at $\dot{V}_{O_2\max}$. The TSA $\dot{V}_{O_2\max}$ was $0.9 \text{ l}\cdot\text{min}^{-1}$ or $12.9 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ lower than TS $\dot{V}_{O_2\max}$ ($p<0.01$ and $p<0.001$ respectively). The $13 \text{ b}\cdot\text{min}^{-1}$ lower HR_{\max} during TSA was also significant ($p<0.01$). The differences in R_{\max} and \dot{V}_E/\dot{V}_{O_2} ratio at $\dot{V}_{O_2\max}$ (0.05 and 1.8 respectively) were not significantly different between TSA and TS.

The mean scores for TSA $\dot{V}_{O_2\max}$ were $0.45 \text{ l}\cdot\text{min}^{-1}$ or $6.7 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ higher than SBC $\dot{V}_{O_2\max}$ ($p<0.005$). No differences were found for the mean HR_{\max} and R_{\max} , the latter reflecting maximal effort by the swimmers (MacDougall et al., 1982) in both TSA and SBC. The ventilatory equivalent (\dot{V}_E/\dot{V}_{O_2}) at $\dot{V}_{O_2\max}$ was 4.7 lower in TSA than SBC ($p<0.05$).

Figure 8 shows the results of the submaximal \dot{V}_{O_2} data expressed at submaximal HR ranges. No significant differences occurred at the low and medium HR ranges, but a difference did exist at the high range ($p<0.005$). As exercise intensity increased, the SBC \dot{V}_E/\dot{V}_{O_2} ratio increased until the higher tension settings were reached, where the ratio decreased (Figure 9). The opposite trend occurred during TSA, but the observed ratio fluctuated more than in SBC.

Discussion

TSA versus TS. The mean TS $\dot{V}_{O_2\max}$ was in close agreement with previous studies (Magel and Faulkner, 1967; Magel, 1971). The TSA $\dot{V}_{O_2\max}$ was considerably lower than fullstroke work, but was similar to the data of Holmer (1974) when

comparisons between arm only freestyle swimming were made. TSA was the same test as TS, except the contribution of leg kick was eliminated. Therefore, the significantly lower $\dot{V}_{O_2\max}$ score for TSA compared with TS was due to a lower active muscle mass. This result has also been demonstrated in swimming (Holmer, 1974) and in combined arm and leg studies (Secher et al., 1977; Millerhagen et al., 1983). An increase in active muscle mass (primarily by slow twitch fibres) results in both an increase in \dot{V}_{O_2} (Ivy et al, 1980), which also drives HR (Cardus, 1979). This is supported by the higher HR_{\max} in TS.

No differences were found between TSA and TS for \dot{V}_E/\dot{V}_{O_2} at $\dot{V}_{O_2\max}$, which suggested that ventilation imposed a minimum restriction on $\dot{V}_{O_2\max}$ (Brooks and Fahey, 1984). In addition, the \dot{V}_E/\dot{V}_{O_2} ratios for TSA and TS were low compared to previous studies involving trained swimmers (Magel et al., 1975; Gergley et al., 1984), but higher than others (Bonen et al., 1980). Furthermore, when the ratios from the present study were compared to other exercise situations (McArdle et al., 1973; Bhambhani and Singh, 1985), they were found to exhibit high economy of ventilation, i.e., a low volume of air ventilated per unit volume of oxygen consumed. Therefore, the elite swimmers in the present study were highly efficient at acquiring and utilising oxygen.

TSA versus SBC. A significantly higher $\dot{V}_{O_2\max}$ was found in TSA compared with SBC. Gollnick (1982) suggested that when muscular tension was raised above 20% of maximum voluntary contraction (MVC), arterial occlusion occurred, resulting in lower muscle blood flow (MBF), and reduced the volume of oxygenated blood that reached the working muscles. It was possible that the 20% MVC criterion was met earlier during SBC than TSA, creating a greater reliance on anaerobic energy sources. The early demand imposed on the swimmer during SBC would induce fatigue more rapidly than in TSA, and the result would be a lower $\dot{V}_{O_2\max}$.

An increase in active muscle mass results in an increased HR, with a corresponding linear increase in \dot{V}_{O_2} (Rowell, 1980). Figure 3 shows that a significant difference ($p < 0.005$) existed between SBC and TSA for \dot{V}_{O_2} at HR_{max} only, which suggested a greater muscle recruitment during TSA towards the end of the test.

A number of differences existed which could account for the similarities in submaximal \dot{V}_{O_2} , but higher \dot{V}_{O_2max} in TSA. Firstly, swimmers were tightly strapped to the swim bench, limiting all body movements to only the arms and upper shoulder region. When exercise commenced in TSA, only arm work was required to maintain a stationary swimming position. Therefore, only the arm muscles were used in both TSA and SBC during the initial power output (PO) levels. Furthermore, a greater muscle recruitment occurred in TSA (upper shoulder for arm recovery phase, trunk muscles to aid the propulsive phase) to maintain correct stroke mechanics (Counsilman, 1971; Barthels, 1978) and increased PO towards the end of the test. Thus a higher \dot{V}_{O_2max} in TSA.

The primary mechanical disadvantage of the swim bench exercise is the elimination of the sculling action (Schleihauf, 1982). In the present study that body roll was an important factor in TSA as it allowed the swimmer to apply force over a large distance while accelerating the arm, thereby maintaining the correct sculling action (Counsilman, 1971; 1981). During SBC, the arms of the swimmer moved at a constant velocity, and stopped prior to the pulling action. Therefore, during SBC a greater energy requirement would be necessary to overcome inertia, and decrease mechanical efficiency.

An increase in active muscle mass during TSA should elicit a higher HR_{max} .

Since no significant differences were found between TSA and SBC, other

factors must have either elevated HR during TSA or depressed HR during SBC. Face immersion bradycardia (Magel et al., 1982) may have been responsible for lowering TSA HR_{max} . Furthermore, in the absence of a water environment to dissipate heat, the increase in body temperature would increase SBC HR_{max} (Fox and Mathews, 1982). Cardus (1979) suggested that at maximal exercise HR is rarely linear with \dot{V}_{O_2} , and can level off (negative acceleration). So even with a higher \dot{V}_{O_2max} during TSA compared with SBC, HR_{max} be as high in SBC.

The \dot{V}_E/\dot{V}_{O_2} ratio at maximum level was significantly higher in SBC than in TSA ($p < 0.05$), which suggested a lower ventilatory efficiency for the swim bench exercise. The observed trend for SBC \dot{V}_E/\dot{V}_{O_2} (Figure 9) was uncommon in tests of \dot{V}_{O_2max} (Bhambhani and Singh, 1985). The low SR with a low breathing frequency (Holmer, 1974) during SBC, may have suppressed \dot{V}_E , while exercise demand increased \dot{V}_{O_2} (low \dot{V}_E/\dot{V}_{O_2} ratio) at the higher PO. The opposite trend occurred for TSA, in which the SR increased to over 100_{spm} (as opposed to <76_{spm} for SBC), which produced a high \dot{V}_E/\dot{V}_{O_2} ratio. This indicated that SBC did not allow the body to function physiologically in the same manner as in the TSA protocol.

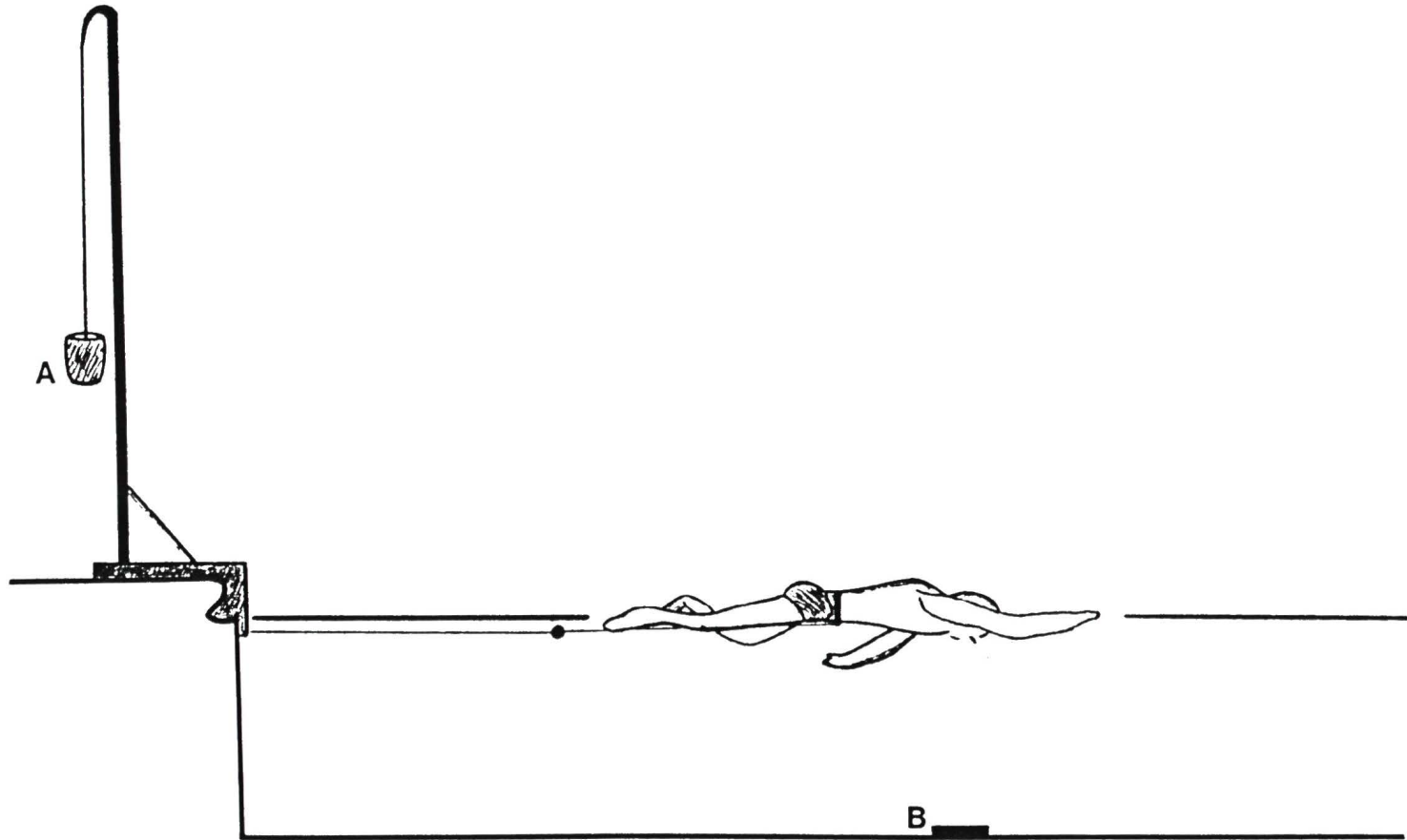
In the comparison of TSA with TS, leg musculature was found to significantly contribute to \dot{V}_{O_2max} . When TSA and SBC were compared, submaximal \dot{V}_{O_2} was similar in both tests. However, at maximum intensity, additional muscles, especially those of the hip and upper shoulder, were recruited, and increased TSA \dot{V}_{O_2max} to a significantly higher level than SBC \dot{V}_{O_2max} . In addition, a more specific stroke replication was possible in TSA than SBC, resulting in earlier fatigue during SBC.

References

- Barthels, K.M. (1978). The mechanism for body propulsion in swimming. In J. Terauds and F.W. Bedingford (Eds). **Swimming III. International Series on Sports** 8:45-54. University Park Press, Baltimore.
- Bergh, U., Kanstrup, I-L. and Ekblom, B. (1976). Maximal oxygen uptake during exercise with various combinations of arm and leg work. **Journal of Applied Physiology** 41 (2):191-196.
- Bhambhani, Y. and Singh, M. (1985). The effects of three training intensities on $\dot{V}_{O_2\max}$ and \dot{V}_E/V_{O_2} ratio. **Canadian Journal of Applied Sports Sciences** 10 (1):44-51.
- Bonen, A., Wilson, B.A., Yarkony, M. and Belcastro, A.N. (1980). Maximal oxygen uptake during free, tethered and flume swimming. **Journal of Applied Physiology** 48 (2):232-235.
- Brooks, G.A. and Fahey, T.D. (1984). **Exercise Physiology: Human Bioenergetics and its Application**. John Wiley and Sons, New York.
- Cardus, D. (1979). Exercise testing: Methods and uses. **Exercise and Sports Science Review** 6:59-103.
- Carter, J.E.L. (1982). Body composition of Montreal Olympic athletes. **Medicine in Sport** 16:107-116.
- Corry, I. and Powers, N. (1982). Maximal aerobic power measurement in runners and swimmers. **British Journal of Sports Medicine** 16 (3):154-160.
- Counsilman, J.E. (1971). The application of Bernoulli's Principle to human propulsion in water. In L. Lewillie and J.P. Clarys (Eds). **First International Symposium on Biomechanics in Swimming**. University Libre de Bruxelles, Brussels, 59-71.
- Counsilman, J.E. (1981). Hand speed and acceleration. **Swimming Technique** May, 22-26.
- Fox, E.L. and Mathews, D.K. (1981). **The Physiological Basis of Physical Education and Athletics**. Saunders College, Philadelphia.
- Gergley, T.J., McArdle, W.D., DeJesus, P., Toner, M.M., Jacobowitz, S., and Spina, R. (1984). Specificity of arm training on aerobic power during swimming and running. **Medicine and Science in Sports and Exercise** 16 (4):349-354.
- Gollnick, P.D. (1982). Peripheral factors as limitations to exercise capacity. **Canadian Journal of Applied Sports Sciences** 7 (1):14-21.
- Holmer, I. (1974). Physiology of swimming man. **Acta Physiologica Scandinavica**. Suppl.:407.

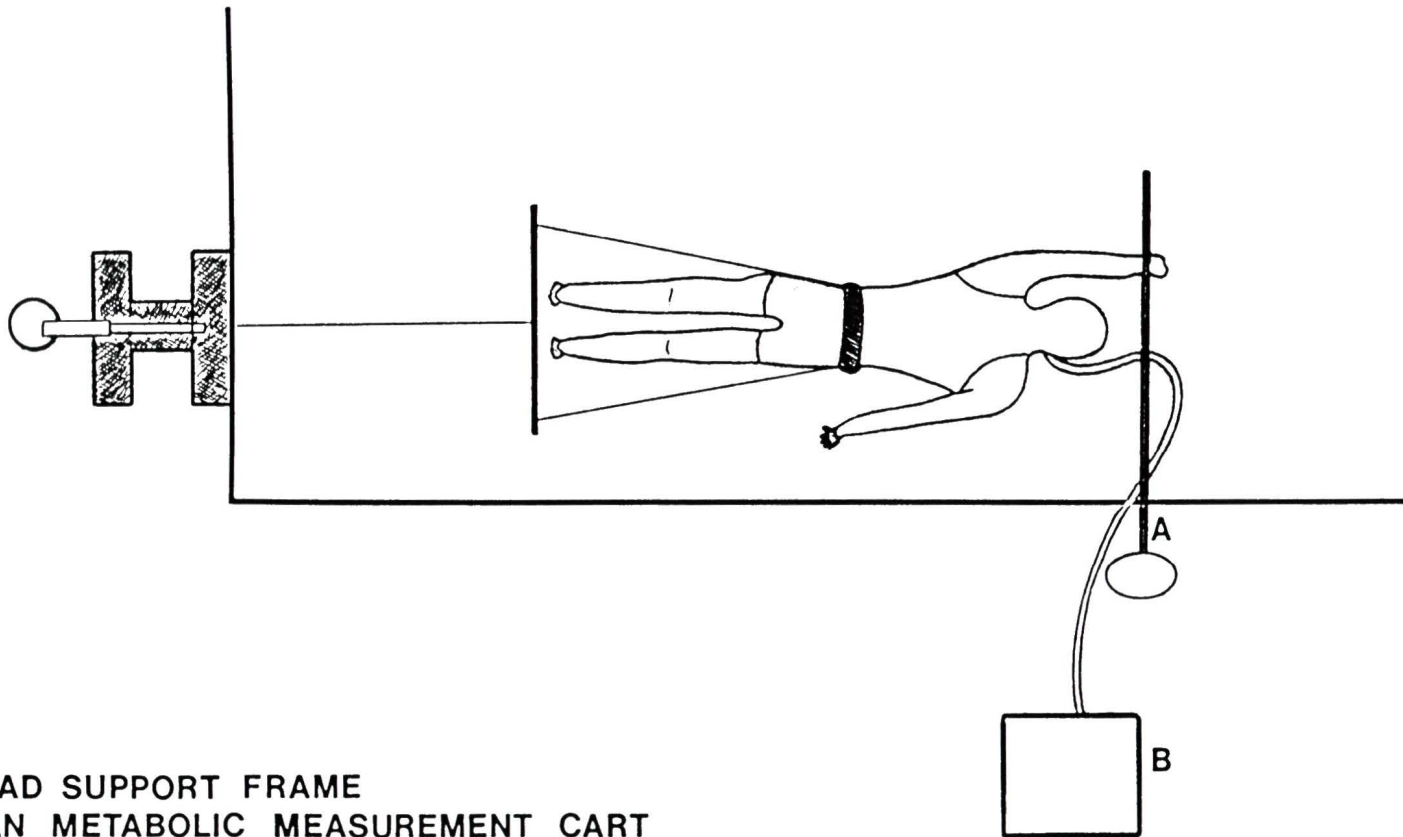
- Ivy, J.L., Withers, R.T., Van Handel, P.J., Elger, D.H. and Costill, D.L. (1980). Muscle respiratory capacity and fiber type as determinants of lactate threshold. **Journal of Applied Physiology** 48 (3):523-57.
- MacDougall, J.D., Wenger, H.A. and Green, H.J. (1982) **Physiological Testing of the Elite Athlete**. Canadian Association of Sports Sciences. Mutual Press Limited, Toronto.
- Magel, J.R. (1971). Comparison of the physiologic response to varying intensities of submaximal work in tethered swimming and treadmill running. **Journal of Sports Medicine** 11:203-212.
- Magel, J.R. and Faulkner, J.A. (1967). Maximum oxygen uptakes of college swimmers. **Journal of Applied Physiology** 22 (5):929-938.
- Magel, J.R., Foglia, G.F., McArdle, W.D., Gutin, B., Pecher, G.S and Katch, F.I. (1975). Specificity of swim training on maximum oxygen uptake. **Journal of Applied Physiology** 38 (1):151-155.
- Magel, J.R., McArdle, W.D., Weiss, N.L., Stone, S. and Newman, A. (1982). Heart rate response to apnea and face immersion. **Journal of Sports Medicine and Physical Fitness** 22 (2):135-146.
- McArdle, W.D., Katch, F.I. and Pecher, G.S. (1973) The effects of continuous versus discontinuous treadmill and bicycle tests for max \dot{V}_{O_2} . **Medicine and Science in Sports and Exercise** 5 (3):156-160.
- Millerhagen, J.O., Kelly, J.M. and Murphy, R.J. (1983). A study of combined arm and leg exercise with application to Nordic skiing. **Canadian Journal of Applied Sports Science** 8 (2):92-97.
- Roberts, J.A. and Alspaugh, J.W. (1972). Specificity of training effects resulting from programmes of treadmill running and bicycle ergometer riding. **Medicine and Science in Sports and Exercise** 4 (1):6-10.
- Rowell, L.B. (1980). What signals govern the cardiovascular responses to exercise? **Medicine and Science in Sports and Exercise** 12 (5):307-315.
- Schleihauf, R.E. (1982). 3-D Computer stroke analysis. **Swimming Technique** August, 20-25.
- 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. **Journal of Applied Physiology** 36 (5):515-518.
- Secher, N.H., Clausen, J.P., Klausen, K., Noer, I. and Trap-Jensen. (1977). Central and regional circulatory effects of adding arm exercise to leg exercise. **Acta Physiologica Scandinavica** 100:288-297.

Figure 6a. Side view of the experimental setup for the tethered swimming protocol.



A = BUCKET
B = MARKER

Figure 6b. Overhead view of the experimental setup for the tethered swimming protocol.



A = OVERHEAD SUPPORT FRAME
B = BECKMAN METABOLIC MEASUREMENT CART

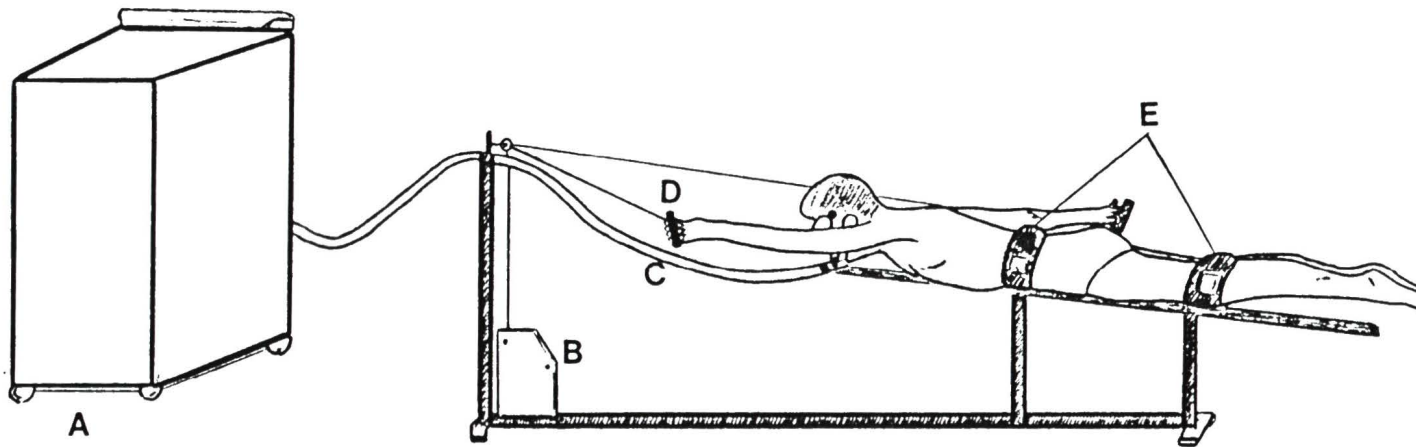
TABLE 8

AN EXAMPLE OF A TETHERED SWIMMING LOAD PROGRESSION

Maximum tether load (TL_{max}) = 12.00 kg

Weight Added (kg)	Accumulated Weight (kg)	Accumulated Time (min)
4.00	4.00	0.0
2.00	6.00	2.0
2.00	8.00	4.0
1.50	9.50	6.0
1.50	11.00	8.0
1.00	12.00	10.0

Figure 7. Side view of the experimental setup for the Biokinetic swim bench protocol.



- A = BECKMAN METABOLIC MEASUREMENT CART
- B = TENSION SETTING
- C = GAS ANALYSIS HOSE
- D = HAND PADDLE ATTACHMENT
- E = STRAPPING

TABLE 9

SWIM BENCH LOAD PROGRESSIONS

Swim Bench Setting	Time (min)
6	2
5	2
4	2
3	2
Rest	15
2	2

TABLE 10
MEAN AGE, WEIGHT (Wt), HEIGHT (Ht), TOTAL BODY FAT (TBF)
AND LEAN BODY MASS (LBM) OF THE SWIMMERS

	Age (yrs)	Wt (kg)	Ht (cm)	TBF (%)	LBM (kg)
Women (n=5)	18.6 (0.6)	64.4 (5.1)	172.4 (3.6)	15.1 (1.6)	54.1 (3.2)
Men (n=8)	19.0 (0.6)	73.1 (1.1)	177.9 (1.8)	7.4 (0.5)	67.7 (1.1)
Group (n=13)	18.8 (0.4)	69.7 (2.3)	175.7 (1.8)	10.3 (1.3)	62.5 (2.3)

Note :

Standard errors shown in parentheses

TABLE 11

$\dot{V}_{O_2\text{MAX}}$, HR_{MAX} , \dot{V}_E/\dot{V}_{O_2} RATIO AND R_{MAX}
 RESULTS FOR TETHERED SWIMMING (TS) AND
 TETHERED SWIMMING ARMS ONLY (TSA)(n=13)

	TS	TSA	p
$\dot{V}_{O_2\text{max}}$ ($\text{l}\cdot\text{min}^{-1}$)	4.14 (0.6)	3.24 (1.8)	.01
$\dot{V}_{O_2\text{max}}$ ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$)	59.4 (0.6)	46.5 (2.1)	.001
HR_{max} ($\text{b}\cdot\text{min}^{-1}$)	184 (2)	171 (3)	.001
\dot{V}_E/\dot{V}_{O_2}	29.1 (1.1)	30.9 (0.9)	NS
R_{max}	1.16 (.04)	1.11 (.02)	NS

Note :

Group means shown

Standard error in parentheses

'p' indicates significance of 't' test

TABLE 12

$\dot{V}_{O_2\text{MAX}}$, HR_{MAX}, \dot{V}_E/\dot{V}_{O_2} RATIO AND R_{MAX}
RESULTS FOR TETHERED SWIMMING ARMS ONLY (TSA) AND
SWIM BENCH CONTINUOUS (SBC) ERGOMETRY (n=13)

	TSA	SBC	p
$\dot{V}_{O_2\text{max}}$ (l·min ⁻¹)	3·24 (1·8)	2·79 (0·6)	·005
$\dot{V}_{O_2\text{max}}$ (ml·kg ⁻¹ ·min ⁻¹)	46·5 (2·1)	39·8 (0·6)	·005
HR _{max} (b·min ⁻¹)	171 (3)	172 (2)	NS
\dot{V}_E/\dot{V}_{O_2}	30·9 (0·9)	35·6 (1·4)	·05
R _{max}	1·11 (·02)	1·10 (·02)	NS

Note :

Group means shown

Standard error in parentheses

'p' indicates significance of 't' test

Figure 8. Submaximal \dot{V}_{O_2} ($\text{ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$) responses during tethered swimming arms only (TSA) and swim bench ergometry (SBC), expressed at a given submaximal HR ($\text{b}\cdot\text{min}^{-1}$) range.

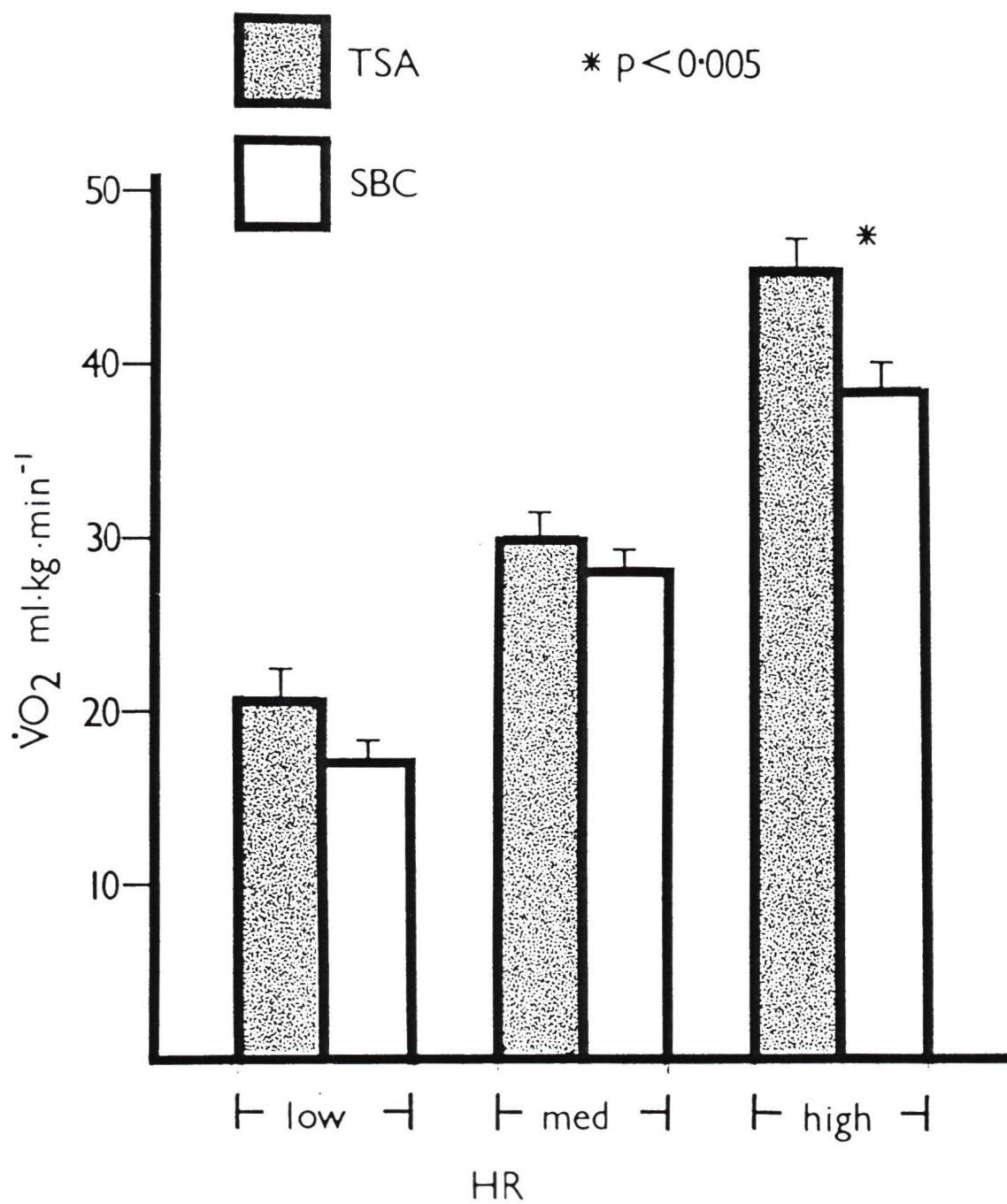
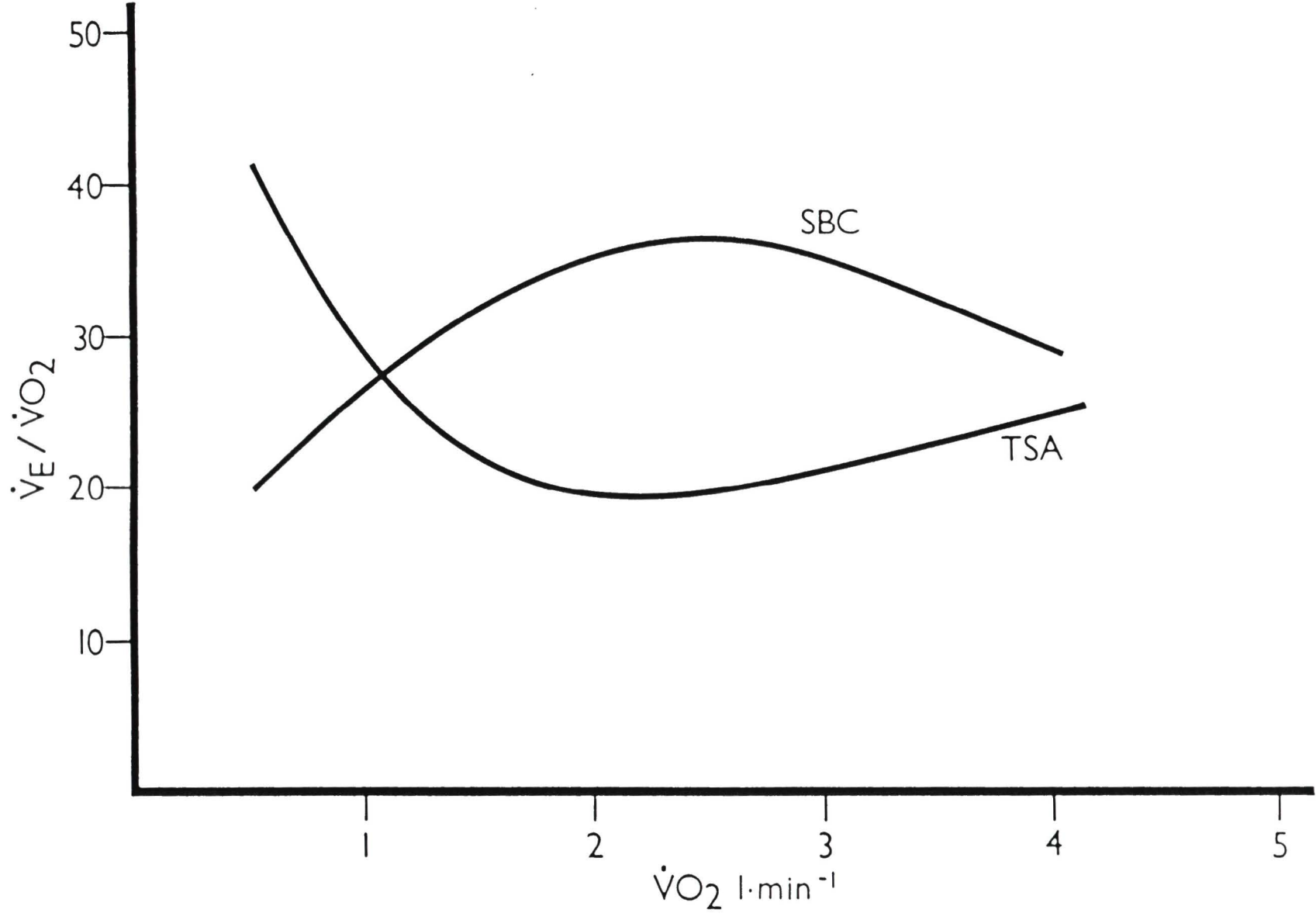


Figure 9. Diagrammatic representation of the changes in ventilatory equivalent (\dot{V}_E/\dot{V}_{O_2}) during tethered swimming arms only (TSA) and swim bench ergometry (SBC).



SUMMARY

No differences existed in $\dot{V}_{O_2\max}$ when competent swimmers performed exercise to exhaustion using a continuous (SBC) or a discontinuous (SBD) Biokinetic swim bench protocol. From an administrative standpoint, therefore, SBC should be used when testing groups of individuals.

Tethered swimming (TS) $\dot{V}_{O_2\max}$ was significantly higher than swim bench (SBC) $\dot{V}_{O_2\max}$ ($p < 0.001$). This result indicated that SBC $\dot{V}_{O_2\max}$ was not a valid measure of TS $\dot{V}_{O_2\max}$ in elite swimmers. In addition, a stepwise regression analysis showed that SBC $\dot{V}_{O_2\max}$ was a poor predictor of TS $\dot{V}_{O_2\max}$ when testing elite swimmers.

In a comparison of TS and tethered swimming with the legs immobilised (TSA), a higher $\dot{V}_{O_2\max}$ was elicited by the swimmers during TS. It was concluded that a higher active muscle mass was responsible for the difference. A significantly higher $\dot{V}_{O_2\max}$ was found when TSA was compared with SBC, but no differences existed in \dot{V}_{O_2} at the submaximal power outputs. This suggested that at maximal effort in tethered swimming, a greater active muscle mass was recruited due to more correct stroke mechanics (primarily by trunk and shoulder musculature), thereby increasing $\dot{V}_{O_2\max}$.

FURTHER RESEARCH

- 1) Further research utilising swim bench ergometry should involve a protocol in which SR increases throughout the test. When using the Bioknetic swim bench, initial loads should be set at a high tension and low SR, but increased by raising SR and lowering tension. This will allow the a swimmer to duplicate the SR and breathing patterns elicited during TS.
- 2) A swim bench, which more precisely duplicates the in water stroke mechanics, needs to be developed. It is difficult to mimic the sculling action, but the arm acceleration phase can be reproduced on a dry-land machine.
- 3) When a new swim bench is developed, studies similar to the present one should be performed to determine whether a higher correlation can be found between TS and SBC, compared to the correlation between TS and SBC in present study. In addition, information will be obtained as to whether stroke rate or the type of muscular contraction limits swim bench $\dot{V}_{O_2\max}$ (i.e., comparisons between the two types of swim bench can be made).

RECOMMENDATIONS

- 1) Given the present situation of $\dot{V}_{O_2\max}$ being the standard indicator of the fitness level of a swimmer, this thesis was designed to find a cheaper more accessible method of predicting $\dot{V}_{O_2\max}$ in swimming. Tethered swimming was found to be the most valid measure when compared with swim bench ergometry, therefore it is recommended that for future testing and monitoring of elite swimmers, a tethered swimming protocol should be utilised.
- 2) Most elite swimmers, such as those in the present study, have a $\dot{V}_{O_2\max}$ of 60 ml·kg⁻¹·min⁻¹ and above (55 ml·kg⁻¹·min⁻¹ for female swimmers). What becomes

of utmost importance at this level is swimming technique and experience. Therefore, testing $\dot{V}_{O_2\max}$ in elite swimmers may not be appropriate. What would be more important are tests of tolerance to fatigue and swimming speed (e.g., performance swims).

APPENDIX A

INFORMED CONSENT FORM



UNIVERSITY OF VICTORIA

PO BOX 1700, VICTORIA, BRITISH COLUMBIA, CANADA V8W 2Y2
 TELEPHONE (604) 721-7211, TELEFAX 049-7222

Sport and Fitness Testing Centre

School of Physical Education
 721-8373

INFORMED CONSENT
 FOR
 PHYSIOLOGICAL ASSESSMENTS

In order to assess physiological function(s) the following laboratory assessments will be performed:

Lab Initial	Subject Initial
----------------	--------------------

Submaximal Cardio-Respiratory Function

You will exercise on an ergometer at 75% of predicted maximum heart rate. The following indicated variables will be measured:

- | | | | |
|--------------------------|-----|-------------------------------|-------|
| a) ventilatory responses | ___ | c) thermoregulatory responses | ___ |
| b) heart rate responses | ___ | d) other | _____ |

Maximal Cardio-Respiratory Function

You will exercise on an ergometer with progressively increasing loads to elicit maximal responses in the following indicated variables:

- | | | | |
|-----------------------|-----|----------------|-------|
| a) oxygen consumption | ___ | c) ventilation | ___ |
| b) heart rate | ___ | d) other | _____ |

Submaximal and/or Maximal Muscular Contractions

You will perform submaximal or maximal muscular contractions in the following modes:

- ___ isometric ___ isotonic ___ isokinetic ___ eccentric

Blood Chemistry

Blood samples may be taken prior to, during, or post-exercise by:

- | | | | |
|-----------------|-----|---------------------|-----|
| a) venipuncture | ___ | b) finger tip prick | ___ |
|-----------------|-----|---------------------|-----|

Lab Subject
Initial Initial

Body Composition

---	---	Lean body mass and percent body fat may be assessed by: a) anthropometric measures ___ b) body densitometry ___
---	---	Tests will be administered by qualified personnel under the direct supervision of the investigator(s).
---	---	Blood samples will be taken by a qualified laboratory technician or registered nurse.
---	---	Training will be monitored by the investigator(s) or trained assistants.
---	---	Test and training data and results will be treated in a confidential manner and used only to describe group responses.
---	---	Absolute confidentiality of individual results will be maintained unless specific approval has been given to other use of the material by each subject, or guardian where necessary.
---	---	While it is highly unlikely that a subject should be injured or taken ill during a test or training session, lab personnel are trained in emergency procedures and emergency equipment is on-site at all times.
---	---	All laboratory activity will be completed proximal to medical and/or paramedical assistance.
---	---	The maximal exercise loads imposed will not exceed those which might be expected of an athlete during sports performance.

I have read the above and agree to participate in this research project/fitness appraisal at my own risk. I regularly take part in strenuous physical activity at least as intense as these tests. I realize that I may expect a thorough explanation and/or demonstration of any procedures and that I may terminate participation at any time in any or all procedures of my own volition.

Having voluntarily assumed participation and the risks thereof, in the project, I hereby disclaim and release the University of Victoria, its agents, servants or employees, including all personnel involved in the research project fitness appraisal from any and all liability that might otherwise arise as a result of my participation as a research subject in this study/or fitness appraisal.

NAME: _____ DATE: _____
(please print)

SIGNATURE: _____

I, the undersigned guardian, am guardian of _____, the intended subject. I have discussed the experimentation with the subject and have read the material supplied by the experimentors. I agree on behalf of the subject to permit his/her participation on the terms and subject to the waiver and release of the University of Victoria hereinbefore set out.

GUARDIAN'S SIGNATURE: _____
(where applicable)

DL:gs
84/10/25

APPENDIX B

PAR-Q FORM

PARTICIPANT IDENTIFICATION

PHYSICAL ACTIVITY READINESS QUESTIONNAIRE (PAR-Q)*
A Self-administered Questionnaire for Adults

PAR Q & YOU

PAR-Q is designed to help you help yourself. Many health benefits are associated with regular exercise, and the completion of PAR-Q is a sensible first step to take if you are planning to increase the amount of physical activity in your life.

For most people physical activity should not pose any problem or hazard. PAR-Q has been designed to identify the small number of adults for whom physical activity might be inappropriate or those who should have medical advice concerning the type of activity most suitable for them.

Common sense is your best guide in answering these few questions. Please read them carefully and check the YES or NO opposite the question if it applies to you.

YES NO

1. Has your doctor ever said you have heart trouble?
2. Do you frequently have pains in your heart and chest?
3. Do you often feel faint or have spells of severe dizziness?
4. Has a doctor ever said your blood pressure was too high?
5. Has your doctor ever told you that you have a bone or joint problem such as arthritis that has been aggravated by exercise, or might be made worse with exercise?
6. Is there a good physical reason not mentioned here why you should not follow an activity program even if you wanted to?
7. Are you over age 65 and not accustomed to vigorous exercise?

If
You
Answered

YES to one or more questions

If you have not recently done so, consult with your personal physician by telephone or in person BEFORE increasing your physical activity and/or taking a fitness test. Tell him what questions you answered YES on PAR-Q, or show him your copy.

programs

After medical evaluation, seek advice from your physician as to your suitability for:

- unrestricted physical activity, probably on a gradually increasing basis.
- restricted or supervised activity to meet your specific needs, at least on an initial basis. Check in your community for special programs or services.

NO to all questions

If you answered PAR-Q accurately, you have reasonable assurance of your present suitability for:

- A GRADUATED EXERCISE PROGRAM - A gradual increase in proper exercise promotes good fitness development while minimizing or eliminating discomfort.
- AN EXERCISE TEST - Simple tests of fitness (such as the Canadian Home Fitness Test) or more complex types may be undertaken if you so desire.

postpone

If you have a temporary minor illness, such as a common cold.

* Developed by the British Columbia Ministry of Health. Conceptualized and critiqued by the Multidisciplinary Advisory Board on Exercise (MABE). Translation, reproduction and use in its entirety is encouraged. Modifications by written permission only. Not to be used for commercial advertising in order to solicit business from the public.

Reference: PAR-Q Validation Report, British Columbia Ministry of Health, May, 1978.

* Produced by the British Columbia Ministry of Health and the Department of National Health & Welfare

APPENDIX C

REVIEW OF LITERATURE

Review of Literature

The complexity of the metabolic and mechanical functions occurring during exercise has resulted in a vast number of testing procedures, capable of measuring these functions with great accuracy. Certain exercise situations allow the collection of reliable data to be a relatively straight forward process, e.g., treadmill running. However, as the mechanical nature of the exercise becomes more complex, additional problems arise. A good example of this is swimming, where both the stroke patterns and the water environment make data collection more difficult.

The purpose of this review is to discuss the relevance of oxygen consumption (\dot{V}_{O_2}) and maximum oxygen consumption ($\dot{V}_{O_2\max}$) with regard to exercise in general, and with specific reference to swimming. A review of ergometry and testing protocols will be followed by a discussion of swimming specific test procedures.

Aerobic Metabolism

The endurance capacity of an individual centres around the ability of the body to transport oxygen to the muscles and the ability of the muscles to utilise that oxygen (Rusko et al., 1978). $\dot{V}_{O_2\max}$ has become the most commonly used test of endurance capacity in an individual (Åstrand and Rodahl, 1977; Fox and Mathews, 1981; MacDougall et al., 1982). It has been suggested that $\dot{V}_{O_2\max}$ is the single best predictor of endurance performance and power output. (Miyamura and Honda, 1972; Burke et al., 1977; Thomson and Scrutton, 1978; Rusko et al., 1978).

However, even though high correlations have been found between power output and $\dot{V}_{O_2\max}$ (Costill et al., 1973), considerable controversy exists as to the

limiting factors on $\dot{V}_{O_2\max}$. Ultimately, $\dot{V}_{O_2\max}$ is genetically determined (Saltin and Åstrand, 1967), but before this 'genetic ceiling' is met, other factors may be involved. It would seem likely that \dot{V}_{O_2} should be limited by the availability of oxygen, but research has indicated contradictory evidence. Kaijser (1971) utilised a gas mixture of 100% oxygen and found a similar oxygen extraction to that with an ambient gas mixture. Similar results were obtained by Doll and co-workers (Hollozy, 1973), where high oxygen tensions (PO_2) were found in venous blood during exercise. However, Weltman and co-workers (Weltman et al., 1978) found that a gas mixture of 100% oxygen significantly increased $\dot{V}_{O_2\max}$.

Another factor is the ratio of $NAD^+/NADH$ in the cytoplasm and the mitochondria itself (Wenger and Reed, 1976; Newsholme, 1977; Holloszy, 1975). NAD acts as a carrier for hydrogen ions through the mitochondrial membrane as well as throughout the electron transfer chain. A low $NAD^+/NADH$ ratio is required in the cytoplasm, whilst a high ratio is necessary in the mitochondria. If these criteria are not met, fatigue will occur, inspite of a high PO_2 in the muscular blood supply.

It has also been postulated that muscle fibre type and fibre size may limit oxygen consumption (Holloszy, 1975; Åstrand, 1978). Slow twitch fibres (SO) may have fully utilised their oxygen capacity, and the high PO_2 in the venous blood may be due to a relatively high percentage of fast twitch fibres (non-oxidative).

Subcellular Adaptation

A number of adaptations occur as a result of increasing the capacity of an individual to consume oxygen through endurance training. Both the size and number of mitochondria in muscle increase (Holloszy, 1973; 1975; Gollnick, 1973), resulting in an increased ability to oxidise free fatty acids (FFA) and spare muscle

glycogen stores (Gollnick, 1977).

Further subcellular changes occur with regard to mitochondrial enzyme concentrations and activity (Holloszy, 1973; 1975; Houston, 1982; Fox and Mathews, 1982). Succinate dehydrogenase, aconitase and malate dehydrogenase are three of the tricarboxylic acid cycle enzymes (Lehninger, 1975) that increase in quantity from 35% up to as much as 200% (Holloszy, 1975). These enzymes are essential in transferring hydrogen ions (H^+) to the electron transport system, where the cytochrome carriers continue the transfer until terminal oxidation occurs. Increases in mitochondrial cytochrome 'c' have been found as a result of training. Activities of the other cytochromes are difficult to analyse as they are tightly bonded to the mitochondrial membrane (Lehninger, 1975).

Circulatory Adaptation

The subcellular adaptations discussed above augment the \dot{V}_{O_2} of an individual. Concurrent with these changes are systemic adaptations which have been found to be peripheral and central in nature. A study involving one legged training showed an increased capacity of the central circulatory system as a result of peripheral stimuli (Saltin et al., 1976). During exercise in the trained leg, a significantly lower quantity of lactate was produced, glycogen depletion was reduced, and oxygen extraction was greater, than in the untrained leg. However, $\dot{V}_{O_2\max}$ in the untrained leg was increased as a result of training. The conclusion was drawn that training one leg increases the total circulatory capacity of an individual, thereby offering a training effect on the non-exercised leg.

The size of the muscle mass used during exercise has been found to have a major effect on the central circulatory adaptation. In a comparison between the cycle (BE) and treadmill (TM) ergometer, \dot{V}_{O_2} , cardiac output (\dot{Q}) and arterial

venous O_2 difference $(a-v)O_2$ was significantly lower in the BE test (Miyamura and Honda, 1972). Further studies have consolidated these findings, indicating that the larger mass involved was responsible for the differences (McArdle et al., 1973; Pechar et al., 1974).

In addition to comparisons of running and cycling, the influence of arm exercise on \dot{V}_{O_2} has been of interest. Recent studies have confirmed that due to the smaller muscle mass utilised during physical work, $\dot{V}_{O_2\max}$ during arm exercise compared to leg was approximately 75% of leg work (Vokac et al., 1975, Thomson and Scrutton, 1978). Similarly, Reybrouck and co-workers (Reybrouck et al., 1975), found arm $\dot{V}_{O_2\max}$ to be 68% of leg and 60% of combined arm/leg $\dot{V}_{O_2\max}$ respectively.

Some discrepancy exists regarding the effect of arm work on \dot{Q} , HR, and \dot{V}_E . Reybrouck et al (1975) showed \dot{V}_{O_2} , \dot{Q} , \dot{V}_E and HR to be higher in arm exercise than leg exercise during submaximal work. However, other research has shown the reverse situation (Vokac et al., 1975). However, there appears to be general agreement as to the physiological adjustments at maximum work loads;

- 1) maximal workload of arms is 50-60% of legs (Vokac et al., 1975)
- 2) $\dot{V}_{O_2\max}$ in arm work ranges between 60-80% of legs (Secher and Oddershede, 1974; Vokac et al., 1975; Reybrouck et al., 1975; Thomson and Scrutton, 1978; Corry and Powers, 1982)
- 3) myocardial oxygen requirements are greater in upper rather than lower body exercise at submaximal and maximal workloads (Amundsen et al., 1980).

Mechanical Load Factors

Maximal oxygen uptake, as previously defined (Åstrand and Rodahl, 1977), is an important component in all swimming events (Bonner, 1980; Houston, 1978).

$\dot{V}_{O_2\max}$, therefore, is an important criterion to assess with regard to maximising performance. Previous research indicates that swimmers have an elevated $\dot{V}_{O_2\max}$, resulting from a large muscle mass used to overcome resistive (drag) forces and to maintain stability in the water (Holmer, 1974c; 1982; Åstrand, 1978).

The buoyant force is that which acts in opposition to the weight of the swimmer (Hay, 1978). The heavier the swimmer, the greater the buoyant force required to prevent sinking. However, body weight is composed of materials (e.g., muscle, bone and fat) of differing densities (or specific gravities). Depending on the ratio of these materials, a greater or lesser sinking effect will take place. Fat is very light (specific gravity approximately 0.8), therefore a swimmer with a high percentage of fat was more likely to float than a lean swimmer, and less muscular exertion will be used on body support (Dobeln and Holmer, 1974).

Movement through water produces additional resistive forces. Hay (1978) highlighted three important forces; a) surface drag, turbulence (loss of energy) in the fluid layer immediately surrounding the swimmer, b) form drag, resistance with the relative oncoming flow of water, caused by the cross-sectional area of the body, and, c) wave drag, waves produced at the interface between the water and air. These three forces are collectively known as 'body drag' (Di Prampero et al., 1974).

Body drag is largely determined by body shape and size. Skilled swimming technique can reduce some drag by adopting correct streamlined positions, but body size has been shown to be important with regard to \dot{V}_{O_2} (Di Prampero et al., 1974). Furthermore, as swimming velocity increases, drag increases as a squared function (Counsilman, 1968). At high speeds, therefore, body drag is the main resistive load, and mechanical efficiency (largely determined by stroke technique) becomes of greater importance.

According to East (1970), 94% of a swimming race is spent stroking, whilst 6% is spent on starts and turns. This high percentage emphasizes the importance of stroke rate (SR) and stroke length (SL) in maximising efficiency. Kornecki and Bober (1978) suggest a shorter duration of the stroke cycle to maximise efficiency in butterfly. This agrees with previous findings (East, 1970) where elite butterfly swimmers were characterised by a high SR and long SL compared to non elite swimmers.

From a mechanical viewpoint, maximal force should be applied over the greatest possible distance and time i.e., low SR and high SL (East, 1970; Hay, 1978; Craig and Pendergast, 1979). This would require great strength and power in arm musculature which top swimmers possess, but most swimmers do not. The combination of low SR and high SL, therefore, would result in local muscular fatigue.

It is generally agreed by the above mentioned authors that submaximal velocities are achieved by a low SR and a high SL, but at maximal swimming speeds the reverse combination occurs. Recent data are not available in this area, and advances in stroke technique may have altered this relationship.

Cardio-Respiratory Adaptations to Swimming

As a result of the above mentioned forces, central and subcellular adaptations occur similar to those found as a result of endurance running or cycling. These include enhanced enzyme systems in both the cytoplasm and nucleus of a muscle cell, increased capillarisation, increased FFA turnover and an increase in muscle fibre area, particularly the SO and fast oxidative glycolytic (FOG) fibres (Åstrand, 1978; Costill, 1978; Houston, 1978).

The stresses imposed on the cardio-respiratory system differ from running, primarily as a result of the water environment. Respiration is affected by swimming stroke (SR), as the SR increases, so does respiratory frequency (Holmer, 1974c; Kipke, 1978).

It has been suggested that respiration and lung capacity may limit \dot{V}_{O_2} during swimming. Dynamic (or airway) and elastic lung resistances are increased during swimming (Deroanne et al., 1971). This inevitably causes a reduction in lung capacity, due in part to a decrease in vital capacity and bronchial diameter. In addition, underwater expiration must overcome high pressure and is therefore prolonged, whilst inspiration is shortened.

These respiratory difficulties, however, do not affect oxygen saturation in the blood, or the extraction by muscle. It has been found that swimmers have a greater pulmonary diffusing capacity than other athletes due to a larger pulmonary bed (Magel and Anderson, 1969). Consequently, oxygen extraction is high, resulting in a lower (a-v) O_2 at maximal work loads (Dixon and Faulkner, 1971; Deroanne et al., 1971; Kasch, 1978).

The lower $\dot{V}_{O_{2max}}$ found in swimming compared to running or cycling is mainly accounted for by the circulatory system. Blood flow during swimming is directed to the intestinal organs and the skin as well as to working muscles, therefore the opportunity to extract oxygen is decreased (Holmer, 1974c). Maximal \dot{Q} , SV and HR are lower during swimming hence the availability of oxygenated blood is lowered (Magel and Anderson, 1969; Dixon and Faulkner, 1971; Holmer, 1974c). Holmer (1974c) has suggested that the lower maximum heart rates found during swimming compared with running may be a result of breath holding or face immersion. More recent data supports this theory (Magel et al., 1982). Finally, the support offered by water to the swimmer results in less muscular action to

maintain stability and less oxygen is consumed (Holmer, 1974c).

Efficiency and Energy Output

The more efficient the stroke mechanics, the lower the \dot{V}_{O_2} at any given swimming velocity (Holmer, 1974c). Data on elite swimmers reveal the mean $\dot{V}_{O_2\max}$ for the four strokes to be 4.34, 4.49, 4.47, and 4.65 $\text{l}\cdot\text{min}^{-1}$ for freestyle (FR), butterfly (BF), breaststroke (BR) and backstroke (BK) respectively (Magel and Faulkner, 1967; Magel, 1970; Cunningham and Eynon, 1973; Holmer, 1974a; 1974c). These results conflict with the present world best times, with the exception of FR (Table 12). It is possible that recent advances in swimming technique would account for the discrepancies between \dot{V}_{O_2} and the relative efficiency of the other three strokes. For example in butterfly developments in the kick timing, hip action, arm recovery and the hand pitch during the push phase of the arm pull, have culminated in a more fluent stroke action, thereby minimising drag and maximising efficiency.

A similar principle exists for backstroke and breaststroke, although the latter has seen the greatest changes in the last four years. In BR, there is an exaggerated hyperextension of the back to aid the kicking action, and the kick itself involves an orientation of the knees and thighs which greatly reduces drag. Recent data on oxygen consumption of the four strokes is not available, but it would seem likely that $\dot{V}_{O_2\max}$ values would differ from those previously stated.

The contribution of the leg kick and arm stroke have been studied in relation to both the effect on propulsion (i.e., velocity) and oxygen consumption (energy efficiency). In all four strokes, \dot{V}_{O_2} was greatest in leg kick alone, but swimming velocity was lower than both whole stroke and arm work (Holmer, 1974c). The exception was BR, in which leg, arm and whole stroke were closely matched with

TABLE 1

WORLD RECORDS FOR MEN SWIMMING 100M AND 200M (1984)

RECORD TIME, MEAN SWIMMING VELOCITY AND THE PERCENTAGE OF

FREESTYLE VELOCITY ARE SHOWN

STROKE DISTANCE		TIME	VELOCITY	%
	(m)	(min ⁻¹)	(m.sec ⁻¹)	
FR	100	0·49·36	2·03	100·0
	200	1·47·44	1·86	100·0
BK	100	0·55·19	1·81	89·2
	200	1·58·86	1·68	90·3
BR	100	1·01·65	1·62	79·8
	200	2·13·34	1·50	80·6
BF	100	0·53·08	1·88	92·6
	200	1·57·04	1·71	92·4

Performances in 50-metre pools since Jan 1, 1984

Official Results of the 1984 Olympic Games (LAOC, 1984)

FR=Freestyle

BR=Breastroke

BK=Backstroke

BF=Butterfly

regard to \dot{V}_{O_2} and velocity. Also, at a given velocity, arm work alone elicited the lowest \dot{V}_{O_2} in all strokes. \dot{V}_{O_2} peak and maximum velocity was always greatest in whole stroke.

In terms of efficiency, Holmer (1974c) found FR arm action to be the most efficient, followed by whole stroke and leg kick. In BR there was a low average efficiency, and indicated why BR is the slowest of the four competitive strokes. Watkins and Gordon (1983) suggested that leg kick did not directly contribute to propulsion in freestyle, but indirectly helped by stabilising the trunk and streamlining the body. It is probable that a similar case exists for BK and BF, whereas BR would gain considerable propulsion from the legs.

Training the Aerobic System

$\dot{V}_{O_2\max}$ can be elevated through training. In a nine week endurance training programme utilising a bicycle ergometer, Davies and co-workers (1979) showed a 25% increase in $\dot{V}_{O_2\max}$. In active individuals, increases are more difficult, and training intensities of at least 75% HR_{\max} have been necessary to elicit any change (Burke and Franks, 1975). The magnitude of any $\dot{V}_{O_2\max}$ increase is related to initial fitness, intensity, duration and frequency of training (Fox and Mathews, 1981; Åstrand and Rodahl, 1977). In addition, the mode or specificity of training, as well as recovery, are critical (Magel et al., 1975; McCafferty and Horvath, 1977; Gergley et al., 1984).

Swimming training is mostly interval in nature, where high intensity work loads are interspersed with frequent rest intervals. Competition swim training has been shown to enhance all the subcellular and central functions previously discussed, with a subsequent increase in $\dot{V}_{O_2\max}$ (Houston, 1978). The specific adaptations resulting from swimming training were well illustrated by Holmer

(1972b) in a study of identical twins, one of whom was involved in competitive training. In the arm swimming test, the trained twin had a 49% greater $\dot{V}_{O_2\max}$, and performed at a greater velocity. In swim tests on all four strokes, plus arm and leg work only, the trained twin elicited a $\dot{V}_{O_2\max}$ of at least 24% greater than the non trained twin.

Determination of $\dot{V}_{O_2\max}$: Testing Protocol

When testing $\dot{V}_{O_2\max}$, the instrument used must be specific to the exercise mode, and it must be a reproducible and valid measure. Subcellular and circulatory responses are specific in nature (McCafferty and Horvath, 1977). A number of studies have emphasized that the ergometer used to measure these responses was specific, e.g., tethered swimming (TS) apparatus to measure physiological adaptations to swimming, or a cycle ergometer to measure responses to cycling (Roberts and Alspaugh, 1972; Magel et al., 1975; Pechar et al., 1974; Eriksson et al., 1978). Recent data suggested that TS was equally valid in predicting $\dot{V}_{O_2\max}$ as the swim flume and free swimming (Bonen et al., 1980).

Validity of a measure is lowered when the test does not require the use of the same muscle groups or a similar technique to that used in the actual exercise. In a $\dot{V}_{O_2\max}$ test using the arms, Bar-Or and Zwiren (1975) found the reliability of an arm test to be $r=0.94$. The subjects used the same muscles each time, therefore the arm test was a reliable measure of arm $\dot{V}_{O_2\max}$. However as a test of whole body $\dot{V}_{O_2\max}$, validation with the Treadmill was only $r=0.74$. Using the arm cranking test for swimming $\dot{V}_{O_2\max}$, therefore, may not be appropriate as it does not simulate the swimming arm action.

Three types of protocol are presently used in tests of maximum oxygen consumption; 1) a continuous test with a set workload, 2) a discontinuous test with

increases in workload, and, 3) a continuous test with increases in workload (Åstrand and Rodahl, 1977; MacDougall et al., 1982). Selected studies suggest that a continuous test with increases in workload tax the cardiorespiratory system to a maximum (McArdle et al., 1973; Kasch et al., 1976). When using smaller muscle groups a discontinuous protocol has been suggested (Cardus, 1979; MacDougall et al., 1982), to prevent fatigue acting as a limiting factor in obtaining maximum values. The present study (Chapter I) suggested that either a continuous or a discontinuous test could be used.

Swim Bench and Tethered Swimming Ergometry

The swim bench ergometer is presently used as a testing device for muscular strength and power (Costill et al., 1980; Thornton and Flavell, 1981; Sharp et al., 1982; Swaine and Reilly, 1983). These studies have shown a high correlation with sprint performance and muscular power, as well as determining ideal power curves for each stroke.

Armstrong and Davies (1981) used the swim bench to test $\dot{V}_{O_2\max}$ with a discontinuous protocol. Values obtained were 66% of the TM $\dot{V}_{O_2\max}$. Similar results were found by Gergley and co-workers (1984) where swim bench values 49.9% below the TM. No published data exist in which swim bench work has been compared with a swim specific protocol.

Summary

Many subcellular adaptations occur as a result of training which increase the oxygen utilisation capacity of an individual. It is unlikely that O_2 availability limits $\dot{V}_{O_2\max}$ during swimming. It is more likely a result of the inability of the cells to remove H^+ ions. Cardio-respiratory adaptation allows the oxygenated blood to be transported to the working muscles more efficiently.

In water, an individual has to overcome a greater resistive force than on land. This force is affected by body shape, body composition and swimming mechanics, which in turn effect \dot{V}_{O_2} . The measurement of $\dot{V}_{O_2\max}$ in swimmers is often performed by using a tethered swimming test, however, the swimming flume and free swimming are also used. The swim bench has been developed as a training device, but at present it has not been used to predict $\dot{V}_{O_2\max}$ in swimmers, or been compared to a swim specific $\dot{V}_{O_2\max}$ test.

REFERENCES

- Amundson, L.R., Takahashi, M., Carter, C.L. and Nielsen, D.H. (1980). Exercise response during wall-pulley versus bicycle ergometer work. **Physical Therapy** 60 (2):173-178.
- Armstrong, N. and Davies, B. (1981). An ergometric analysis of age group swimmers. **British Journal of Sports Medicine** 15 (1):20-26.
- Åstrand, P-O. and Rodahl, K. (1977). **Textbook of Work Physiology**. McGraw-Hill, New York.
- Åstrand, P-O. (1978). Aerobic Power. In B. Eriksson and B. Furberg (Eds) **Swimming Medicine IV**. International Series on Sports Sciences 6:127-131. University Park Press, Baltimore.
- Bar-Or, O. and Zwiren, L.D. (1975). Maximal oxygen consumption test during arm exercise reliability and validity. **Journal of Applied Physiology** 38 (3):424-426.
- Bonen, A., Wilson, B.A., Yarkony, M. and Belcastro, A.N. (1980). Maximal oxygen uptake during free, tethered and flume swimming. **Journal of Applied Physiology** 48 (2):232-235.
- Bonner, H.W. (1980). Energy systems used during swimming. **Swimming Technique**, November, 10-13.
- Burke, E.J. and Franks, B.D. (1975). Changes in $\dot{V}_{O_2\max}$ resulting from bicycle training at different intensities holding the total mechanical work constant. **Research Quarterly** 46 (1):31-37.
- Burke, E.J., Cerney, F., Costill, D.L. and Fink, W. (1977). Characteristics of skeletal muscle in competitive cyclists. **Medicine and Science in Sports and Exercise** 9 (2):109-112.
- Cardus, D. (1979). Exercise testing : Methods and uses. **Exercise and Sports Science Review** 6:59-103.
- Corry, I. and Powers, N. (1982). Maximal aerobic power measurement in runners and swimmers. **British Journal of Sports Medicine** 16 (3):154-160.
- Costill, D.L. (1978). Adaptations in skeletal muscle during training for sprint and endurance swimming. In B. Eriksson and B. Furberg (Eds) **Swimming Medicine IV**. International Series on Sports Sciences 6:233-248. University Park Press, Baltimore.
- Costill, D.L., Thomason, H. and Roberts, E. (1973). Fractional utilization of the aerobic capacity during distance running. **Medicine and Science in Sports and Exercise** 5 (4):248-252.
- Costill, D.L., Sharp, R. and Troup, J. (1980). Muscle strength: Contributions to sprint swimming. **Swimming World** 21 (2):29-34.

- Counsilman, J.E. (1968). **The Science of Swimming**. Prentice-Hall, New Jersey.
- Craig, A.B. and Penedergast, D.R. (1979). Relationship of stroke rate, distance per stroke, and velocity in competitive swimming. **Medicine and Science in Sports and Exercise** 11 (3):278-283.
- Cunningham, D.A. and Eynon, R.B. (1973). The working capacity of young competitive swimmers, 10-16 yrs of age. **Medicine and Science in Sports and Exercise** 5 (4):227-231.
- Davies, J.A., Frank, M.H., Whipp, B.J. and Wasserman, K. (1979). Anaerobic threshold alterations caused by endurance training in middle-aged men. **Journal of Applied Physiology** 46 (6):1039-1046.
- Deroanne, R., Pirany, F., Dujardin, J. and Petit, J.M. (1971). Mechanical properties of the lungs during swimming. In L. Lewillie and J. P. Clarys (Eds) **First International Symposium on Biomechanics in Swimming** :207-215. Universite Libre de Bruxelles, Brussels.
- Di Prampero, P.E., Pendergast, D.R., Wilson, D.W. and Rennie, D.W. (1974). Energetics of swimming in man. **Journal of Applied Physiology** 37 (1):1-5.
- Dixon, R.W. and Faulkner, J.A. (1971). Cardiac outputs during maximum effort running and swimming. **Journal of Applied Physiology** 30 (5):653-656.
- Dobel, W. Von. and Holmer, I. (1974). Body composition, and oxygen uptake in man during water treading. **Journal of Applied Physiology** 37 (1):55-59.
- East, D.J. (1970). Swimming: An analysis of stroke frequency, stroke length and performance. **New Zealand Journal of Physical Education and Recreation** 3:16-25.
- Eriksson, B.O., Holmer, I. and Lundin, A. (1978). Physiological effects of training in elite swimmers. In B. Eriksson and B. Furberg, B.O. **Swimming Medicine IV**. International Series on Sports Sciences 6:177-187. University Park Press, Baltimore.
- Flavell, E.R. and Counsilman, J.E. (1981) Introduction to Biokinetics. In E.R.Flavell (Ed) **Biokinetic Strength Training** 1:1-8. Isokinetics, Inc., Albany.
- Fox, E.L. and Mathews, D.K. (1981). **The Physiological Basis of Physical Education and Athletics**. Saunders College, Philadelphia.
- Gergley, T., McArdle, W., DeJesus, F., Toner, M., Jacobowitz, S. and Spina, R. (1984). Specificity of arm training on aerobic power during swimming and running. **Medicine and Science in Sports and Exercise** 16 (4):349-354.
- Gollnick, P.D. (1977). Free fatty acid turnover and the availability of substrates as a limiting factor in prolonged exercise. **Annals of the New York Academy of Sciences** 301:64-71.
- Gollnick, P.D., Armstrong, R., Saltin, B., Saubert, C., Sembrowich, L. and Shepard, R. (1973). Effects of training on enzyme activity and fibre type

- composition of human skeletal muscle. **Journal of Applied Physiology** 34:107-111.
- Hay, J.D. (1978). **Biomechanics of sports techniques** (2nd Ed.). Prentice-Hall, New Jersey.
- Holloszy, J.O. (1973). Biochemical adaptations to exercise : Aerobic metabolism. In J. Wilmore (Ed) **Exercise and Sport Sciences Reviews** 1:45-71. Academic Press, New York.
- Holloszy, J.O. (1975). Adaptation of skeletal muscle to endurance exercise. **Medicine and Science in Sports and Exercise** 7 (3):155-164.
- Holmer, I. (1974a). Propulsive efficiency of breaststroke and freestyle swimming. **European Journal of Applied Physiology** 33:95-103.
- Holmer, I. (1974b). Energy cost of arm stroke, leg kick, and the whole stroke in competitive swimming styles. **European Journal of Applied Physiology** 33:105-118.
- Holmer, I. (1974c). Physiology of swimming man. **Acta Physiologica Scandinavica** Suppl. 407.
- Holmer, I. (1983). Energetics and mechanical work in swimming. In A.P. Hollander, P. Huijing and G de Groot (Eds). **Biomechanics and Medicine in Swimming** :154-164. Human Kinetics Publishers, Champaign, IL.
- Houston, M.E. (1978). Metabolic responses to exercise, with special reference to training and competition swimming. In B. Eriksson and B. Furberg (Eds). **Swimming Medicine IV**. International Series on Sports Sciences 6:207-232. University Park Press, Baltimore.
- Houston, M.E. (1982). Exercise Biochemistry. In J. J. Jackson and H. A. Wenger (Eds). **The Sports Sciences : University of Victoria Physical Education Series** 4:42-51. Morriss Printing, Victoria.
- Kaijser, L. (1971). Oxygen supply as a limiting factor in physical performance. In J. Keul (Ed) **Limiting Factors in Physical Performance**, 253-266. Georg Thieme Publishers, Stuttgart.
- Kasch, F.W. (1978). Maximal oxygen uptake in older male swimmers during free swimming and stationary cycling. In B. Eriksson and B. Furberg (Eds). **Swimming Medicine IV**. International Series on Sport Sciences 6:143-146.
- Kipke, L. (1978). Dynamics of oxygen intake during step-by-step loading in a swimming flume. In B. Eriksson and B. Furberg (Eds). **Swimming Medicine IV**. International Series on Sport Sciences 6:137-142.
- Kornecki, S. and Bober, T. (1978). Extreme velocities of a swimming cycle as a technique criterion. In B. Eriksson and B. Furberg (Eds). **Swimming Medicine IV**. International Series on Sport Sciences 6:402-407.
- Lehninger, A.L. (1975). **Biochemistry** (2nd Ed). Worth Publishers, Inc., New York.

- MacDougall, J.D., Wenger, H.A. and Green, H.J. (1982). **Physiological Testing of the Elite Athlete**. Canadian Association of Sports Sciences. Mutual Press Limited, Toronto.
- Magel, J.R. and Andersen, K.L. (1969). Pulmonary diffusing capacity and cardiac output in young trained Norwegian swimmers and untrained subjects. **Medicine and Science in Sports and Exercise** 1 (3):131-139.
- Magel, J.R. (1970). Propelling force measured during tethered swimming in the four competitive swimming styles. **Research Quarterly** 41 (1):68-74.
- Magel, J.R., Foglia, G.F., McArdle, W.D., Gutin, B., Pecher, G.S., and Katch, F.I. (1975). Specificity of swim training on maximum oxygen uptake. **Journal of Applied Physiology** 38 (1):151-155.
- Magel, J.R., McArdle, W.D., Weiss, N.L., Stone, S. and Newman, A. (1982). Heart rate response to apnea and face immersion. **Journal of Sports Medicine and Physical Fitness** 22 (2):135-146.
- Magel, J.R., McArdle, W.D., Toner, M., and Delio, D.J. (1978). Metabolic and cardiovascular adjustment to arm training. **Journal of Applied Physiology** 45 (1):75-79.
- Martindale, W.O. and Robertson, D.G.E. (1984). Mechanical energy in sculling and in rowing on an ergometer. **Canadian Journal of Applied Sports Science** 9 (3):153-163.
- McArdle, W.D., Katch, F.I. and Pecher, G.S. (1973). Comparison of continuous and discontinuous treadmill and bicycle tests for max \dot{V}_{O_2} . **Medicine and Science in Sports and Exercise** 5 (3):156-160.
- McCafferty, W.B. and Horvath, S.M. (1977). Specificity of exercise and specificity of training : a subcellular review. **Research Quarterly** 48 (2):358-371.
- Miyamura, M. and Honda, Y. (1972). Oxygen intake and cardiac output during treadmill and bicycle exercise. **Journal of Applied Physiology** 32:185-188.
- Newsholme, E.A. (1977). The regulation of intracellular and extracellular fuel supply during sustained exercise. **Annals of the New York Academy of Sciences** 301:81-91.
- Pecher, G.S., McArdle, W.D., Katch, F.I., Magel, J.R. and Delucia, J. (1974). Specificity of cardiorespiratory adaptation to bicycle and treadmill running. **Journal of Applied Physiology** 36 (6):753-756.
- Reybrouck, T., Heigenhauser, G.F. and Faulkner, J.A. (1975). Limitations to maximum oxygen uptake in arm, leg, and combined arm-leg ergometry. **Journal of Applied Physiology** 38 (5):774-779.
- Roberts, J.A. and Alspaugh, J.W. (1972). Specificity of training effects resulting from programmes of treadmill running and bicycle ergometer riding. **Medicine and Science in Sports and Exercise** 4 (1):6-10.

- Rusko, H., Havu, H. and Karvinen, E. (1978). Aerobic performance capacity in athletes. **European Journal of Applied Physiology** 38:151-159.
- Saltin, B and Astrand, P-O. (1967). Maximal oxygen uptake in athletes. **Journal of Applied Physiology** 23:353-368.
- Saltin, B., Nazar, K., Costill, D.L., Stein, E., Jansson, E., Essen, B. and Gollnick, P.D. (1976). The nature of the training response; peripheral and central adaptations to one-legged exercise. **Acta Physiologica Scandinavica** 96:289-305.
- Schleihauf, R.E. (1982). 3-D Computer stroke analysis. **Swimming Technique** August, 20-25.
- Secher, N.H. and Oddershede, I. (1974). Maximal oxygen uptake rate during swimming and bicycling. In L. Lewillie and J. P. Clarys (Eds). **Swimming II**. International Series on Sports Sciences, 137-142. University Park Press, Baltimore.
- Sharp, R.L., Troup, J.P. and Costill, D.L. (1982). Relationship between power and sprint freestyle swimming. **Medicine and Science in Sports and Exercise** 14 (1):53-56.
- Swaine, I. and Reilly, T. (1983). The freely-chosen swimming stroke rate in a maximal swim and on a biokinetic swim bench. **Medicine and Science in Sports and Exercise** 15 (5):370-375.
- Thomson, J.M. and Scrutton, E.W. (1978). Physiological adaptation to long-term upper-body work. **Canadian Journal of Applied Sport Sciences** 3:103-108.
- Thornton, N. and Flavell, E.R. (1981). Electronic assisted dryland stroke analysis. In E. R. Flavell (Ed) **Biokinetic Strength Training** 1:59-64. Isokinetics, Inc., Albany.
- Vokac, Z., Bell, H., Bautz-Holter, E. and Rodahl, K. (1975). Oxygen uptake/heart rate relationship in leg and arm exercise, sitting or standing. **Journal of Applied Physiology** 39 (1):54-59.
- Watkins, J. and Gordon, A.T. (1983). The effects of leg action on performance in the sprint front crawl stroke. In A.P. Hollander, P. Huijing and G de Groot (Eds). **Biomechanics and Medicine in Swimming** :310-314. Human Kinetics Publishers, Champaign, IL.
- Weltman, A., Katch, V. and Sady, S. (1978). Effects of increasing oxygen availability on bicycle ergometer endurance performance. **Ergonomics** 21 (6):427-437.
- Wenger, H.A. (1981). The many faces of aerobic fitness. In J.J.Jackson and H.D.Turkington (Eds) **Quality Programming in H.P.E.R.** 55-62. Victoria, Morriss Printing Company Ltd.
- Wenger, H.A. and Reed, A.T. (1976). Metabolic factors associated with muscular fatigue during aerobic and anaerobic work. **Canadian Journal of Applied Sport Sciences** 1:43-48.

PARTIAL COPYRIGHT LICENSE

I hereby grant the right to lend my thesis (the title of which is shown below) to users of the University of Victoria Library, and to make single copies only for such users or in response to a request from the Library of any other university, of similar institution, on its behalf or for one of its users. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by me or a member of the University designated by me. It is understood that copying or publication of this thesis for financial gain shall not be allowed without written permission.

Title of Thesis:

**EXPERIMENTAL STUDIES PREDICTING MAXIMUM OXYGEN CONSUMPTION
IN SWIMMING USING SWIM BENCH ERGOMETRY**

Author



ASHLEY I. MEERLOO

June 21st 1985
