



RETURNING MATERIALS:
Place in book drop to
remove this checkout from
your record. **FINES** will
be charged if **book** is
returned after the date
stamped below.

--	--	--

**THE METABOLIC ASSESSMENT OF ELITE
MALE AND FEMALE SWIMMERS USING A CONTINUALLY
ADJUSTED TETHERED SWIM PROTOCOL**

By

Thomas T. Kurowski

A DISSERTATION

**Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of**

DOCTOR OF PHILOSOPHY

**School of Health Education, Counseling
Psychology and Human Performance**

1987

ABSTRACT

THE METABOLIC ASSESSMENT OF ELITE MALE AND FEMALE SWIMMERS USING A CONTINUALLY ADJUSTED TETHERED SWIM PROTOCOL

By

Thomas T. Kurowski

The metabolic responses to maximum work of 65 female and 55 male national-caliber swimmers were examined using a tethered swim test that employed a continually adjusted loading protocol. The intent of this study was to: (a) provide information concerning the physiological responses of elite female swimmers and contrast their responses with those of a similar group of male subjects; and (b) to differentiate, within each sex, between the metabolic responses of swimmers specializing in sprint and distance events and between responses of swimmers ranked by performance in the upper and lower 20% of each sex group.

Analysis of variance indicated that the male swimmers had significantly higher absolute metabolic values than did the females with the exception of heart rate. These differences persisted but were reduced when the data was expressed relative to body weight and were further reduced when expressed relative to lean body weight. Work/recovery curves show the males to have significantly higher oxygen uptake and respiratory quotient values during work and recovery. Females had consistently higher heart rates during work and recovery.

Male distance swimmers had significantly higher peak oxygen uptakes than male sprinters in both absolute and relative terms. Male

sprinters had significantly higher peak respiratory quotients than the distance swimmers. There were no differences between female sprint and distance swimmers when the metabolic data was expressed in absolute terms. When expressed in terms relative to body weight and lean body weight, female distance swimmers had significantly higher peak oxygen uptakes than female sprinters. Work/recovery curves indicate more efficient performance by both male and female distance swimmers when compared to sprinters.

Male swimmers ranked in the upper 20% of their group had significantly higher peak absolute oxygen uptakes than did the males ranked in the lower 20%. These differences disappeared when the data was expressed relative to body weight or lean body weight. Female swimmers showed no differences in peak metabolic values between those ranked in the upper and lower 20% of their group. Work/recovery curves for the male swimmers indicate those swimmers that were more successful were also more efficient than the less successful swimmers of their group. This pattern was reversed when similarly ranked female swimmers were compared.

DEDICATION

To my family.

ACKNOWLEDGEMENTS

Deepest appreciation is extended to Dr. William Heusner for his patience and support during my graduate career and for his continued guidance throughout all phases of this project.

Further gratitude is due to Drs. Wayne Van Huss, Kwok-Wai Ho, and John Downs for their assistance, encouragement and input into this study.

Special thanks is extended to Jo Ann Janes, David Anderson, Robert Wells and Ken Stephens for their friendship and assistance throughout my stay at Michigan State University.

Finally, I would like to acknowledge my father and mother, Ted and Virginia, for their unending love and support, my wife, Julie, for her patient love, and my brothers, Dave and Ted, Jr. for not asking about the book.

TABLE OF CONTENTS

	<u>Page</u>
LIST OF TABLES	vi
LIST OF FIGURES	vii
CHAPTER I - THE PROBLEM	1
Statement of the Problem	5
Rationale	5
Significance of the Problem	7
Limitations	8
CHAPTER II - REVIEW OF SELECTED RELATED LITERATURE	10
Metabolic Assessment of Well-Trained Swimmers	10
Protocol Selection	14
Comparison of Swimmers by Sex, Distance, and Rank	16
CHAPTER III - METHODS AND MATERIALS	19
Overview	19
Subjects	20
Apparatus	21
Personnel	23
Test Protocol	25
Metabolic Determination	28
Statistical Analysis	31
CHAPTER IV - RESULTS AND DISCUSSION	33
Physical Characteristics	33
Sex	33
Distance	34
Rank	34
Peak Energy Metabolism	38
Sex	38
Distance	41
Rank	46
Work and Recovery Curves	49
Sex	49
Distance	56
Rank	65

	<u>Page</u>
Discussion.	75
Comparison by Sex	75
Comparison by Distance.	102
Comparison by Rank.	109
CHAPTER V - SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS	116
Summary	116
Conclusions	117
Recommendations	118
APPENDIX	
Appendix A.	120
REFERENCES.	122

LIST OF TABLES

<u>Table</u>		<u>Page</u>
1	Physical Characteristics of Subjects.	35
2	Physical Characteristics of Subjects by Distance.	36
3	Physical Characteristics of Subjects by Rank.	37
4	Physiological Variables for Male and Female Subjects During Tethered Swimming.	39
5	Physiological Variables at Peak $\dot{V}O_2$ Expressed Relative to Body Weight and Lean Body Weight (LBW) for Male and Female Subjects During Tethered Swimming	40
6	Physiological Variables for Male Subjects by Distance During Tethered Swimming.	42
7	Physiological Variables at Peak $\dot{V}O_2$ for Male Subjects Expressed Relative to Body Weight and Lean Body Weight (LBW) by Distance	43
8	Physiological Variables for Female Subjects by Distance During Tethered Swimming.	44
9	Physiological Variables at Peak $\dot{V}O_2$ for Female Subjects Expressed Relative to Body Weight and Lean Body Weight (LBW) by Distance	45
10	Physiological Variables for Male Subjects by Rank During Tethered Swimming.	47
11	Physiological Variables at Peak $\dot{V}O_2$ for Male Subjects Expressed Relative to Body Weight and Lean Body Weight (LBW) by Rank	48
12	Physiological Variables for Female Subjects by Rank During Tethered Swimming.	50
13	Physiological Variables at Peak $\dot{V}O_2$ for Female Subjects Expressed Relative to Body Weight and Lean Body Weight (LBW) by Rank	51

LIST OF FIGURES

<u>Figure</u>		<u>Page</u>
1	Mean Oxygen Uptakes (ml/kg/min) for Male and Female Swimmers During Exercise and Recovery	52
2	Mean Heart Rates (beats/min) for Male and Female Swimmers During Exercise and Recovery	54
3	Mean Respiratory Exchange Ratios (RER) for Male and Female Swimmers During Exercise and Recovery. . .	55
4	Mean Oxygen Uptakes (ml/kg/min) for Male Short and Middle-Distance Swimmers During Exercise and Recovery.	57
5	Mean Oxygen Uptakes (ml/kg/min) for Female Short and Middle-Distance Swimmers During Exercise and Recovery.	58
6	Mean Heart Rates (beats/min) for Male Short and Middle-Distance Swimmers During Exercise and Recovery.	60
7	Mean Heart Rates (beats/min) for Female Short and Middle-Distance Swimmers During Exercise and Recovery.	61
8	Mean Respiratory Exchange Ratios (RER) for Male Short and Middle-Distance Swimmers During Exercise and Recovery.	63
9	Mean Respiratory Exchange Ratios (RER) for Female Short and Middle-Distance Swimmers During Exercise and Recovery.	64
10	Mean Oxygen Uptakes (ml/kg/min) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Males	66
11	Mean Oxygen Uptakes (ml/kg/min) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Females	68

<u>Figure</u>		<u>Page</u>
12	Mean Heart Rates (beats/min) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Males	69
13	Mean Heart Rates (beats/min) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Females	71
14	Mean Respiratory Exchange Ratios (RER) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Males . . .	72
15	Mean Respiratory Exchange Ratios (RER) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Females . .	74

CHAPTER I

THE PROBLEM

The metabolic assessment of both trained and sedentary individuals has occupied work physiologists for many years. Accordingly, a great deal is known about the adaptations that occur consequent to chronic physical activity.

Scientific research in swimming originated more than 60 years ago with the collection of expired air from a swimmer paced by a rowboat in a lake (148). Another early method used to estimate oxygen requirements while swimming consisted of the subject holding his breath throughout the swim effort with a subsequent collection of expired air during recovery. This technique, the oxygen debt technique, was previously reported by Sargent (192) and was used in several investigations (2,132). The earliest use of a tethered swim ergometer seems to have been in 1919 when Liljestr nd and Lindhard (147) reported data for cardiac output during static swimming using a rebreathing technique. Van Huss and Cureton (223) used an all-out tethered swim for one minute following a 100-yard drop-off test to estimate metabolic performance during swimming.

Experimentation involving swimming, coupled with work using other exercise modalities, has demonstrated a relatively high degree of specificity in the training adaptations to chronic physical activity. Researchers have noticed that the mode of training of a muscle group is

an important consideration since improvements in maximal oxygen uptake are best demonstrated when a close similarity exists between the exercise test and the form of muscular work used in training. Furthermore, a valid determination of an individual's peak oxygen uptake for lower body (treadmill or cycle) exercise has been reported to be dependent upon selection of the proper protocol (72,98,137). Protocol selection, therefore, also may be particularly important for upper body exercise where peak oxygen consumption seems to be limited by peripheral rather than central circulatory factors (79,130,155). This contention is supported by the lack of a "centrally-limited" plateau in oxygen uptake as is demonstrated in both arm cranking (194) and swimming ergometry (203). The lack of a plateau in oxygen uptake is evident in flume swimming as well as in tethered swimming. However, failure to reach a plateau in oxygen consumption during a maximal effort swim test might be due simply to a lack of the necessary graded increments of work load under both flume and tethered swim conditions.

Free swim tests have been used previously but are cumbersome procedurally and may yield relatively large errors in ventilation (32). The swimming flume permits standardization of testing procedures and the metabolic evaluation of subjects during swimming. Yet, due to prohibitive costs, few investigators have ready access to a swimming flume. The tethered swimming apparatus appears to offer many of the same advantages as land-based ergometers but at considerably less expense than the flume. In addition, Bonen et al. (32) have demonstrated that flume swimming, free swimming and tethered swimming yield essentially identical oxygen uptake results.

Tethered swim tests have employed both continuous (32,122,204) and intermittent (23,24,63,76,96,151,153,169) protocols. Intermittent protocols minimize the effects of accumulated localized fatigue and thus should elicit higher values for peak oxygen uptake than do continuous protocols. However, an intermittent aquatic test poses unique problems such as heat loss to the water during rest periods. A continuous protocol eliminates the problem of resting heat loss but presents the possibility of premature test termination caused by localized muscular fatigue due to improper load increments. Particularly in untrained, convalescing, aged or younger subjects, increments that are too large can surpass the ability of small muscle groups to maintain functional integrity while failing to illicit the maximal oxidative capacity of all involved motor units. This is suggested by the previously mentioned failure of both arm cranking and swimming ergometry to allow an individual to reach a plateau in oxygen uptake. To avoid such a problem, the present study incorporated a continuous tethered swim protocol with decreasing load increments as the work stages progressed. One objective of this investigation, therefore, was to obtain information on the metabolic responses of highly trained male and female swimmers to a maximum-effort tethered swim test using a continually adjusted loading protocol.

Competitive swimming has developed remarkably since the early studies of Liljestrand in 1919 (147,148). World records are broken more frequently than in most sports, partly as a result of the marked increase in training volume and partly due to the increased employment of specific training programs to enhance performance capacities in

particular strokes or at specified distances. Consequently, it is no surprise that interest in swimming research has risen to meet the demand by physiologists, coaches and swimmers for additional knowledge concerning the specific adaptations brought about by intense swim training. However, the different physiological requirements and adaptations for sprint and distance training regimens have not been adequately addressed. Furthermore, although metabolic distinctions have been made between trained and recreational swimmers, few data exist that show systematic differences in the physiological responses to a swimming test within a well-trained group of national-caliber swimmers.

Finally, the present investigation represents only the second report of metabolic data on elite female swimmers obtained using a tethered swim ergometer. Bell (24) reports data for females, while two articles have included the combined results of male and female swimmers (32,122). The lack of information on female swimmers using a tethered swim test represents a gap in knowledge concerning the metabolic responses of well-trained female swimmers to a swimming test. This information seems especially relevant in light of the recent increases in participation, training and competition of females of all ages, as well as the relative availability of tethered swim ergometry.

In view of these several deficiencies in knowledge, the second and most important goal of the present investigation was to use the modified tethered swim protocol to assess the metabolic responses, to a maximum-effort swimming test, of swimmers who differ in sex, preferred

event distance, and competitive performance rank. The number (male n = 55, female n = 66) and quality (times ranging from 100.0% to 112.3% of the American record in each subject's best event) of the swimmers tested surpass those of previous studies and thus contribute to the uniqueness of the present investigation.

Statement of the Problem

This study was designed to assess selected metabolic responses of well-trained, national-caliber swimmers to a maximum-effort tethered swim test which employs a continually adjusted loading protocol. The major subgoals of the investigation were: (a) to provide information concerning well-trained female swimmers and to contrast their responses with those of a similar group of male subjects; and (b) to attempt to differentiate, within each sex, between the metabolic responses of swimmers specializing in sprint and distance events and between the responses of swimmers ranked by performance in the upper and lower 20% of each sex group.

Rationale

When cycle ergometer or treadmill tests are used, maximum oxygen uptake relative to body weight is generally less for well-trained swimmers than for similarly dedicated runners (189). Swimmers are heavier than runners in most cases. They also train in a horizontal position and in a medium that eliminates weight bearing and is favorable to heat exchange. Additionally, swimmers use their arms to generate a large part of the necessary propulsive force. It has become increasingly apparent that cardiopulmonary (central) and metabolic (peripheral) training adaptations are activity specific. Consequently,

tests requiring different postures, different muscle movements, and different circulatory adjustments than are used during training are not likely to elicit maximum physiological responses.

The difference between small- and large-muscle exercise contributes to the failure to reach a "centrally-limited" oxygen uptake plateau in both arm cranking (194) and swimming ergometry (203). The lack of adequately graded loading increments has plagued protocols of both types of exercise tests in the past and may be responsible for the development of local peripheral fatigue prior to performance at "centrally-limited" maximum capabilities. Research is needed to develop adequate physical work capacity tests for swimmers and other individuals trained for upper-body performance. The present study represents an attempt to satisfy this need as the loading protocol was adjusted, relative to each swimmer, so that smaller weight increments were added at each successive work stage. The hypothesis was that local muscular fatigue would be partially delayed and, therefore, the likelihood of attaining a "centrally-limited" maximum oxygen consumption would be increased.

Anatomical and physiological factors have been demonstrated to be partially responsible for performance differences between males and females. Although several reports detail no differences between males and females in skeletal muscle fiber-type distribution or enzymatic activities (52,53,190), others have suggested the possibility of a sexual dimorphic response to training in both rats and humans (6,166,193). In swimming, possible energy-metabolism differences may be confounded by variations in thermoregulation, bouyancy and drag

(related to body surface area) that exist between and within the sexes due to differential body fat distributions. In addition, little information is available concerning the basic metabolic responses of female swimmers to a tethered swim test. Therefore, the present investigation was conducted to determine the metabolic responses of well-trained, national-caliber male and female swimmers using an adjusted loading protocol.

Since elite swimmers currently train many hours daily, there is a critical need for a swimming ergometer to assess the relative effectiveness and efficiency of training programs of varying intensities and durations. Given the possibility of an improved tethered swim protocol, it was hypothesized that swimmers who specialize in sprint events can be distinguished from swimmers who train for distance races. Furthermore, it was hypothesized that, even within a relatively homogenous group of well-trained swimmers, those athletes whose performances rank them in the top 20% of the group can be distinguished metabolically from those ranked in the lower 20%.

Significance of the Problem

When compared to cycling or running, swimming has not been subjected to extensive physiological analysis until recently. This deficit possibly is due, at least in part, to the complexity of collecting metabolic data in the water. However, recent advances in sophistication of swimming training methods, the hours and years of training involvement, and the early onset of swimming competition certainly justify further study of the activity. The ultimate significance of the present study, therefore, rests largely in the

refinement of the instrumentation and methods of tethered swimming in order to more accurately assess the effects of chronic and acute bouts of swimming on health and performance. Of course, knowledge of the metabolic responses of elite, well-trained male and female swimmers substantially increases the data base necessary for further study in this field. Finally, a potential contribution of the present investigation is the possible facilitation of using improved swimming ergometry for the assessment of preventive or rehabilitative exercise regimens that are prescribed for sedentary, elderly, disabled, or convalescing individuals.

Limitations

1. The absolute values obtained in this investigation are representative only of male and female swimmers of similar age, training, and performance status as those used in the current study who are tested with a tethered swim ergometer.
2. It was not possible to supervise either diet or activity patterns for the subjects prior to their exercise tests.
3. There was no way to know with certainty if each subject performed to exhaustion in the tethered swim test.
4. There was no specific information available concerning the specific training regimens used by those individuals categorized as sprint or distance swimmers or by those ranked by performance in the upper or lower 20% of their respective groups.

5. The physiological effects of the conditions imposed upon the swimmer by the tethered swim and/or the breathing apparatus are not known and must, therefore, be considered to be part of the total test condition.

CHAPTER II

REVIEW OF SELECTED RELATED LITERATURE

The maximal metabolic power of human beings has interested physiologists for many years. However, a scientific approach to the assessment of the physiological responses to swimming has lagged behind research conducted using land-based ergometry. This probably has been due to the difficulties posed by the collection of metabolic data in an aquatic environment. Improvements in the instrumentation available coupled with an interest in the abilities of well-trained swimmers to work in an aquatic environment have produced increasing numbers of scientific investigations.

This review of related literature will be divided into the following sections: (a) an overview of the research involving the metabolic assessment of well-trained swimmers; (b) a review of the literature involving investigations dealing with protocol selection and its effect on swimming ergometry; and (c) presentation of previous work focusing on the comparisons of groups of well-trained swimmers by sex, distance speciality, or rank (i.e., a performance criteria).

Metabolic Assessment of Well-Trained Swimmers

Liljestrand and Stenstrom (148) seem to be the earliest physiologists with an interest in work in an aquatic environment. They collected expired air by means of a mask leading to a Douglas bag as the subject swam behind a rowboat. Their results suggested a linear

trend towards greater oxygen usage with increasing velocities of swimming. The reliabilities, however, were poor due to their inability to control the work rate. In the same year, Liljestrand and Lindband (147) devised what seems to be the earliest tethered swim test. Their heart minute volume calculations, based on metabolic data, showed poor reliability due to difficulty in reproducing work rates.

Cureton (57) derived practical diagnostic swimming tests and demonstrated their relationship to swimming performance. Van Huss and Cureton (223) subsequently showed these tests to give a good estimate of swimming performance when compared to metabolic capacity estimated during an all-out tethered swim administered after a 100-yd drop-off test. Sargent's (192) oxygen debt technique was shown to be applicable to swimming as well as to running in several investigations (2,132) which demonstrated a linear relationship of oxygen uptake with the rate of work.

The scientific investigation of swimming performance evolved from these early studies with improved methodology as well as with an increased availability of highly trained swimmers.

Free-swim tests have been used with the collection of expired air by means of a Douglas bag that was suspended and carried next to a swimmer by a technician or cart. This method was used by McArdle (159) in estimating the maximum O_2 uptake of male varsity collegiate swimmers. McArdle's swim test used stroke frequency to determine work levels. Each subject swam for 4 min and rested 10 min. Work load was elevated by increasing stroke frequency. Maximum oxygen uptake was estimated as 43.8 ml/kg/min for 5 subjects. Holmer (117), and later

Lavoie et al. (143) obtained slightly higher O_2 uptakes (55-58 ml/kg/min) when testing male and female national-caliber swimmers. These exercise tests consisted of a 500-m swim at maximal speed, following two 250-m swims at progressively increasing speed. Expired air was collected during the last 2 min of the 500-m swim.

Besides being a cumbersome procedure, free swimming has been criticized as allowing for large errors in ventilation because minute ventilation must often be extrapolated from gas collection times of 15-20 sec (32). In addition, another problem with free swimming involves the lack of a standardized procedure with regards to accuracy and reproducibility of swimming speed (111).

The swimming flume was developed in 1972 by Astrand and Englesson (10). Holmer has used this apparatus to examine the capabilities of elite Swedish swimmers of both sexes (111,112,115,116,117). Work rates were generally estimated from each subject's best 200-m time. The tests consisted of swimming for 2 min at a submaximal speed followed by swimming at the maximum velocity chosen. If exhaustion was not reached in 5 min, the velocity was increased by 0.1 m/sec. Exhaustion for all swimmers occurred between 2:15 and 7:35 min. Holmer's data for maximum oxygen uptakes ranges from 58-64 ml/kg/min for men and 45-51 ml/kg/min for women. Telemetered heart rates for both sexes were in the range of 182-192 bpm. Nadel (165) and Eriksson (68) present similar data for elite swimmers using the swimming flume. However, their protocols were discontinuous and Nadel's (165) purpose was to estimate the rate of heat loss in swimming man. This focus necessitated a prolonged period of submaximal work (30 min) before maximum oxygen uptake was attained.

These studies illustrate that the flume allows for a precise standardization of test protocol. However, the instrumentation has not been widely used due to the prohibitive costs of the equipment.

Tethered swim ergometry has been used to estimate the metabolic capabilities of recreational swimmers (76), age group swimmers (24), varsity swimmers (23,96,122,136,151,223), and highly trained national caliber swimmers (32,63,153,169). Maximum oxygen uptakes have been reported in the range of 55-60 ml/kg/min for groups of highly trained swimmers in these studies. Maximum heart rates were also similar to those reported for free and flume swimming. Minute ventilation, O_2 pulse, and cardiac output also have been reported in various studies to be similar to those attained by free and flume swimming tests.

Tethered swimming allows for a more precise determination of work rate than free swimming. Despite this feature, one common element to the aforementioned studies is the lack of a standardized loading schedule for the tethered swim test (see Protocol Selection). In addition, this ergometer has been criticized due to the fact that the hydrodynamic conditions imposed by the test situation differ from those in free and flume swimming (113,117). However, data from college swimmers (153) indicate that the correlations between free and tethered swimming are quite good ($r = 0.90$). Holmer, Lundin and Eriksson (117) also have reported that the oxygen uptakes during free and flume swimming were highly correlated ($r = 0.99$) and did not differ significantly from each other. In the only direct comparison using all three aquatic ergometers, Bonen et al. (32) have reported that flume swimming, free swimming and tethered swimming yield essential identical

oxygen uptake results. Their subjects, however, without exception preferred swimming in the flume to the tethered swim procedure.

Most previous physiological studies of swimming have emphasized the determination of oxygen uptake, heart rate, and respiratory function at peak work capacity. To date, no investigations have examined these parameters throughout the progression of a standardized maximal swimming test.

Protocol Selection

The examination of methods reported in previous work emphasizes the lack of standardization in the protocols of all three swimming exercise tests. Free swimming tests have employed stroke rate to adjust work output (159). Other free swimming tests have used a number of 200-m or 500-m swims (32,143,144) to elicit maximum work rates. Astrand (10,11) instructed subjects to swim at a rate of speed that would exhaust them in "3-4 min". It is obvious that work rate in a free swimming test can be adjusted so that maximum or near maximum metabolic capacity can be estimated. However, work levels cannot be standardized between subjects due to mechanical differences in stroke techniques as well as the individual differences in the perception of a maximal effort. This limitation would be even more apparent in marginally trained individuals.

Protocol selection for the swimming flume has involved estimation of swimming speeds based on 200-m times (112,117). Other methods have initiated the test at submaximal speeds and have increased velocities by increments ranging from .1 to .95 m/sec at various time intervals

(2 to 7 min) of the test (11,32,114,115,116,117,165). In addition, swimming flume tests have been continuous and discontinuous (165).

Tethered swim test have displayed even more disparity between test protocols. Initial loads have varied, ranging from 1 kg to 5 kg (63,76,96,122,151,153,169,204). Two reports do not detail initial loads (23,32). Tests have been continuous (32,133,204) and discontinuous (23,24,63,76,96,151,169). Work level times have ranges from 2 to 6 min. Loading increments of 1.1 kg (24,63,76,96,122,151,153,169,204), 1.4 kg (96), and 2.5 kg (23) have been used to increase the work loads at each level of testing. The addition of 1.1 to 2.5 kg near the beginning of a tethered swim test would have the desired effect of increasing the load on the working musculature. However, the addition of even 1.1 kg near the end of a test increases the possibility of terminating the swim due to local muscular fatigue rather than to the attainment of maximal working capacity. This contention is supported by Magel and Faulkner's (153) observation that their subjects seemed to be impaired by muscular distress before maximum oxygen uptake was attained.

The criterion of a plateau in oxygen uptake despite increasing work loads has been suggested to represent the attainment of a centrally-limited maximum oxygen uptake (67,202). Shephard et al. (202) has proposed that this plateau is reached with increments of oxygen uptake <0.15 l/min or 2.0 ml/kg/min from the penultimate to the final work load. Only one study has reported data showing a plateau in oxygen uptake during swimming (115). Shephard et al. (203) have contended that inadequate loading increments are the reason that a

plateau in oxygen consumption is not readily demonstrated during swimming tests. These observations are supported by the loading protocols examined in the literature.

Comparison of Swimmers by Sex, Distance, and Rank

Data for male and female trained swimmers has been presented in the same report by only a handful of investigators (16,24,32,68,111,117,122,143,189). The swimmers in these studies ranged in age from 16 to 20 years. The heights and weights reported were typical for active male and females of similar ages. Percentage of body fat has been reported in several studies. Values range from 8.3 to 10.8% for males and from 16 to 19% for females (116,121,165,170,172,210,211,221).

Differences in absolute peak oxygen uptake values range from 31% to 56% between male and female swimmers tested by flume (68,111,117) or free swimming (143). When expressed in terms relative to body weight, these differences in peak oxygen uptakes between males and females are reduced to 20-40% during flume swimming (68,111,117) and to 5-24% during free swimming (143). No reports examine the oxygen uptake data relative to fat-free mass.

To date, only one study has examined the metabolic capacity of well-trained female swimmers using tethered swimming. Bell (24) reports maximum oxygen uptakes of 2.8 l/min (52.3 ml/kg/min) which were 31% (19% relative to body weight) lower than values attained for similarly trained male swimmers. The subjects in this study were 15-16 year old age-group swimmers. No studies report data for male and female elite swimmers. Also, no investigations are reported examining

metabolic differences between male and female swimmers during the step-wise progression of work and subsequent recovery.

Most swimmers have been found to excel at either short (200-yd or less) or middle-distance (more than 200-yd) swimming events. Only on rare occasions have any excelled at the national or international level in both distance specialities. Few studies have attempted to distinguish physical and physiological characteristics of the distance specialities in swimming (29,121,173,203,219). Of these studies, two (121,219) present the body composition data for the same group of female swimmers, two (173,203) present physical and metabolic characteristics for only a small number of males and one (29) does not distinguish between the sexes. This paucity of information is surprising since the metabolic requirements of a "sprint" and "distance" event can be quite different.

One area of difficulty in the examination of differences in distance specialities lies in the categorization of a "sprint" or "distance" swimmer. Since the longest swimming race is generally 1650-yd, the time of completion for an average swimmer (19 min or less) does not metabolically qualify the event as a distance race (222). In addition, a decision must be made as to the assignment of swimmer who specializes in events of 400-yd (4 min) into a sprint or distance category. Finally, in many cases, despite swimming primarily short events, a swimmer will still be trained with an endurance program rather than a sprint training regimen. This may be true in females to a greater extent than in males.

In presenting anatomical characteristics of sprint and distance swimmers, Bloomfield and Sigersteth (29) used the coaches' subjective evaluations based on the number of times the swimmer could complete 100- and 200-yard efforts in an interval workout. This information was combined with a "drop-off" ratio computed from a 25-yd swimming time taken from a push-off start and the best official performance time for 200-yd to assign subjects to the sprint or distance group. Shephard et al. (205) tested male swimmers on a treadmill who competed in short-distance events (20-110 sec duration), middle-distance events (120-140 sec), or long-distance events (5-15 min). Their results demonstrate higher peak oxygen uptake values in distance swimmers than in sprint or middle-distance swimmers. Several investigators (121,173,219) did not report the criteria they used to categorize their subjects by distance. Ohkuwa et al. (173), using a cycle ergometer, found higher peak oxygen uptakes in distance swimmers than in sprinters. No other studies have compared the metabolic capacities of sprint and distance swimmers.

Comparisons have been made between the metabolic responses to work tests of recreational and trained swimmers (47,111,115,118,152). However, no investigations have attempted to distinguish between the metabolic capacities of swimmers within groups of highly trained, national caliber swimmers of either sex.

CHAPTER III

METHODS AND MATERIALS

The tethered swimming test used in the present study is similar in concept to the static swim reported by Van Huss and Cureton in 1955 (223). This device has been used by other investigators in a variety of forms and with numerous protocols (23,24,32,63,76,96,122, 151,153,169,204). However, the subjects, apparatus, technical personnel, metabolic measurements, test protocol and data analysis used in the present study all contribute to its uniqueness.

Overview

After entering the water, each subject was required to swim in order to maintain a specific position in the pool while a resistive force was exerted by a tethering device. Resistance was provided by an adjustable weight hung over the pool deck that was attached to the swimmer through a pulley system. The swimmer attempted to maintain a specified position (designated by markers in the pool) as weight gradually was added to impose an increasing workload. This stepwise increase in work load parallels the speed and/or gradient increases used during a progressive treadmill test. The tethered swim test was terminated when the subject was no longer able to meet the metabolic demands required to maintain position in the pool.

Subjects

The subjects for this study were 56 male and 67 female Caucasian swimmers who were selected to attend a two-week Olympic Development Camp at the United States Olympic Training Center in Colorado Springs, Colorado during the summer of 1979. The ages of the males ranged from 14 years 9 months to 22 years. The females ranged in age from 13 years 4 months to 22 years. The swimmers were selected subjectively by a national panel of coaches under the auspices of the U.S. Olympic Committee. All of the subjects had been involved in competitive swimming programs for a minimum of four years, with the older swimmers participating for as long as 12 years. Each subject trained 10 to 11 months of the year with daily swimming volumes ranging from 8,000 to 20,000 yards per day depending on the season as well as the nature (sprint or distance) of each swimmer's competitive events.

A written questionnaire was used to obtain information from each swimmer concerning his/her competitive background, training regimen, past performances and subjective self-evaluation of best event and present level of conditioning. To quantify the performance level of each subject, the fastest performance time in each swimmer's best event was expressed as a percentage of the existing American record for that stroke and distance. These quality ratings ranged from 100.5 to 109.5 for the males and from 100.0 to 112.3 for the females which provides clear evidence that the group consisted of highly trained, highly competitive swimmers.

Before any testing, the subjects were informed as to the purpose of the study, their extent of involvement, any known or potential

risks, and their right to terminate participation at will without penalty. Both the swimmer and a parent or guardian (in the case of a minor) expressed understanding by signing a statement of informed consent.

The height of each subject was measured prior to his/her arrival at the tethered swim test site. At the same time, skinfold measurements were made for the determination of percent fat and lean body weight (LBW) by the Sloan-Weir method (208). Weight was determined immediately prior to each test session on site.

Apparatus

The metabolic data were collected using a tethered swim ergometer. Although similar equipment has been previously described (32,153) several aspects of the apparatus employed in the present study are unique and contribute substantially to the efficiency of the ergometer. A canvas belt was fitted comfortably around the waist of the swimmer. Attached to each side of the belt were nylon cords which extended beyond the swimmer's feet where they were connected to the ends of a wooden dowel (90 cm in length, 2.5 cm in diameter). This harness arrangement permitted the subject to kick freely. Another nylon cord, attached to the center of the dowel, was passed backwards through a system of two low-friction plastic pulleys and was attached to a plastic bucket which served as a weight pan for the loading system. The pulleys were fixed to a metal frame and were arranged so that, although the bucket and the weights it contained hung vertically over the pool deck, the resistive force was applied horizontally along

the direction of the swimmer's movement slightly below the water's surface.

The metal frame which held the pulley and weight system was attached to an aluminum platform that was supported by four individually adjustable legs. The platform (7.32 m long) was situated diagonally across a corner of the pool with a clearance of 101 to 107 cm above the water surface. This platform, which was the primary supporting structure of the ergometer, defined the direction in which the tethered subject attempted to swim and served as a walkway above the subject. To accommodate components of the gas collection equipment (further described later), a trolley arrangement was attached to the side of the platform which allowed the gas collection apparatus to be maintained directly above the swimmer within the 2.5-m range of movement that was allowed by the tether.

The recording of accurate gas collection times, heart beats per collected expiratory bag, and respiratory expirations per bag were accomplished by means of a master control unit. Electrical signals from a direct lead ECG and a thermistor probe in the respiratory valve (details follow) were relayed to the control unit. An additional signal was transmitted to the control unit as a result of switching a two-way valve which controlled the selection of the collection bag for expired gas (details follow). As a result, once the tethered swim test was initiated, a technician was able to record the amount of the time expiratory gas was collected in each bag, the numbers of heart beats and expirations for each gas collection period, and the total elapsed time of the test.

The tethered swim apparatus was deployed on a permanent basis in an indoor pool. Water temperature (27-29° C) remained relatively constant throughout the study. Barometric pressures were obtained twice daily from the U.S. Weather Bureau station in Colorado Springs.

Personnel

Following are the job descriptions of the various technicians that were required to conduct a tethered swim test:

1. The responsibilities of the technician at the master control unit included the coordination of the entire test protocol. The person manning the control unit initiated the test, monitored the total elapsed time and individual gas-collection bag times, and relayed timing and loading information to the remainder of the test personnel. It was from this technician that the other stations took their cues to increase or decrease loading (see Test Protocol), to change gas-collection bags (see Metabolic Determinations), and to inform the subject of the test progress. In addition, the technician manning the control unit was responsible for recording the total time each gas sample was collected, the heart beats and expirations during each gas bag collection, and the elapsed time of the overall base, exercise and recovery periods.
2. A two-way switching valve was located above the swimmer on a trolley that was connected to the walkway (see Apparatus and Metabolic Determinations). The technician that was situated on the walkway was responsible for attaching gas-collection bags to the switching valve, changing the bags at appropriate

commands from the technician at the master control unit, and positioning the valve on the trolley to accommodate the swimmer's forward and backward movements. The switching valve was turned to change collection bags only on inspiration which was signaled by a light on the trolley that was triggered by the thermistor probe in the respiratory valve.

3. The loading progression and timing were predetermined using an estimate of the subject's maximum load (see Test Protocol). The technician responsible for loading responded to cues from the technician at the control unit to increase or to hold the resistance constant during each subsequent gas-collection period (30-s during exercise). The technician also was responsible for removing a bench from under the weight bucket and reducing the load by 0.5 kg at the beginning of the last 30-s collection period during exercise.
4. A technician in the water was responsible for getting the swimmer into the tether and the head piece which contained a respiratory valve. This technician established and maintained verbal communication with the subject to relay instructions regarding the swimmer's position in the tether and to offer encouragement during the test.
5. Adjustable, highly visible markers were submerged in front of the swimmer during the test to add a visual communication link informing the subject as to the progress of the test. The final 30-s exercise period ("sprint") was designated with a large red "S" to signal the beginning of a maximal 30-s

effort. The technician changing the markers took cues from the technician at the control unit.

6. A technician evacuated the gas collection bags and operated the gas analyzers (see Metabolic Determinations). This technician calibrated the gas analyzers before every subject and recorded gas analysis values for future calculations of metabolic data.
7. At least one technician was responsible for transporting the recently filled gas bags to the gas analysis station as well as for returning evacuated bags for reuse to the technician situated on the walkway.
8. A technician was responsible for the energy metabolism calculations.

Test Protocol

Each subject reported to the test site and was given the test on two separate occasions. In the first session, the subjects were given a detailed explanation of the equipment, the purpose of the test, possible implications of the results, and a step-by-step account of the test procedures. On both test occasions, the subjects were allowed a warm-up period followed by a period of orientation with the tethered swim equipment. Each swimmer was tethered without the gas-collection apparatus and allowed to swim against varying resistance. The gas-collection apparatus then was adjusted on each individual to both the technician's and the subject's satisfaction. Another period of tethered swimming followed to further familiarize the swimmer with the test situation. This adjustment period also provided opportunity to

examine the various components of the test apparatus ensuring proper functioning of the tether and gas-collection equipment.

Prior to the initiation of the first test and after the adjustment period, an estimation was made of the maximum load against which each swimmer could sustain position in the water. This was accomplished by instructing the subject to swim in the tether and to attempt to maintain position under the front end of the trolley while weight was progressively and rapidly added to the bucket in small increments. Markers positioned beneath the swimmer on the pool bottom, as well as laterally in the peripheral field of vision, established the target position. The total swim time for this preliminary estimation was limited to approximately 30-s to minimize the possibility of local muscular fatigue contaminating the results of the subsequent swimming test. The estimation concluded as soon as the subject began to lose position. The weight at termination was designated as the maximum load for that subject's first tethered swim test and was the basis for calculating the standard load progression for the swimmer (Appendix A).

Each test consisted of a base period, an exercise period, and a recovery period. The base period was 5 min in duration with the work load being held constant at only 25% of the subject's estimated maximum load. During the base period, expired gas was collected in 60-s intervals beginning at the third minute. At the end of the base period, an increment of weight was added and a visual signal was given to the subject to indicate the beginning of the exercise period. After each subsequent 30-s interval, the load was either held constant or increased according to the previously calculated loading progression

(Appendix A). The objective of the loading progression was to gradually build the work load in increasingly smaller increments as the swimmer approached maximal effort. The loading progression was designed for each subject with the expectation that the estimated maximum load would be encountered during the last 30-s of the fifth min of exercise. During the exercise test, the actual maximum load was determined as that which was in the loading bucket (including the bucket itself) when the swimmer finally was pulled backwards 2 m so that the bucket came to rest on a bench 50 cm in height. The 30-s gas collection period during which the bucket came to rest on the bench was completed and was designated as the penultimate exercise period. Upon completion of this period, the bench was taken from beneath the weight bucket and 0.5 kg of weight was removed. The swimmer then was encouraged verbally to exercise for an additional 30-s and to attempt to regain his original position under the front end of the trolley. This final 30-s exercise period was, in each case, considered to be a maximal effort by the subject. The purpose of the bench removal and the reduction in resistance during the last 30-s exercise period was twofold: (a) to ensure a continued maximal effort since, without the bench, the weight would still be supported by the swimmer; and (b) to allow the swimmer a "fighting chance" to advance his/her position in the tether while avoiding test termination due to local muscular fatigue rather than maximal metabolic effort.

For each subject's second swim test, the estimation of the maximum load was eliminated. Alternatively, the actual maximum load that was determined during the first test was used for the calculation of the load progression in the second test.

Due to time restrictions, the recovery period in the first test was limited to 5 min while the subsequent test included a 15-min recovery. In both cases, the work load was reduced to the level of the base period immediately following the last 30-s exercise period. That load was retained for the duration of the recovery period. Collection of expired gas proceeded in 30-s intervals for the initial 2 min of recovery and in 60-s intervals for the remainder of the period.

Metabolic Determinations

Metabolic measurements were determined by means of open-circuit spirometry utilizing the Douglas bag method. The swimmers were fitted with a rubber mouthpiece that was attached to a low-resistance two-way respiratory valve similar to the type described by Daniels (58). The valve was built into an adjustable headpiece that was held secure by an adjustable band around the head and by a strap under the chin. A noseclip was used to prevent expiration through the nose. To avoid leakage of water into the system, lengths of flexible corrugated plastic tubing (diameter 2.5 cm) were attached to both the inspiratory and expiratory sides of the respiratory valve. The expiratory tubing was attached to a two-way switching valve which was suspended directly over the subject on the trolley that was attached to the main platform. The length of the tubing from the expiratory side of the respiratory valve to the two-way valve on the trolley remained constant throughout the study because the height of the platform and trolley from the water surface could be adjusted to correct for any fluctuations in the water level of the pool. Expired gas samples were

collected continuously in neoprene meteorological balloons (120 liter, Kaysam Corporation of America, 27 Kentucky Avenue, Paterson, NJ) that were attached to each outflow side of the two-way switching valve on the trolley and were suspended upward and outward by metal struts. There was no noticeable back pressure in the breathing valve and gas-collection system, nor were any substantial difficulties in swimming encountered with the apparatus.

Expired pulmonary volumes were measured by evacuating the collection bags through a calibrated dry gas meter (Singer, American Meter Company, Model DTM-11). The CO_2 output and the O_2 uptake were calculated from the volume and composition of the expired gas. Gas analyses were performed using oxygen (Beckman OM-14) and carbon dioxide (Beckman LB2) analyzers. Helium was used to set the zero point of the analyzers. The gas analyzers were calibrated before each subject using helium and a standard gas sample that had been analyzed previously (17.78% O_2 and 4.31% CO_2) with a Haldane Chemical Analyzer (Arthur H. Thomas Co., Philadelphia, PA). All expired air was analyzed within 10 min of collection. Gas volumes were corrected to STPD.

Heart and respiration rates were monitored continuously during the base, exercise and recovery periods. Heart rate measurements were made electrocardiographically. Before each test session, adhesive-mounted surface electrodes were placed over the seventh rib intercostal space on each side of the midaxillary line. This placement was found to produce the clearest signal during swimming. The heart rate signals were transmitted to the main control unit where the number of beats per

respiratory bag was recorded and the heart rate per minute was calculated. To determine ventilatory frequency, a thermistor probe was mounted within the respiratory valve. This probe reacted to changes in gas temperature during inspiration and expiration. The signal was transmitted to the master control unit where respirations per bag were recorded. In addition, the signal was transmitted to the trolley which held the two-way switching valve that regulated expired gas collection. At this point, a light was activated upon the initiation of each inspiration thus enabling a bag change to take place at a point in the respiratory cycle where no expired gas sample would be lost.

All energy metabolism measures were determined by standard techniques of open-circuit spirometry on each expired gas bag that was collected during the base, exercise, and recovery periods. Reported energy metabolism variables included the peak oxygen uptake (peak $\dot{V}O_2$), 15-min net oxygen debt, and 2-min net oxygen debt as well as the following parameters obtained at peak $\dot{V}O_2$: minute ventilation (\dot{V}_E), respiratory frequency, ventilation per respiration (\dot{V}_E/resp), oxygen uptake per respiration (O_2/resp), heart rate (HR), oxygen pulse, respiratory exchange ratio (RER), and ventilatory equivalent ($\dot{V}_E/\dot{V}O_2$). In addition, the following variables were created from the previously determined metabolic parameters:

1. Steady state $\dot{V}O_2$ (ml/kg/min) -- defined as the mean of the $\dot{V}O_2$ (ml/kg/min) in the last five exercise bags (the last 2.5 min of exercise). This period roughly corresponded to a plateauing of the oxygen uptake curve when plotted bag by bag.

2. Percentage of peak steady state $\dot{V}O_2$ -- defined as (steady state $\dot{V}O_2$ /peak $\dot{V}O_2$) x 100.
3. Initial rate of $\dot{V}O_2$ -- defined as the rate of increase in oxygen uptake from the initiation of exercise until the end of the second minute.

Heart rate, RER, and oxygen uptake work/recovery curves were constructed for the comparison groups. During the base and recovery periods, the values of each of these variables were determined for each bag of expired gas. The data were pooled by comparison groups. This was easily accomplished because each test produced the same number of expired gas bags for each of these periods. However, the length of the exercise period, although designed to last for approximately five minutes, varied from 3.5 to 7 min between individuals. For this reason, when constructing the work/recovery curves, each exercise period was standardized to 5 min. This was accomplished by using each subject's last five bags of expired gas during exercise to determine the values for the last 2.5 min of exercise. The first 2.5 min of exercise were treated in the same way. Each subject's first five bags of expired gas were used. This procedure standardized the effective work period for each subject at five minutes for purposes of comparative data analysis.

Statistical Analysis

All descriptive values are presented as means \pm standard errors. The following three independent variables were chosen: sex, distance (sprint -- 200 yards and less versus middle-distance -- over 200 yards), and rank (upper 20% -- those swimmers ranked in the upper 20%

of their group based on a quality rating versus lower 20% -- those swimmers ranked in the lower 20% of their group based on the quality rating). Data for both the distance and rank variables were obtained from a written questionnaire. Each swimmer was asked to list his/her best event and performance time in that event. From this information, the subjects were classified into one of the two distance categories. A quality rating then was determined by expressing the swimmer's best time as a percentage of the existing American record in his/her event. The upper and lower 20%, based on this quality rating, were designated as the comparison groups for the independent variable rank. For distance and rank, the male and female data were analyzed separately. One-way analysis of variance was used (Statistical Package for the Social Sciences). The dependent variables included physical characteristics, energy metabolism parameters (absolute and relative), and values obtained during each 60-s or 30-s gas collection period of base, exercise, and recovery (heart rate, RER, and oxygen uptake). Statistical significance was set at the .10 level. This level was chosen due to the high degree of performance homeogeneity between the comparison groups within each sex as well as the desire to minimize the possibility of making a type II statistical error at this early stage of tethered swim investigation.

CHAPTER IV

RESULTS AND DISCUSSION

Results

This chapter will be divided into four sections. Selected physical characteristics of the subjects will be examined first. Next will follow a presentation of metabolic parameters obtained at the time of peak oxygen consumption. The third section will address the work/recovery curves for oxygen consumption, heart rates and respiratory exchange ratio's obtained during each gas-collection period. Data will be presented in absolute and relative terms where appropriate. Within each of the first three sections, the data will be analyzed using sex, distance, and rank as independent variables. The final section of this chapter will be a discussion of the more important results.

Physical Characteristics

Sex

Table 1 contains the physical characteristics of the male and female swimmers used in this study. As expected, there are highly significant differences between the sexes in height, weight, percentage of body fat, and lean body weight (LBW) with the males being taller, heavier and leaner than the females. Although the two groups were reasonably similar in age, the males were significantly older.

Distance

Table 2 presents the physical characteristics of the swimmers when distance is used as the independent variable. In this table, and in subsequent analyses where sex is eliminated, the data are dichotomized within each sex. For the variable distance, "short" designates swimmers whose best events were 200 yards or less and "middle" designates swimmers whose best events were over 200 yards in length. The sample contained no real "long-distance" or "distance" swimmers although the training regimens of all subjects provided extensive aerobic work. The longest event was 1650 yards which is a middle-distance event as it takes approximately 15 min for men and 16 min for women to complete. For the females, Table 2 shows that there were no significant differences between the short- and middle-distance groups in any of the selected physical characteristics. Male swimmers also showed little difference between the short- and middle-distance groups (Table 2). Although both male groups were approximately the same weight, the sprint group had significantly less body fat than did the middle-distance group.

Rank

The data in Table 3 represent the physical characteristics of the swimmers when grouped according to each swimmer's best time expressed as a percentage of the existing American record in his or her best event. Swimmers were included in this analysis if they were rated in the top or bottom 20% of the males or females tested. As in the analysis based on distance, there were no significant differences between groups in the physical characteristics of the female swimmers.

TABLE 1. Physical Characteristics of Subjects

	Males	Females	F-Ratio	P-Value
Age (months)	217 \pm 2.3 (55)	202 \pm 2.2 (66)	20.036	.000
Height (cm)	181 \pm 0.9 (54)	170 \pm 0.6 (65)	113.292	.000
Weight (kg)	73.0 \pm 0.9 (55)	60.4 \pm 0.7 (66)	123.214	.000
Fat %	9.5 \pm 0.27 (55)	18.8 \pm 0.29 (66)	586.309	.000
LBW (kg)	66.3 \pm 0.76 (55)	48.9 \pm 0.48 (66)	295.847	.000

TABLE 2. Physical Characteristics of Subjects by Distance

	Males				Females			
	Short	Middle	F-Ratio	P-Value	Short	Middle	F-Ratio	P-Value
Age (months)	217 ± 2.9 (38)	216 ± 3.9 (17)	.055	.816	204 ± 2.9 (45)	199 ± 2.9 (21)	1.015	.318
Height (cm)	181 ± 1.1 (37)	180 ± 1.5 (17)	.114	.738	170 ± 0.7 (44)	169 ± 1.2 (21)	.329	.568
Weight (kg)	72.8 ± 1.03 (38)	73.2 ± 1.6 (17)	.037	.849	61.0 ± 0.9 (45)	59.0 ± 1.2 (21)	1.646	.204
Fat %	8.6 ± 0.29 (38)	10.2 ± 0.51 (17)	8.504	.005	18.9 ± 0.35 (45)	18.6 ± 0.52 (21)	.336	.564
LBW (kg)	66.5 ± 0.92 (38)	65.7 ± 1.37 (17)	.282	.597	49.4 ± 0.61 (45)	48.0 ± 0.76 (21)	1.813	.183

TABLE 3. Physical Characteristics of Subjects by Rank

	Males				Females			
	Upper 20%	Lower 20%	F-Ratio	P-Value	Upper 20%	Lower 20%	F-Ratio	P-Value
Age (months)	236 ± 4.6 (12)	206 ± 5.4 (9)	17.367	.001	205 ± 6.0 (14)	205 ± 3.1 (14)	.005	.942
Height (cm)	184 ± 1.7 (12)	179 ± 1.8 (9)	3.577	.074	170 ± 1.0 (14)	169 ± 1.5 (13)	.623	.437
Weight (kg)	78.3 ± 1.35 (12)	70.0 ± 2.08 (9)	12.426	.009	60.0 ± 1.56 (14)	59.1 ± 1.33 (14)	.197	.661
Fat %	10.0 ± 0.74 (12)	8.7 ± 0.82 (9)	1.340	.261	18.1 ± 0.64 (14)	19.0 ± 0.64 (14)	.998	.327
LBW (kg)	70.5 ± 1.36 (12)	63.7 ± 1.57 (9)	10.482	.004	49.0 ± 0.97 (14)	47.7 ± 0.78 (14)	1.018	.322

Male swimmers ranked in the top 20% of their group were significantly older, taller, and heavier than those ranked in the bottom 20%. The better males also had higher lean body weights. There was no significant difference in percentage of body fat between the two groups.

Energy Metabolism

Sex

Tables 4 and 5 present selected data on the energy metabolism of male and female swimmers during the tethered swim test. Table 4 contains absolute values of physiological variables while Table 5 expresses the data in terms relative to weight and LBW. As can be seen in Table 4, the male swimmers attained significantly higher metabolic values than did the females for peak $\dot{V}O_2$, 15- and 2-min net O_2 debt, \dot{V}_E , $\dot{V}_E/\text{resp.}$, $O_2/\text{resp.}$, O_2 pulse, RER, steady state $\dot{V}O_2$, and initial rate of $\dot{V}O_2$. Female swimmers reached significantly higher values for heart rate and % of peak steady state $\dot{V}O_2$ than did the males. No significant differences were recorded between sexes for respiratory frequency or ventilatory equivalent ($\dot{V}_E/\dot{V}O_2$).

The results in Table 5 show that significant differences between male and female swimmers were observed with regard to peak $\dot{V}O_2$, 15- and 2-min net O_2 debt, \dot{V}_E , $\dot{V}_E/\text{resp.}$, O_2 pulse and O_2/resp when these values are expressed relative to body weight. The differences parallel those seen in Table 4 where the same variables are expressed in absolute terms. However, when the data are expressed relative to lean body weight (LBW), there is no significant difference between the

TABLE 4. Physiological Variables for Male and Female Subjects During Tethered Swimming

	Males	Females	F-Ratio	P-Value
Peak $\dot{V}O_2$ (l/min)	4.43 \pm 0.062 (54)	3.20 \pm 0.039 (65)	299.873	.000
15 min net O ₂ debt (l)	6.59 \pm 0.237 (47)	4.17 \pm 0.133 (57)	86.210	.000
2 min net O ₂ debt (l)	3.13 \pm 0.088 (53)	2.03 \pm 0.046 (62)	92.988	.000
\dot{V}_E (l/min)*	108.59 \pm 2.086 (54)	78.46 \pm 1.365 (65)	154.776	.000
Resp Frequency*	53 \pm 1.7 (45)	54 \pm 1.5 (60)	.174	.677
\dot{V}_E /Resp (l/resp)	2.14 \pm 0.073 (46)	1.51 \pm 0.043 (60)	60.794	.000
O ₂ /Resp (ml/resp)*	87.71 \pm 3.236 (45)	61.88 \pm 1.788 (60)	55.158	.000
HR (bpm)*	174 \pm 1.2 (51)	180 \pm 1.2 (62)	11.674	.001
O ₂ pulse (ml/beat)*	25.60 \pm 0.397 (51)	17.98 \pm 0.251 (63)	283.240	.000
RER*	1.001 \pm 0.0115 (52)	0.965 \pm 0.0087 (62)	6.565	.012
Ventilatory equivalent* $\dot{V}_E/\dot{V}O_2$	24.56 \pm 0.359 (54)	24.55 \pm 0.310 (65)	.001	.976
Steady State $\dot{V}O_2$ (ml/kg/min)**	56.48 \pm 0.791 (54)	50.17 \pm 0.696 (65)	36.029	.000
%Peak Steady State $\dot{V}O_2$ **	92.40 \pm 0.547 (54)	94.38 \pm 0.410 (65)	8.633	.004
Initial Rate $\dot{V}O_2$ **	11.58 \pm 0.276 (54)	8.84 \pm 0.216 (54)	62.775	.000

*Values attained at peak $\dot{V}O_2$.

**See Text for definition.

TABLE 5. Physiological Variables at Peak $\dot{V}O_2$ Expressed Relative to Body Weight and Lean Body Weight (LBW) for Male and Female Subjects During Tethered Swimming

	Males	Females	F-Ratio	P-Value
Peak $\dot{V}O_2$ (ml/kg/min)	60.93 ± 0.691 (54)	53.25 ± 0.746 (65)	55.286	.000
(ml/kg LBW/min)	67.05 ± 0.813 (54)	65.55 ± 0.810 (65)	1.674	.198
15 min net O_2 debt (ml/kg)	90.7 ± 3.27 (47)	69.1 ± 2.32 (57)	30.420	.000
(ml/kg LBW)	99.73 ± 3.61 (47)	85.2 ± 2.75 (57)	10.687	.002
2 min net O_2 debt (ml/kg)	43.0 ± 1.14 (53)	36.7 ± 0.78 (62)	22.216	.000
(ml/kg LBW)	47.4 ± 1.28 (53)	45.2 ± 0.92 (62)	2.043	.156
\dot{V}_E (l/kg/min)	1.50 ± 0.029 (54)	1.31 ± 0.024 (65)	26.799	.000
(l/kg LBW/min)	1.65 ± 0.032 (54)	1.61 ± 0.028 (65)	.831	.364
\dot{V}_E /resp (ml/kg/resp)	29.6 ± 1.06 (46)	25.2 ± 0.75 (60)	12.280	.001
(ml/kg LBW/resp)	32.5 ± 1.13 (46)	31.0 ± 0.90 (60)	1.111	.294
O_2 pulse (ml/kg/beat)	351 ± 4.3 (51)	300 ± 4.8 (63)	59.853	.000
(ml/kg LBW/beat)	387 ± 4.9 (51)	369 ± 5.3 (63)	5.523	.021
O_2 /resp (ml/kg/resp)	1.21 ± 0.044 (45)	1.03 ± 0.031 (60)	11.656	.001
(ml/kg LBW/resp)	1.33 ± 0.047 (45)	1.27 ± 0.037 (60)	.997	.320

sexes for peak $\dot{V}O_2$, 2-min net O_2 debt, \dot{V}_E , \dot{V}_E/resp , or O_2/resp . Significant differences remain between males and females for the 15-min net O_2 debt and O_2 pulse expressed relative to LBW. Significant differences between metabolic data of male and female swimmers have been reported in part elsewhere (24,68,111,117,143,189). The considerable reduction of these differences when the data are expressed relative to LBW has not been well documented in swimmers and will be discussed subsequently.

Distance

Table 6 contains the metabolic data for male swimmers who specialized in either sprint events (200 yards and below) or middle-distance events (over 200 yards) expressed in absolute terms. These results show several significant differences. The middle-distance swimmers had higher values of peak $\dot{V}O_2$, respiratory frequency, and initial rate of O_2 uptake. The sprint swimmers recorded higher values for \dot{V}_E/resp and RER. The groups could not be distinguished statistically with any other metabolic variable. Further results are expressed in Table 7 relative to body weight and LBW. Male middle-distance swimmers, when compared to sprinters, had significantly higher peak $\dot{V}O_2$ values expressed relative to either body weight or to LBW. In addition, the middle-distance swimmers had significantly higher values for the 2-min net O_2 debt and O_2 pulse expressed relative to lean body weight. Due to the difference in respiratory frequency (Table 6), the sprint swimmers had significantly higher values for \dot{V}_E/resp expressed relative to both body weight and LBW.

TABLE 6. Physiological Variables for Male Subjects by Distance During Tethered Swimming

	Short	Middle	F-Ratio	P-Value
Peak $\dot{V}O_2$ (l/min)	4.35 \pm 0.073 (37)	4.59 \pm 0.109 (17)	3.187	.080
15 min net O ₂ debt (l)	6.65 \pm 0.287 (31)	6.73 \pm 0.432 (16)	.196	.660
2 min net O ₂ debt (l)	3.03 \pm 0.103 (36)	3.32 \pm 0.160 (17)	2.363	.128
\dot{V}_E (l/min)*	107.8 \pm 2.35 (37)	110.2 \pm 4.32 (17)	.282	.598
Resp Frequency*	51 \pm 2.1 (31)	57 \pm 2.3 (14)	3.709	.061
\dot{V}_E /Resp (l/resp)	2.23 \pm 0.094 (31)	1.95 \pm 0.092 (15)	3.676	.062
O ₂ /Resp (ml/resp)*	90.21 \pm 4.280 (31)	82.37 \pm 4.136 (14)	1.236	.272
HR (bpm)*	173 \pm 1.5 (36)	176 \pm 2.1 (15)	1.045	.312
O ₂ pulse (ml/beat)*	25.32 \pm 0.464 (36)	26.28 \pm 0.757 (15)	1.219	.275
RER*	1.02 \pm 0.014 (36)	0.97 \pm 0.017 (16)	3.290	.053
Ventilatory equivalent* $\dot{V}_E/\dot{V}O_2$	24.84 \pm 0.448 (32)	23.97 \pm 0.585 (16)	1.278	.263
Steady State $\dot{V}O_2$ (ml/kg/min)**	56.50 \pm 0.988 (32)	58.64 \pm 1.363 (16)	1.588	.214
%Peak Steady State $\dot{V}O_2$ **	92.71 \pm 0.713 (32)	92.64 \pm 0.947 (16)	.004	.951
Initial Rate $\dot{V}O_2$ **	11.09 \pm 0.277 (37)	12.64 \pm 0.568 (17)	7.702	.008

*Values attained at peak $\dot{V}O_2$.

**See Text for definition.

TABLE 7. Physiological Variables at Peak $\dot{V}O_2$ for Male Subjects Expressed Relative to Body Weight and Lean Body Weight (LBW) by Distance

	Short	Middle	F-Ratio	P-Value
Peak $\dot{V}O_2$ (ml/kg/min)	60.05 \pm 0.812 (37)	62.84 \pm 1.209 (17)	3.699	.060
(ml/kg LBW/min)	65.70 \pm 0.943 (37)	69.97 \pm 1.348 (17)	6.586	.013
15 min net O ₂ debt (ml/kg)	89.8 \pm 3.84 (31)	92.3 \pm 6.21 (16)	.135	.715
(ml/kg LBW)	98.3 \pm 4.22 (31)	102.3 \pm 6.89 (16)	.364	.549
2 min net O ₂ debt (ml/kg)	41.9 \pm 1.35 (36)	45.4 \pm 2.05 (17)	2.143	.149
(ml/kg LBW)	45.9 \pm 1.48 (36)	50.6 \pm 2.33 (17)	3.146	.082
\dot{V}_E (l/kg/min)	1.49 \pm 0.035 (37)	1.51 \pm 0.053 (17)	.064	.802
(l/kg LBW/min)	1.63 \pm 0.038 (37)	1.68 \pm 0.059 (14)	.461	.500
\dot{V}_E /resp (ml/kg/resp)	31.1 \pm 1.41 (31)	26.6 \pm 1.13 (15)	4.270	.045
(ml/kg LBW/resp)	34.0 \pm 1.51 (31)	29.6 \pm 1.24 (15)	3.535	.067
O ₂ pulse (ml/kg/beat)	348 \pm 5.3 (36)	359 \pm 7.4 (15)	1.442	.236
(ml/kg LBW/beat)	381 \pm 5.9 (36)	401 \pm 8.1 (15)	3.490	.068
O ₂ /resp (ml/kg/resp)	1.25 \pm 0.058 (31)	1.12 \pm 0.051 (14)	1.815	.185
(ml/kg LBW/resp)	1.37 \pm 0.063 (31)	1.25 \pm 0.057 (14)	1.288	.263

TABLE 8. Physiological Variables for Female Subjects by Distance During Tethered Swimming

	Short	Middle	F-Ratio	P-Value
Peak $\dot{V}O_2$ (l/min)	3.17 \pm 0.051 (44)	3.26 \pm 0.054 (21)	1.258	.266
15 min net O ₂ debt (l)	4.13 \pm 0.153 (38)	4.24 \pm 0.264 (19)	.157	.694
2 min net O ₂ debt (l)	2.18 \pm 0.051 (41)	2.26 \pm 0.094 (21)	.763	.386
\dot{V}_E (l/min)*	79.14 \pm 1.789 (44)	77.03 \pm 1.973 (21)	.571	.473
Resp Frequency*	56 \pm 2.0 (43)	48 \pm 1.43 (17)	6.097	.017
\dot{V}_E /Resp (l/resp)	1.48 \pm 0.057 (43)	1.58 \pm 0.048 (17)	1.088	.301
O ₂ /Resp (ml/resp)*	59.52 \pm 2.272 (43)	67.85 \pm 2.054 (17)	4.692	.034
HR (bpm)*	180 \pm 1.5 (42)	178 \pm 2.1 (20)	.409	.525
O ₂ pulse (ml/beat)*	17.86 \pm 0.344 (43)	18.24 \pm 0.330 (20)	.499	.483
RER*	0.968 \pm 0.0108 (42)	0.962 \pm 0.0144 (21)	.097	.757
Ventilatory equivalent* $\dot{V}_E/\dot{V}O_2$	24.94 \pm 0.377 (44)	23.68 \pm 0.503 (21)	3.563	.064
Steady State $\dot{V}O_2$ (ml/kg/min)**	48.99 \pm 0.732 (84)	52.64 \pm 1.290 (21)	6.503	.013
%Peak Steady State $\dot{V}O_2$ **	94.08 \pm 0.539 (44)	95.00 \pm 0.573 (21)	1.110	.296
Initial Rate $\dot{V}O_2$ **	9.03 \pm 0.250 (43)	8.51 \pm 0.448 (20)	1.217	.274

*Values attained at peak $\dot{V}O_2$.

**See Text for definition.

TABLE 9. Physiological Variables at Peak $\dot{V}O_2$ for Female Subjects Expressed Relative to Body Weight and Lean Body Weight (LBW) by Distance

	Short	Middle	F-Ratio	P-Value
Peak $\dot{V}O_2$ (ml/kg/min)	52.11 \pm 0.835 (44)	55.62 \pm 1.401 (21)	5.149	.027
(ml/kg LBW/min)	64.27 \pm 0.926 (44)	68.23 \pm 1.455 (21)	5.551	.022
15 min net O_2 debt (ml/kg)	67.49 \pm 2.691 (38)	72.29 \pm 4.408 (19)	.956	.333
(ml/kg LBW)	83.38 \pm 3.166 (38)	88.77 \pm 5.321 (19)	.853	.360
2 min net O_2 debt (ml/kg)	35.73 \pm 0.862 (41)	38.47 \pm 1.537 (21)	2.817	.099
(ml/kg LBW)	44.13 \pm 1.010 (41)	47.21 \pm 1.836 (21)	2.563	.115
\dot{V}_E (l/kg/min)	1.30 \pm 0.030 (44)	1.31 \pm 0.032 (12)	.041	.841
(l/kg LBW/min)	1.61 \pm 0.035 (44)	1.61 \pm 0.046 (12)	.008	.929
\dot{V}_E /resp (ml/kg/resp)	24.39 \pm 0.948 (43)	27.23 \pm 0.955 (17)	3.045	.086
(ml/kg LBW/resp)	30.11 \pm 1.159 (43)	33.36 \pm 1.105 (17)	2.705	.106
O_2 pulse (ml/kg/beat)	294.1 \pm 5.87 (43)	313.2 \pm 7.78 (20)	3.599	.063
(ml/kg LBW/beat)	362.7 \pm 6.44 (43)	383.0 \pm 8.41 (20)	3.660	.060
O_2 /resp (ml/kg/resp)	0.979 \pm 0.0373 (43)	1.166 \pm 0.0434 (17)	8.476	.005
(ml/kg LBW/resp)	1.208 \pm 0.0457 (43)	1.427 \pm 0.0435 (17)	7.944	.007

The metabolic results for the female subjects categorized by swimming distance are shown in absolute terms in Table 8 and in relative terms in Table 9. In contrast to the male swimmers, there was no significant difference between female short and middle-distance swimmers for peak $\dot{V}O_2$ in l/min. A comparison of the respiratory frequencies of the sprint and middle-distance female swimmers shows that the sprinters had higher respiratory rates (Table 8). This result is contrary to that found in the male subjects (Table 6). Other significant differences shown in Table 8 are higher O_2 /resp and higher steady state oxygen uptake values for the female middle-distance swimmers. The female sprinters recorded significantly higher ventilatory equivalents than did the middle-distance subjects.

Table 9 contains selected metabolic data for female sprint and middle-distance swimmers in relative terms. As was true for the males (Table 7), when peak $\dot{V}O_2$ is expressed relative to either body weight or LBW, the values for the female middle-distance swimmers are significantly higher than are those for the female sprinters. The middle-distance subjects also had significantly higher values than did the sprinters in 2-min net O_2 debt and \dot{V}_E /resp expressed relative to body weight as well as in O_2 pulse and O_2 /resp expressed relative to both body weight and LBW.

Rank

Selected metabolic data also were compared within each sex for differences between swimmers whose quality rating placed them in the top and bottom 20% of the available subjects. Table 10 shows these results for males expressed in absolute terms. Statistically

TABLE 10. Physiological Variables for Male Subjects by Rank During Tethered Swimming

	Upper 20%	Lower 20%	F-Ratio	P-Value
Peak $\dot{V}O_2$ (l/min)	4.66 ± 0.130 (12)	4.27 ± 0.128 (9)	4.294	.052
15 min net O ₂ debt (l)	6.85 ± 0.535 (11)	6.65 ± 0.348 (7)	.074	.789
2 min net O ₂ debt (l)	3.39 ± 0.135 (12)	2.83 ± 0.199 (9)	5.917	.025
\dot{V}_E (l/min)*	115.2 ± 3.57 (12)	108.8 ± 2.63 (9)	1.816	.194
Resp Frequency*	53 ± 3.0 (10)	51 ± 3.9 (9)	.190	.669
\dot{V}_E /Resp (l/resp)	2.21 ± 0.121 (10)	2.28 ± 0.225 (9)	.081	.780
O ₂ /Resp (ml/resp)*	90.3 ± 6.01 (10)	89.2 ± 8.96 (9)	.011	.918
HR (bpm)*	172 ± 1.7 (12)	174 ± 2.3 (8)	.219	.645
O ₂ pulse (ml/beat)*	27.03 ± 0.759 (12)	25.03 ± 0.915 (8)	2.836	.109
RER*	0.981 ± 0.0269 (11)	1.009 ± 0.0198 (9)	.646	.432
Ventilatory equivalent* $\dot{V}_E/\dot{V}O_2$	24.78 ± 0.545 (12)	25.62 ± 0.855 (9)	.763	.397
Steady State $\dot{V}O_2$ (ml/kg/min)**	54.81 ± 1.731 (12)	58.20 ± 1.558 (9)	1.967	.177
§Peak Steady State $\dot{V}O_2$ **	91.21 ± 1.169 (12)	94.98 ± 0.619 (9)	6.679	.018
Initial Rate $\dot{V}O_2$ **	11.82 ± 0.668 (12)	11.63 ± 0.552 (9)	.041	.842

*Values attained at peak $\dot{V}O_2$.

**See Text for definition.

TABLE 11. Physiological Variables at Peak $\dot{V}O_2$ for Male Subjects Expressed Relative to Body Weight and Lean Body Weight (LBW) by Rank

	Upper 20%	Lower 20%	F-Ratio	P-Value
Peak $\dot{V}O_2$ (ml/kg/min)	59.54 \pm 1.571 (12)	61.18 \pm 1.443 (9)	.553	.466
(ml/kg LBW/min)	66.25 \pm 1.887 (12)	67.06 \pm 1.570 (9)	.100	.756
15 min net O_2 debt (ml/kg)	87.20 \pm 6.542 (11)	95.11 \pm 4.955 (7)	.747	.400
(ml/kg LBW)	97.02 \pm 7.287 (11)	104.37 \pm 5.345 (7)	.518	.482
2 min net O_2 debt (ml/kg)	43.32 \pm 1.563 (12)	40.49 \pm 2.809 (9)	.877	.361
(ml/kg LBW)	48.25 \pm 1.919 (12)	44.40 \pm 3.090 (9)	1.237	.280
\dot{V}_E (l/kg/min)	1.47 \pm 0.036 (12)	1.56 \pm 0.053 (9)	2.303	.146
(l/kg LBW/min)	1.64 \pm 0.041 (12)	1.71 \pm 0.051 (9)	1.469	.240
\dot{V}_E /resp (ml/kg/resp)	28.4 \pm 1.70 (10)	32.9 \pm 3.47 (9)	1.451	.245
(ml/kg LBW/resp)	31.6 \pm 1.81 (10)	39.9 \pm 3.60 (9)	1.210	.287
O_2 pulse (ml/kg/beat)	346 \pm 9.3 (12)	354 \pm 12.8 (8)	.320	.578
(ml/kg LBW/beat)	384 \pm 10.7 (12)	389 \pm 13.5 (8)	.079	.782
O_2 /resp (ml/kg/resp)	1.16 \pm 0.084 (10)	1.28 \pm 0.130 (9)	.622	.441
(ml/kg LBW/resp)	1.30 \pm 0.092 (10)	1.40 \pm 0.137 (9)	.432	.521

significant differences were observed for peak $\dot{V}O_2$ and 2-min net O_2 debt with higher values found for those swimmers in the top 20% than in those ranked in the bottom 20%.

When the metabolic data were expressed relative to body weight and LBW (Table 11), no differences were revealed between the swimmers ranked in the top 20% and those ranked in the bottom 20% of the male subjects.

The metabolic data of the female swimmers also were examined for differences between groups based on rank in both absolute (Table 12) and relative terms (Table 13). These tables show that there were no statistically significant differences, in either absolute or relative terms, between the female swimmers ranked in the top 20% and those ranked in the bottom 20%.

Work and Recovery Curves

This section will present data obtained during each interval of gas collection throughout the base, exercise, and recovery periods of the tethered swim. Values for oxygen uptake, HR and RER and analyzed by sex, distance, and rank.

Sex

Figure 1 shows the oxygen uptake in ml/kg/min for the male and female swimmers determined throughout the tethered swimming test. Values are given for the base period, for each 30-s gas collection interval during exercise and the first 2 min of recovery, and for each 60-s interval during the remainder of the 15-min recovery period. As expected, the male swimmers attained significantly higher oxygen uptake values during every time interval. The males were 14% higher than the

TABLE 12. Physiological Variables for Female Subjects by Rank During Tethered Swimming

	Upper 20%	Lower 20%	F-Ratio	P-Value
Peak $\dot{V}O_2$ (l/min)	3.18 \pm 0.090 (14)	3.18 \pm 0.093 (13)	.001	.973
15 min net O ₂ debt (l)	4.23 \pm 0.343 (12)	3.74 \pm 0.191 (12)	1.602	.219
2 min net O ₂ debt (l)	2.23 \pm 0.121 (13)	2.15 \pm 0.100 (13)	.312	.582
\dot{V}_E (l/min)*	78.9 \pm 3.016 (14)	80.7 \pm 3.24 (13)	.152	.700
Resp Frequency*	54 \pm 3.0 (12)	55 \pm 3.1 (13)	.015	.903
\dot{V}_E /Resp (l/resp)	1.46 \pm 0.077 (12)	1.54 \pm 0.104 (13)	.309	.584
O ₂ /Resp (ml/resp)*	59.67 \pm 3.520 (12)	61.31 \pm 4.626 (13)	.078	.783
HR (bpm)*	180 \pm 3.0 (11)	183 \pm 2.1 (13)	.663	.424
O ₂ pulse (ml/beat)*	18.33 \pm 0.781 (12)	17.42 \pm 0.489 (13)	1.009	.326
RER*	0.988 \pm 0.0196 (12)	0.973 \pm 0.0192 (13)	.290	.595
Ventilatory equivalent* $\dot{V}_E/\dot{V}O_2$	24.85 \pm 0.729 (14)	25.33 \pm 0.684 (13)	.232	.634
Steady State $\dot{V}O_2$ (ml/kg/min)**	50.54 \pm 0.687 (14)	93.29 \pm 1.159 (13)	.001	.979
%Peak Steady State $\dot{V}O_2$ **	95.08 \pm 1.583 (14)	50.60 \pm 1.631 (13)	1.182	.190
Initial Rate $\dot{V}O_2$ **	8.49 \pm 0.613 (14)	9.14 \pm 0.569 (13)	.598	.447

*Values attained at peak $\dot{V}O_2$.

**See Text for definition.

TABLE 13. Physiological Variables at Peak $\dot{V}O_2$ for Female Subjects Expressed Relative to Body Weight and Lean Body Weight (LBW) by Rank

	Upper 20%	Lower 20%	F-Ratio	P-Value
Peak $\dot{V}O_2$ (ml/kg/min)	53.27 ± 1.553 (14)	54.36 ± 1.936 (13)	.196	.661
(ml/kg LBW/min)	65.03 ± 1.788 (14)	67.15 ± 2.085 (13)	.601	.445
15 min net O_2 debt (ml/kg)	69.58 ± 5.773 (12)	63.56 ± 3.943 (12)	.742	.398
(ml/kg LBW)	85.57 ± 7.004 (12)	78.59 ± 4.519 (12)	.697	.413
2 min net O_2 debt (ml/kg)	36.93 ± 1.809 (13)	37.72 ± 1.979 (13)	.006	.937
(ml/kg LBW)	45.30 ± 2.244 (13)	45.33 ± 2.268 (13)	.000	.991
\dot{V}_E (l/kg/min)	1.32 ± 0.040 (14)	1.38 ± 0.068 (13)	.654	.426
(l/kg LBW/min)	1.61 ± 0.050 (14)	1.71 ± 0.079 (13)	1.082	.308
\dot{V}_E /resp (ml/kg/resp)	24.7 ± 1.32 (12)	26.0 ± 1.50 (13)	.438	.515
(ml/kg LBW/resp)	30.1 ± 15.7 (12)	32.2 ± 1.93 (13)	.753	.394
O_2 pulse (ml/kg/beat)	311 ± 15.9 (12)	298 ± 10.8 (13)	.490	.491
(ml/kg LBW/beat)	379 ± 17.8 (12)	368 ± 11.4 (13)	.287	.597
O_2 /resp (ml/kg/resp)	1.01 ± 0.064 (12)	1.04 ± 0.066 (13)	.081	.779
(ml/kg LBW/resp)	1.23 ± 0.076 (12)	1.28 ± 0.85 (13)	.230	.636

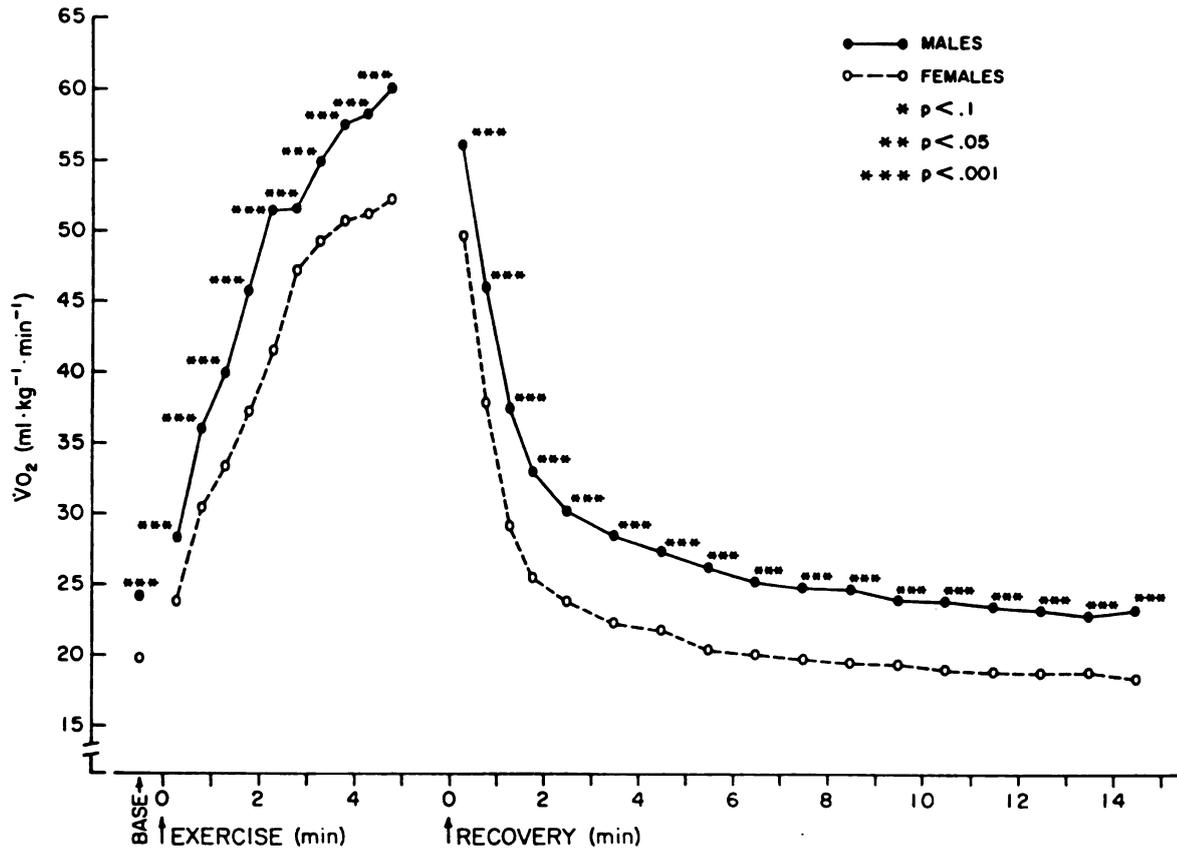


Figure 1.--Mean Oxygen Uptakes (ml/kg/min) for Male and Female Swimmers During Exercise and Recovery.

females at the peak oxygen uptake and 25-28% higher than the females throughout recovery.

Expressing the oxygen uptake data relative to lean body weight (data not shown) greatly diminishes the sex differences. However, small but consistent differences still were observed between the male and female subjects during the last several stages of exercise and during recovery.

The heart rate curves for the males and females are found in Figure 2. The females attained significantly higher heart rates than did the males during the last 2.5 min of exercise and during the first 30-s of recovery (179 ± 1.1 vs 174 ± 1.3 bpm at peak) ($p < .001$). Figure 2 also shows slightly higher heart rates in the males than in the females during recovery. This pattern, although statistically significant during only two time periods, is quite consistent throughout the recovery.

The respiratory exchange ratio (RER) data for the male and female swimmers during work and recovery are seen in Figure 3. The values for the males generally were higher than those for the females during the initial and final stages of the exercise bout. Significant differences were reached between the 1.5 to 2.5 min points ($p < .05$) and during the final min of exercise ($p < .1$). With one exception during recovery, the male swimmers continually recorded higher RER's than did the females (Fig. 3). These differences were statistically significant at the 30-s, 2-min, 3-min, 9-min and 14-min recovery points ($p < .1$). During exercise, the male swimmers reached a peak RER of $.99 \pm .001$ while the females peaked at $.96 \pm .008$. However, during the initial

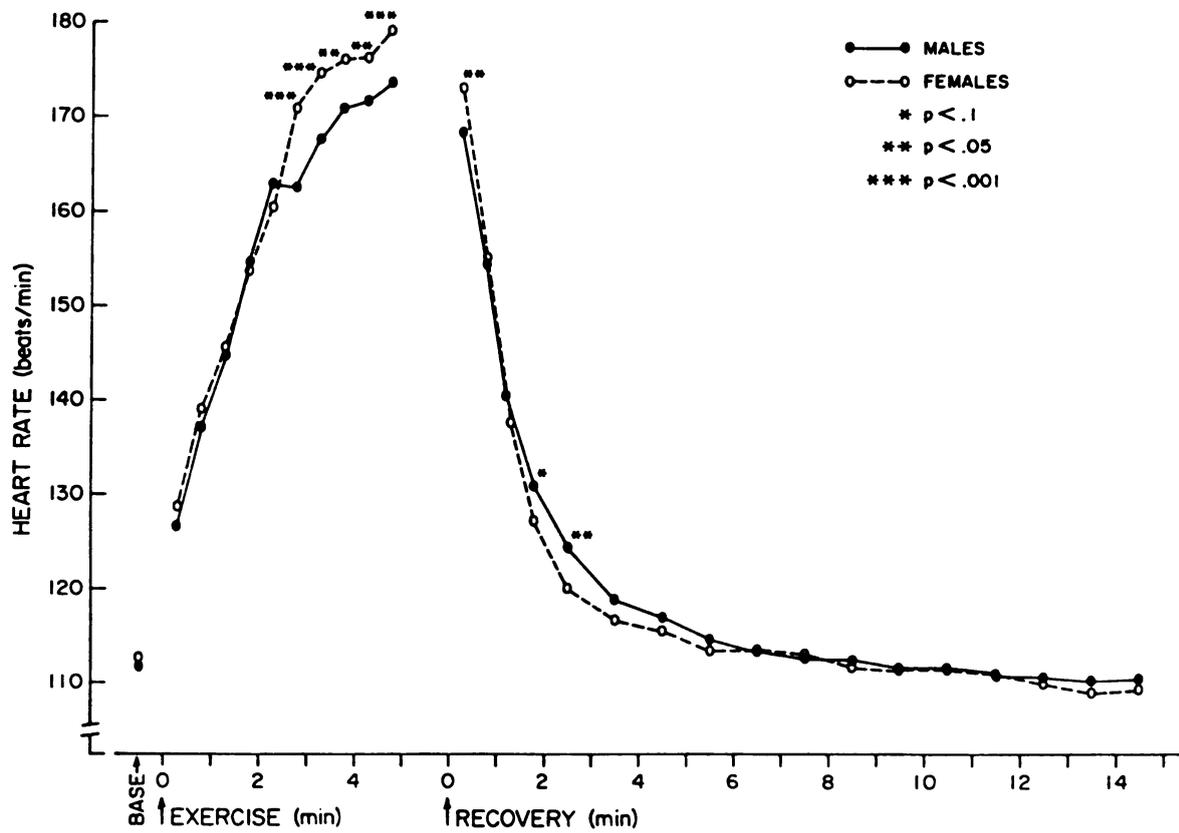


Figure 2.--Mean Heart Rates (beats/min) for Male and Female Swimmers During Exercise and Recovery.

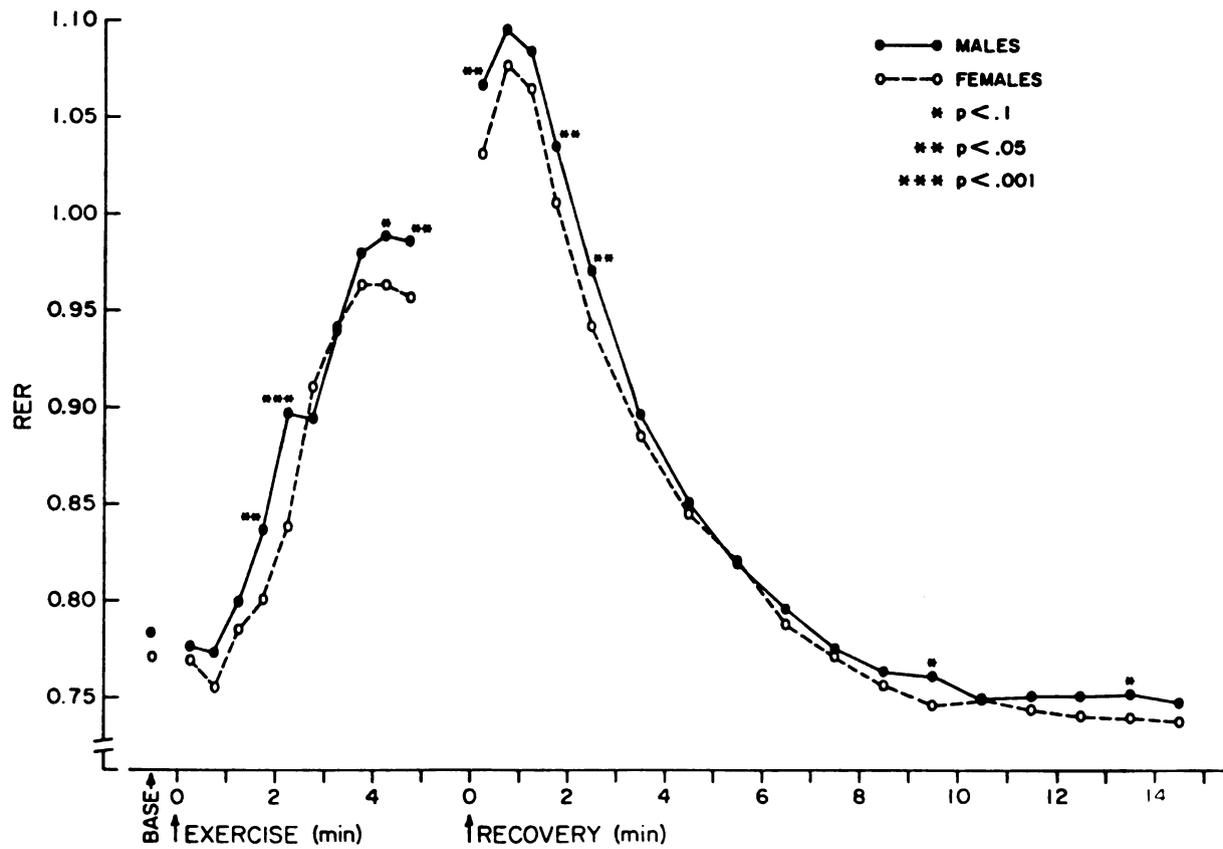


Figure 3.--Mean Respiratory Exchange Ratios (RER) for Male and Female Swimmers During Exercise and Recovery.

portion of recovery both the males and females exhibited a substantial increase in RER ($1.10 \pm .010$ and $1.08 \pm .010$, respectively).

Distance

This section includes results obtained within sexes when the swimmers were grouped according to distance (200 yards and below = short, above 200 yards = middle). Data are presented for oxygen uptake, heart rate, and respiratory quotient during work and recovery.

Figures 4 (males) and 5 (females) depict the oxygen uptake values in work and recovery for the swimmers when grouped according to distance within each sex. The male swimmers who specialized in short distances consumed slightly more oxygen than the middle-distance swimmers during the base period and the initial 2-min of exercise (Fig. 4). However, during the last 3-min of work and the first 1-min of recovery, the middle distance swimmers increased their oxygen uptake beyond that of the sprinters, consuming 7% more at peak value ($p < .05$). These patterns of oxygen utilization were expected and will be discussed subsequently. Oxygen consumptions during the last 14-minutes of recovery were similar in the two groups. When the data were expressed relative to lean body weight (not shown), there were no appreciable changes from the patterns seen in Figure 4 (ml/kg/min) due again to the relative similarity of the lean body weights of the male sprint and middle-distance swimmers seen earlier in Table 2.

The oxygen uptake data during work and recovery for the female sprint and middle-distance swimmers were indistinguishable when expressed relative to body weight (ml/kg/min) during the first 2.5-min of exercise (Fig. 5). However, during the last 2.5-min of the work

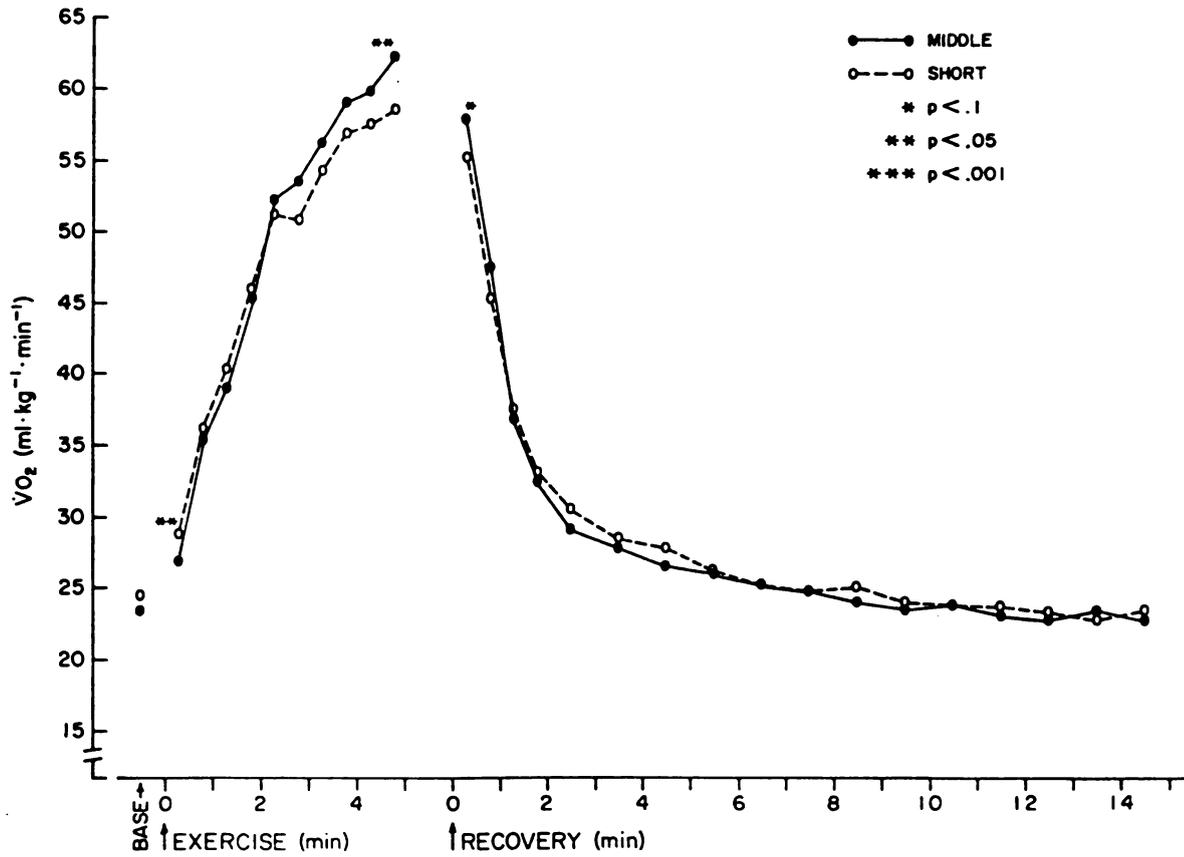


Figure 4.--Mean Oxygen Uptakes (ml/kg/min) for Male Short and Middle-Distance Swimmers During Exercise and Recovery.

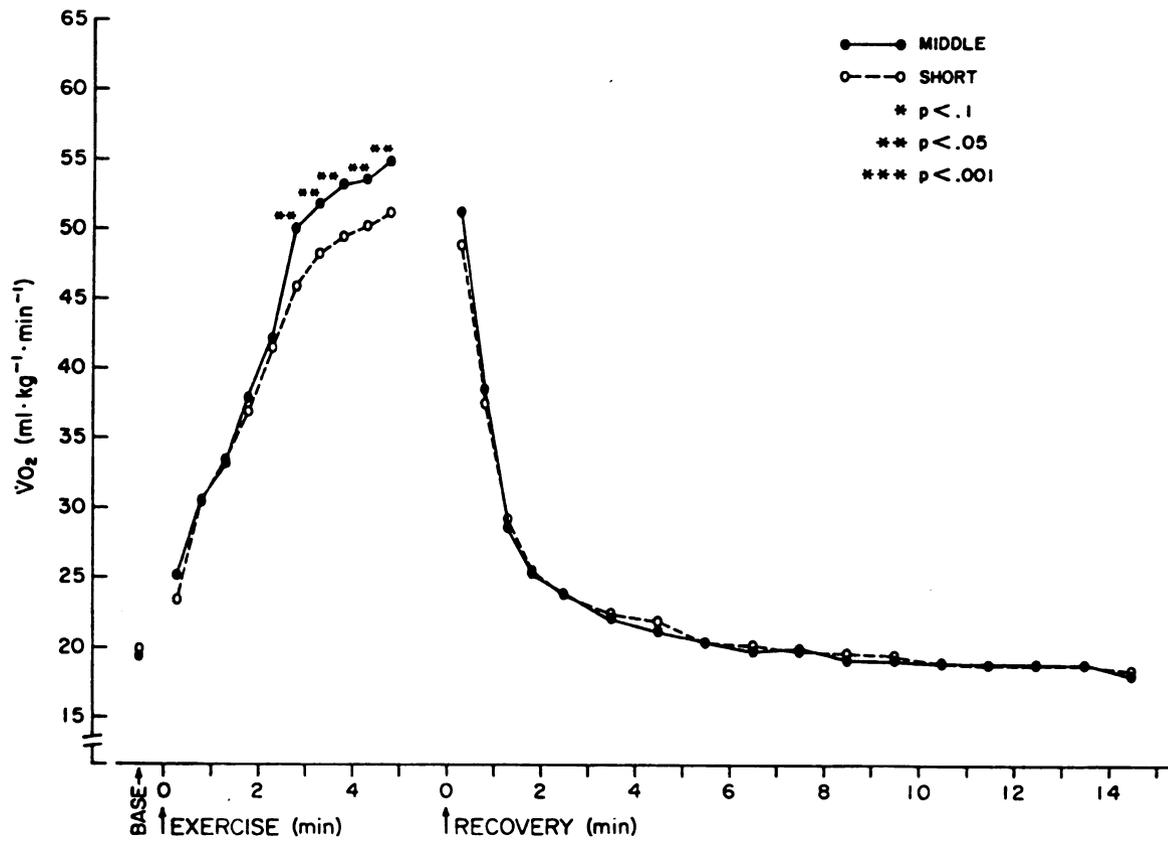


Figure 5.--Mean Oxygen Uptake ($\text{ml}/\text{kg}/\text{min}$) for Female Short and Middle-Distance Swimmers During Exercise and Recovery.

period, the distance swimmers consumed up to 7% more oxygen than did the sprinters ($p < .05$). It also can be seen in Figure 5 that the oxygen consumptions for the female sprinters and middle-distance swimmers during recovery was nearly identical. As was true for the male swimmers, the expression of the oxygen consumption data relative to lean body weight (not shown) did not alter the patterns that were exhibited in Figure 5.

Mean heart rates for sprint and middle-distance swimmers during work and recovery are shown in Figures 6 (males) and 7 (females). The males showed no significant differences during work. Maximum heart rates for both the sprinters and middle-distance swimmers were reached during the last 30-s of exercise (174 ± 1.5 vs 173 ± 2.8 bpm, respectively). Heart rates were lower for the male distance swimmers than for the sprinters throughout the 15-min recovery period. Significance was achieved at all points except during the initial 30-s collection periods ($p < .05$).

The work and recovery heart rate curves for the female sprint and middle-distance swimmers (Figure 7) show patterns similar to those found for the males. However, the female sprinters had consistently higher heart rates throughout the work portion of the curves with significant differences being found at the base, 30-s, 1-min and 2.5-min points ($p < .05$). Maximum heart rates for both the sprint (180 ± 1.2 bpm) and middle-distance (179 ± 2.1 bpm) swimmers were attained during the final 30-s work period. Throughout recovery, the female middle-distance swimmers had consistently lower heart rates than did their sprint

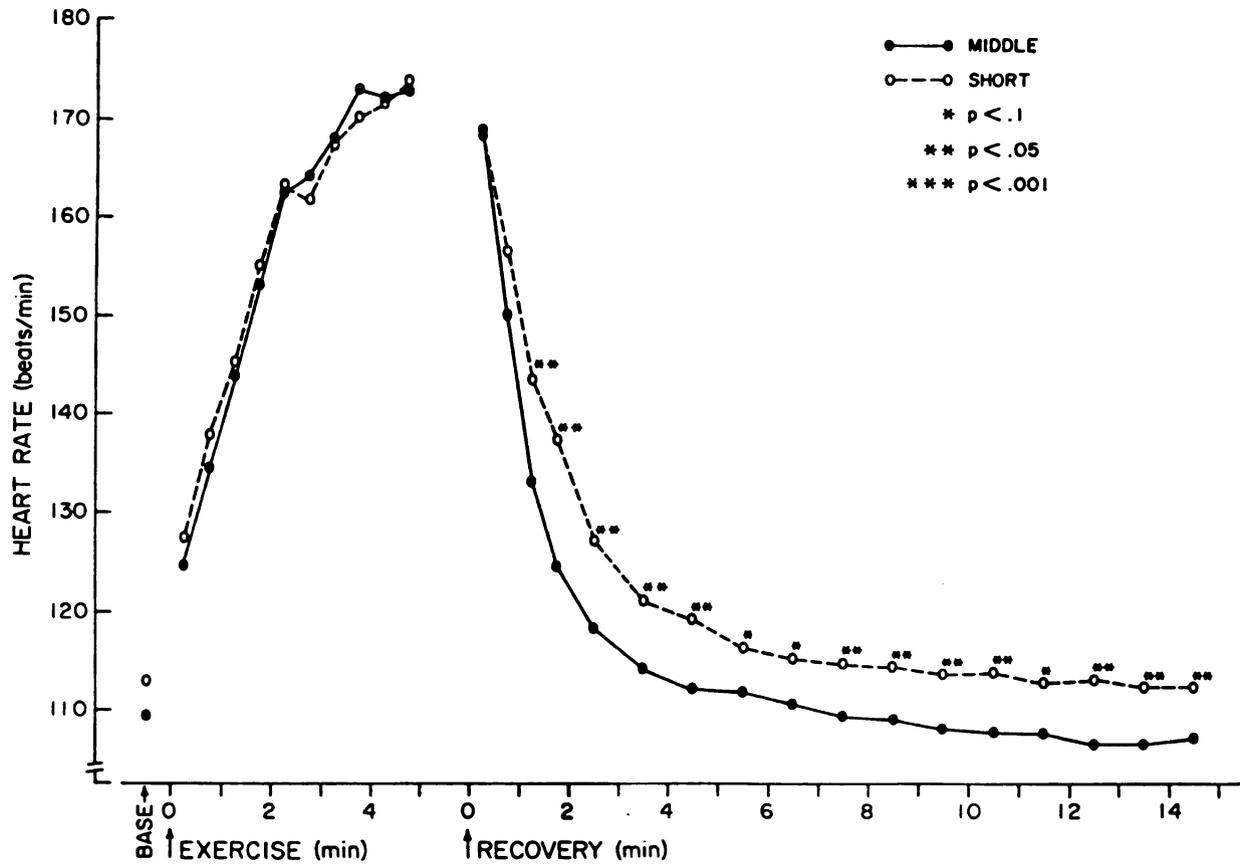


Figure 6.--Mean Heart Rates (beats/min) for Male Short and Middle-Distance Swimmers During Exercise and Recovery.

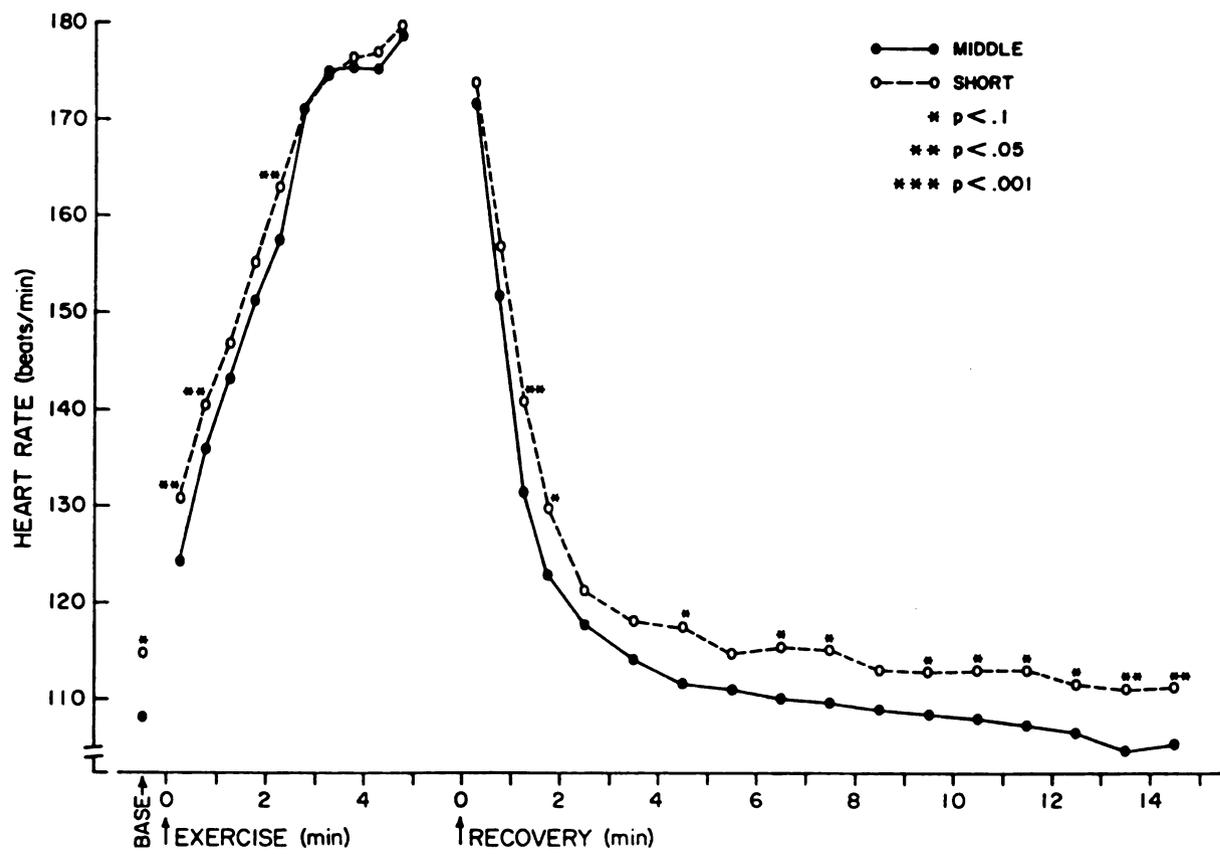


Figure 7.--Mean Heart Rates (beats/min) for Female Short and Middle-Distance Swimmers During Exercise and Recovery.

counterparts. These differences were significant at most points ($p < .05$) after the initial 1-min of recovery.

Respiratory exchange ratios (RER) attained during work and recovery for male and female sprint and middle-distance swimmers are shown in Figures 8 and 9. The male sprinters consistently reached significantly higher values ($p < .05$) than did the male middle-distance swimmers during the work period (Fig. 8). Peak exercise values for both the sprinters ($1.00 \pm .014$) and the middle-distance swimmers ($.96 \pm .018$) were attained during the next to last collection period (Figure 8); however, values for both groups were maintained at near peak levels for the final 1.5-min of exercise. The recovery RER curves show that the male sprinters maintained consistently higher values than did their middle-distance counterparts with RER's increasing to $1.10 \pm .010$ and $1.00 \pm .021$, respectively, during the initial 1.5-min of the recovery period and rapidly declining to minimum values ($0.76 \pm .006$ and $0.73 \pm .007$, respectively) by the eighth min of recovery. The RER values during the final 7-min of recovery were lower than the pre-exercise base values. Significant differences were attained between the groups during these last seven minutes of the recovery period (see Figure 8).

The work/recovery curves showing the RER values of the female groups are seen in Figure 9. During the initial two minutes of exercise, the sprint swimmers had higher values than did those swimming the middle distances. These results were similar to the patterns obtained in the males with the exception that a significant difference was found only at one time point in the females. During the final three minutes of work there were essentially no differences between the

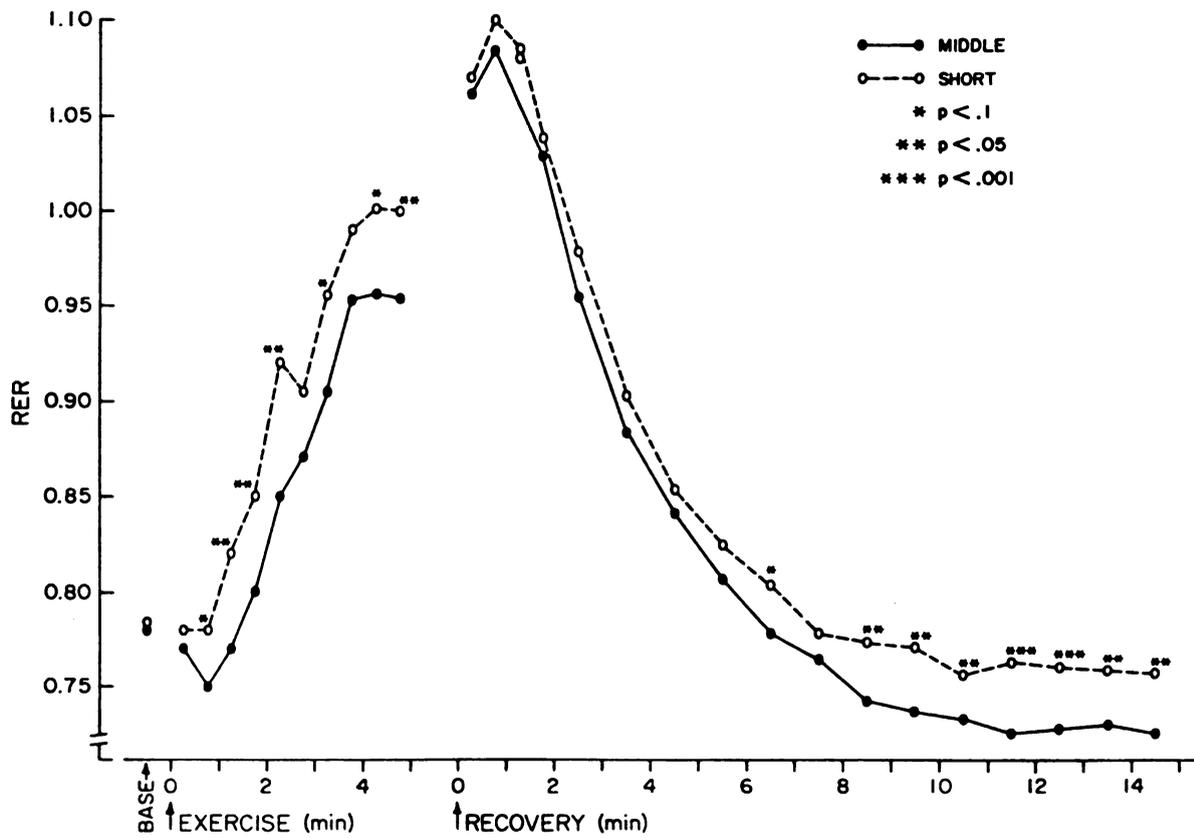


Figure 8.—Mean Respiratory Exchange Ratios (RER) for Male Short and Middle-Distance Swimmers During Exercise and Recovery.

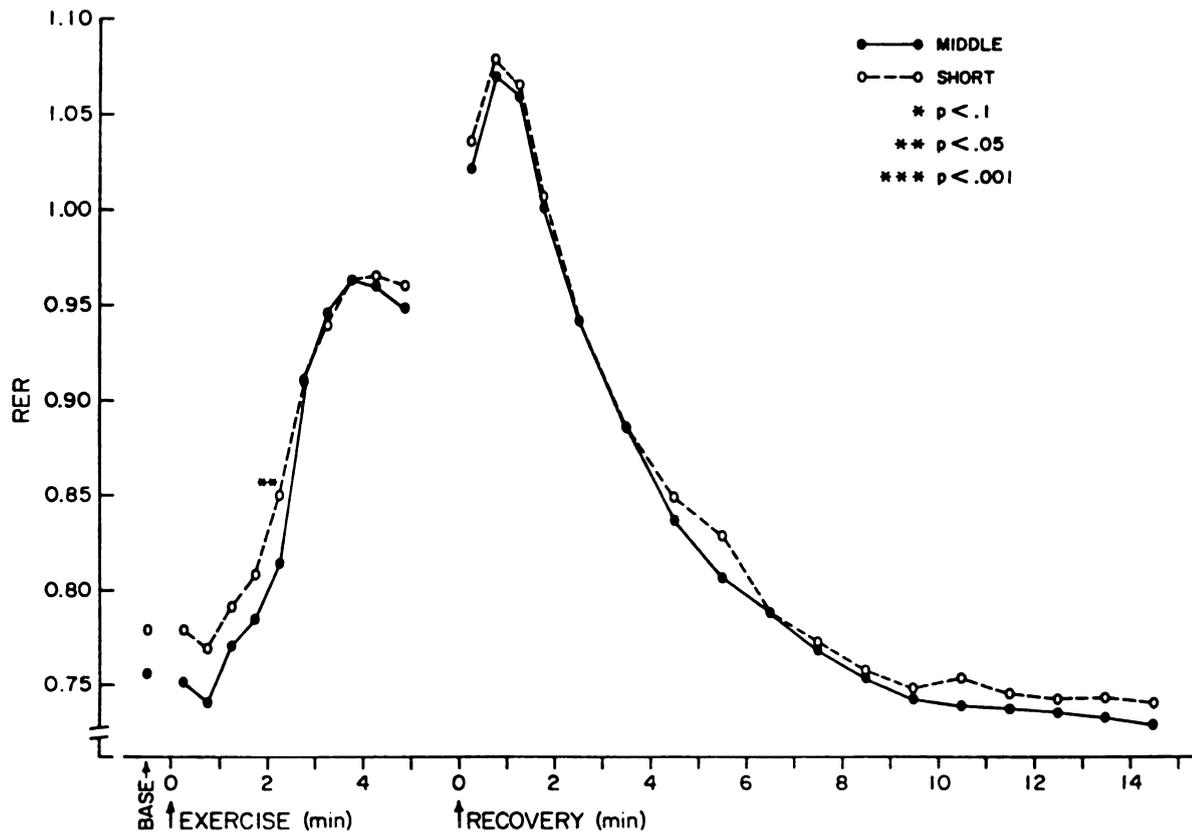


Figure 9.--Mean Respiratory Exchange Ratios (RER) for Female Short and Middle-Distance Swimmers During Exercise and Recovery.

groups with both the sprint and middle-distance swimmers maintaining a RER near their peak exercise values ($.97 \pm .010$ vs $.96 \pm .017$, respectively) for the final 1.5-min of the exercise period. The RER recovery curves (Figure 9) show that middle-distance female swimmers maintained lower RER values than did the sprinters at all but one point in the 15-min period, although their differences were not as pronounced as were those between the male groups (Figure 8). Finally, as with the male swimmers, the post-exercise RER values increased immediately in both the sprint ($1.08 \pm .011$) and middle distance ($1.07 \pm .018$) swimmers. These increases were followed by rapid declines to levels ($.74 \pm .006$ and $.75 \pm .007$ respectively) below those obtained during the base period ($.78 \pm .009$ and $.76 \pm .013$, respectively).

Rank

This section deals with oxygen uptake, heart rate and RER determined throughout the exercise and recovery periods for the male and female swimmers when the comparison groups are delineated by rank (upper 20% vs lower 20% as determined by quality ratings).

Oxygen consumption in relative terms (ml/kg/min) is shown in Figure 10 for the male swimmers. The males ranked in the top 20% of their events consumed significantly less oxygen in the initial 2-min of work than did those ranked in the lower 20% (Fig. 10). Unexpectedly, the higher ranked swimmers continued to consume less oxygen throughout the remainder of the work test. The mean maximum value reached for those males ranked in the top 20% was 59.54 ± 1.571 ml/kg/min while those in the bottom 20% attained 61.18 ± 1.443 ml/kg/min. The recovery pattern of Figure 10 was expected, with the swimmers in the top 20%

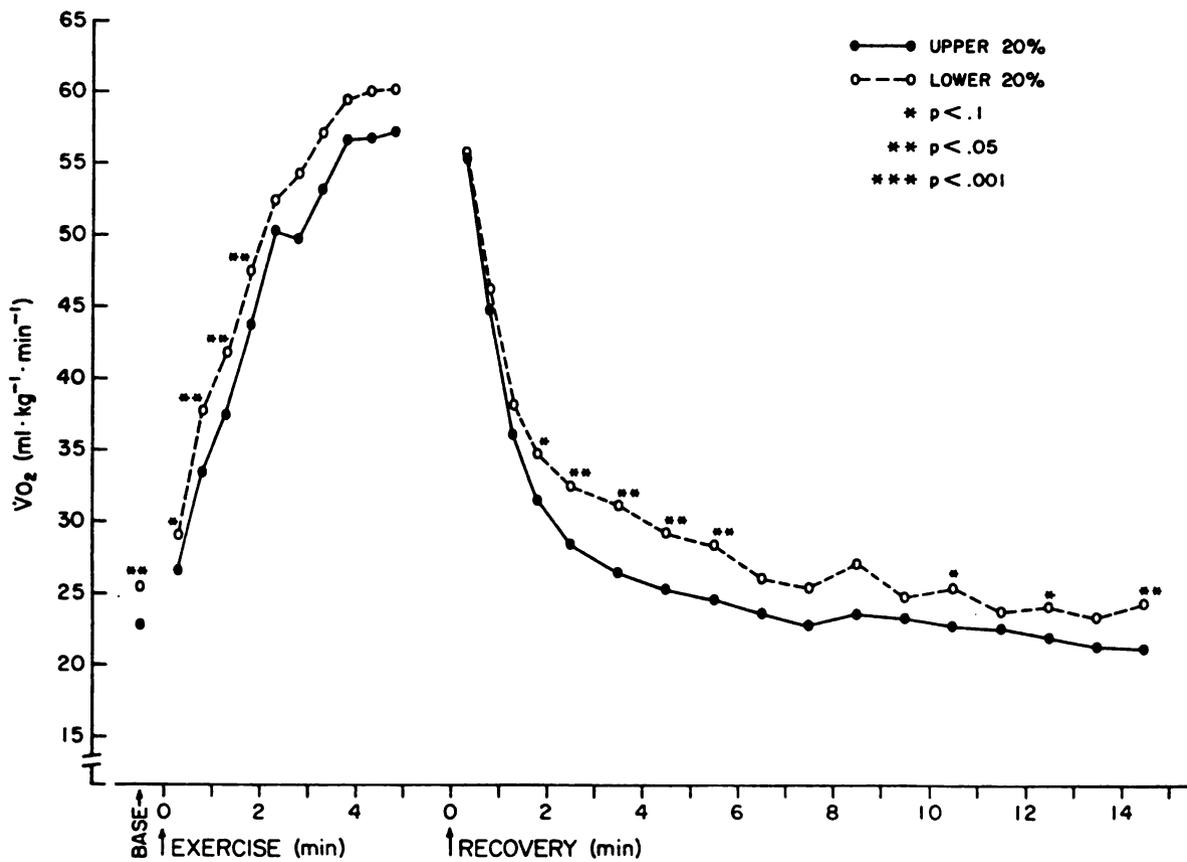


Figure 10.--Mean Oxygen Uptakes (ml/kg/min) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Males.

consuming less oxygen, therefore swimming more efficiently, throughout recovery. Significant differences were observed at several points. The oxygen consumption data expressed relative to lean body weight (not shown) mirrors the patterns seen in Figure 10.

The oxygen consumption data for the upper and lower 20% of the female swimmers during work and recovery (Fig. 11) do not follow the same patterns as were seen in the males. When the data are expressed relative to body weight, those females who ranked in the top 20% consumed slightly more oxygen during the work period (significant only in the initial 30-s interval, $p < .05$) until the last 30-s interval. At that point, those females ranked in the bottom 20% reached a higher peak oxygen uptake than did those in the top 20% (54.36 ± 1.936 vs 53.27 ± 1.553 ml/kg/min, respectively). Consumption was virtually identical for both groups during the initial min of the recovery. After that point, the females in the lower 20% consistently consumed less oxygen than did those ranked in the upper 20%. This difference reached significance at several points, and the patterns completely reversed what was observed previously for the males (Fig. 10). As in the males, no change in patterns was distinguished when the data were expressed as ml/kg LBW/min (data not shown).

The heart rate data during work and recovery also demonstrate dissimilar responses when the males and females are subdivided by rank. Figure 12 shows that, although there were no significant differences in heart rates between the upper and lower male groups during work, the swimmers ranked in the lower 20% consistently had

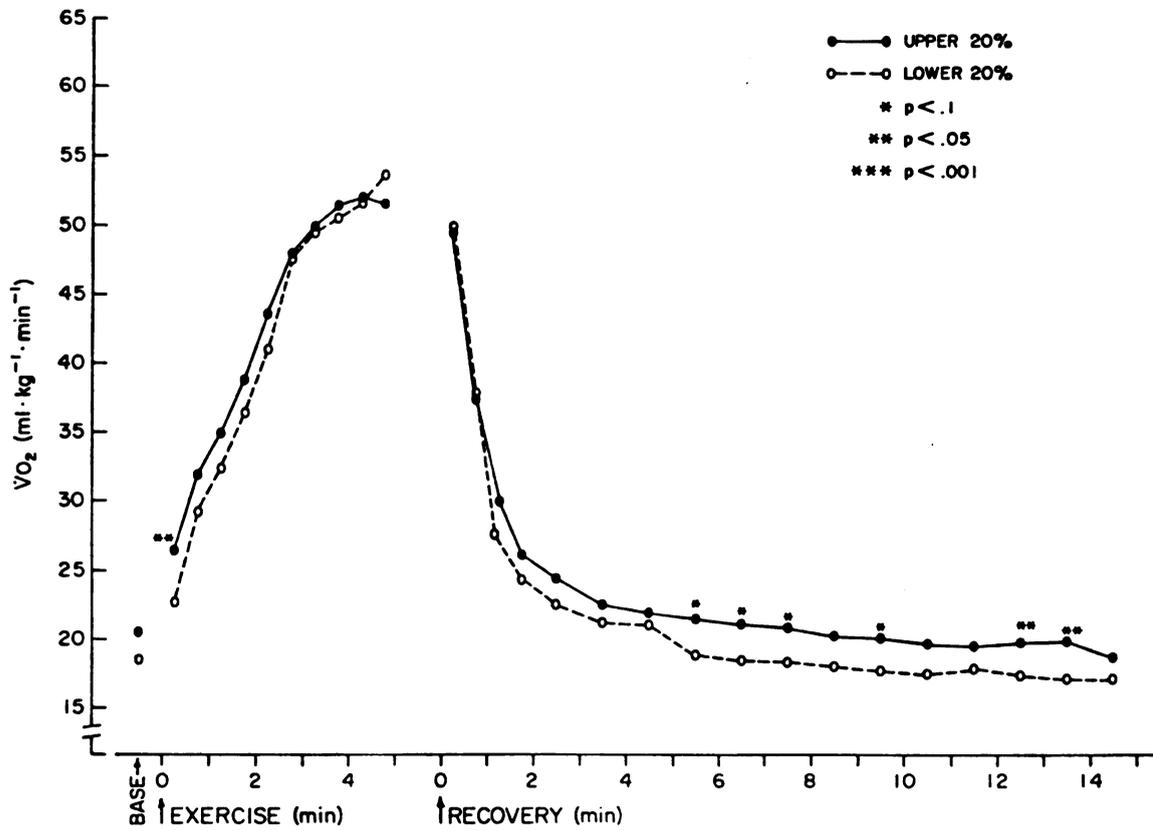


Figure 11.--Mean Oxygen Uptakes (ml/kg/min) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Females.

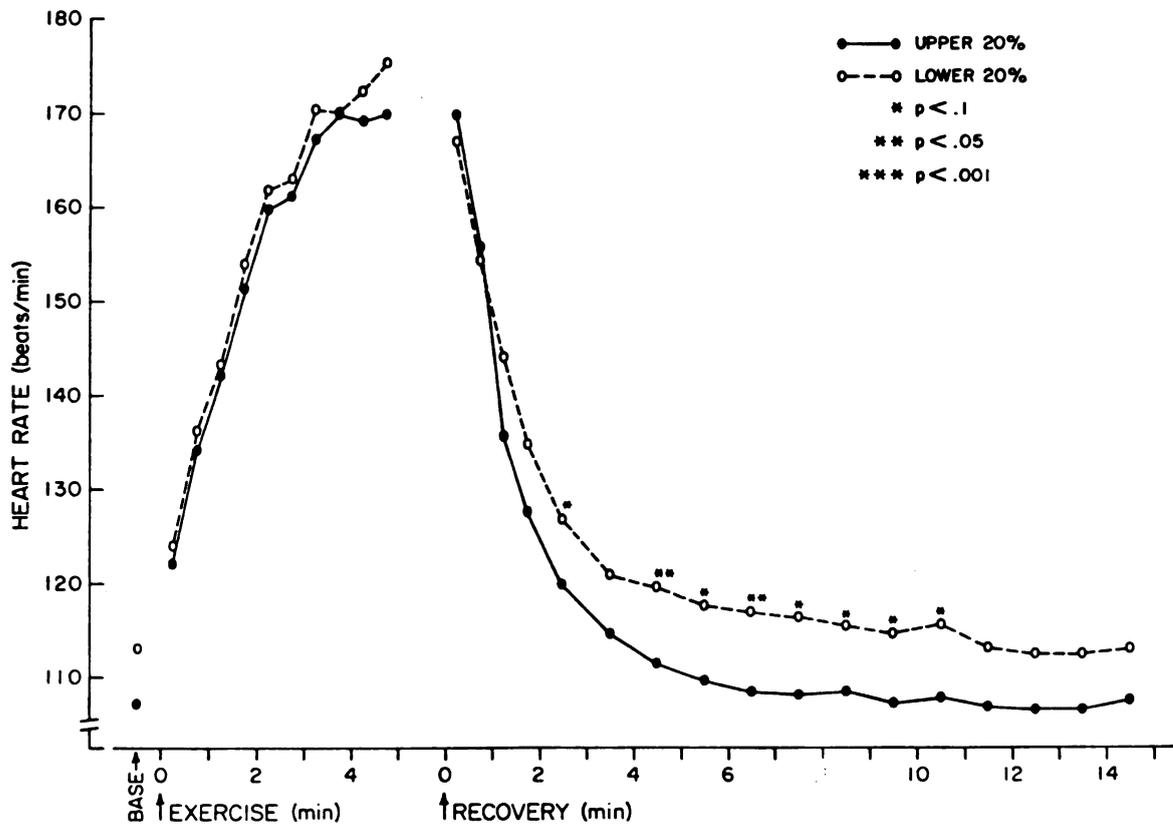


Figure 12.--Mean Heart Rates (beats/min) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Males.

higher heart rates including a higher peak value (175 ± 2.7 vs 170 ± 2.9 bpm). Although recovery heart rates were not different between groups for the initial minute, the remainder of the data show the lower-ranked males to have had consistently higher heart rates with significant differences at several points ($p < .1$, $p < .05$).

The female heart rate data (Fig. 13), although indicating a significantly higher heart rate during the base period for the upper 20% group when compared to the lower-ranked group ($p < .05$), show essentially no heart rate difference during exercise between groups. A higher peak value was reached by the lower-ranked females (182 ± 1.5 vs 179 ± 3.0 bpm). However, in contrast to the male heart rate data (Fig. 12), the female recovery heart rates were consistently higher for the swimmers ranked in the top 20% after the initial 3-min of recovery. These differences, which were significant at several points ($p < .1$), were contrary to the differences between male swimmers ranked by performance. The heart rates in all of the male and female comparison groups returned to baseline values within the 15-min working recovery period.

As was the case for the oxygen consumption and heart rate data, the respiratory exchange ratio (RER) responses to exercise and recovery during the tethered swim test differed between males and females subdivided by rank. For the male swimmers, RER values throughout work (Fig. 14) were significantly higher for the swimmers ranked in the lower 20% than for their higher-ranked counterparts ($p < .05$). Peak exercise values were reached by the lower 20% group at the fourth min

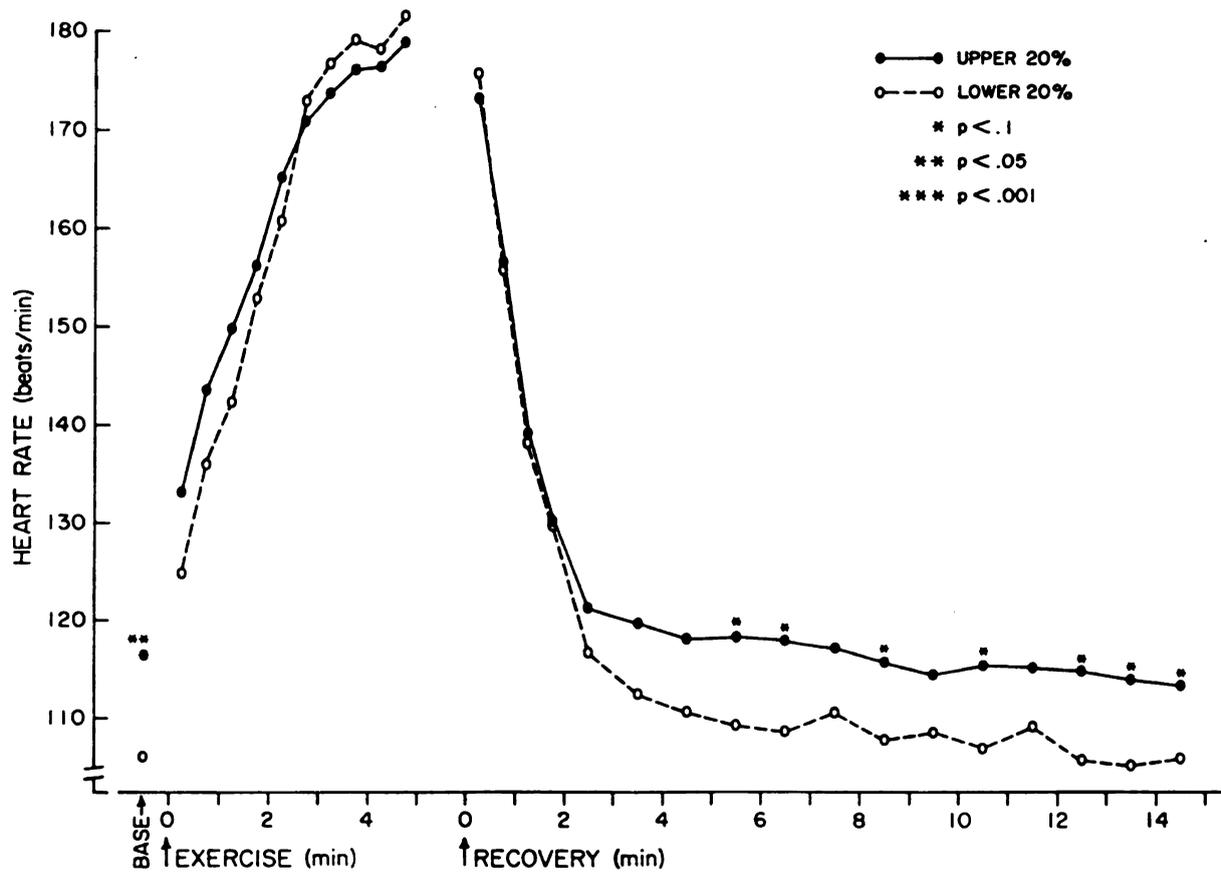


Figure 13.--Mean Heart Rates (beats/min) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Females.

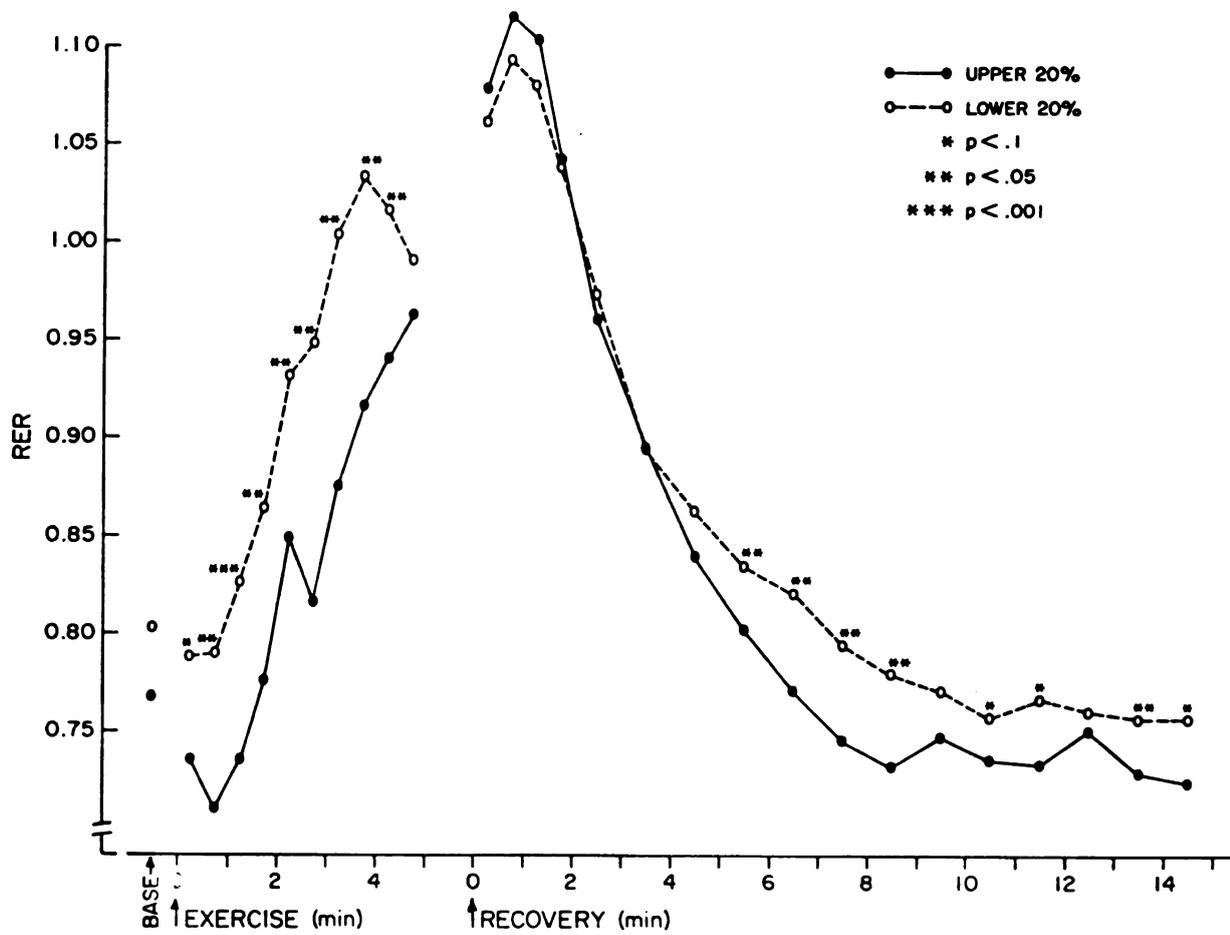


Figure 14.--Mean Respiratory Exchange Ratios (RER) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Males.

($1.03 \pm .023$) and at the fifth min for the upper 20% group ($.97 \pm .022$). Both groups attained their overall peak values during the first min of the recovery (lower 20%, $1.09 \pm .010$; upper 20%, $1.12 \pm .022$). Subsequently, no differences were observed between the groups until the fifth min of recovery when the lower 20% group had significantly higher RER values than did those swimmers ranked in the top 20%.

The RER patterns during work and recovery for the female swimmers differ from those of the males. There were no significant differences between the upper and lower 20% groups of females during work (Fig. 15), although the upper 20% group had consistently higher RER values throughout the period. As with the males, both groups attained their peak values during the first min of recovery. However unlike the males, the lower-ranked group had a higher peak value than did the higher-ranked group ($1.09 \pm .022$ vs $1.06 \pm .017$, respectively). The RER values did not differ between groups during recovery until after the sixth minute (Fig. 15) when the swimmers ranked in the top 20% of their events recorded significantly higher values ($p < .05$). These results also are in contrast to the RER data obtained for the similarly ranked male swimmers.

To summarize the results of the analyses by rank, in the selected metabolic variables examined throughout the exercise and recovery periods (oxygen consumption, heart rate, RER), the relationships between the male groups were in direct contrast to what was observed for the female groups. These findings will be discussed subsequently in an appropriate section.

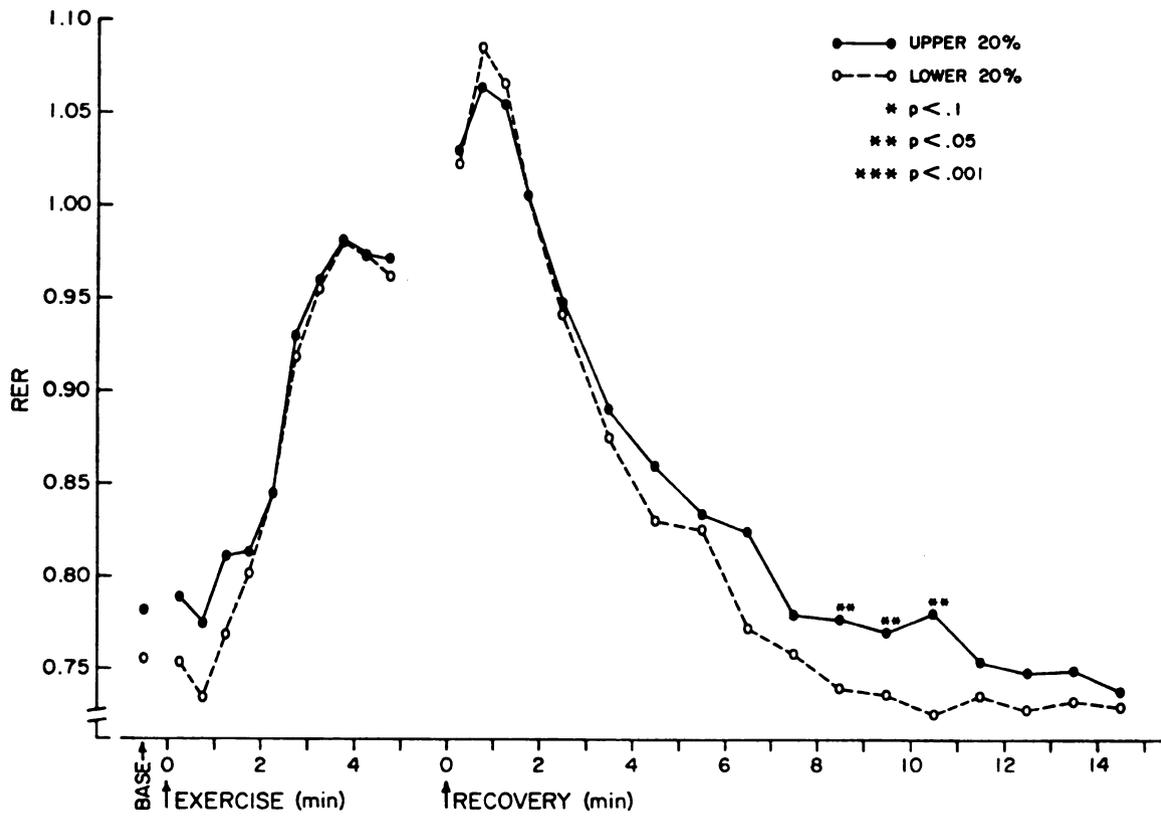


Figure 15.--Mean Respiratory Exchange Ratios (RER) During Exercise and Recovery for Swimmers Ranked in the Upper- versus Lower-Twenty Percent of the Females.

Discussion

The remainder of this chapter will be organized as follows: (a) The results that compare the physical and metabolic characteristics of well-trained male and female swimmers will be considered first. (b) A discussion of the comparison between swimmers of short and middle-distance races will follow. (c) The last section will deal with the results of the comparisons between swimmers ranked in the upper and lower 20% of their events. Where appropriate, discussion will be inserted addressing the tethered swim ergometer and the specific protocol selected as these factors may have affected the physiological evaluations of the swimmers.

Comparisons by Sex

The heights and weights of the male and female swimmers, which are presented in Table 1, are representative of values generally reported for elite, well-trained swimmers of similar age (16,24,32,68,111,117, 122,143,189). Although there are relatively few investigations published that contain estimates of the percentage of body fat for well-trained swimmers (116,121,165,170,172,210,211,221), the values obtained in the present study (males 9.5 ± 0.27 , females $18.8 \pm 0.29\%$) are within the range of those reported. As expected, these values are slightly higher than the body fat estimates obtained from other highly trained athletes involved in aerobically demanding, weight-bearing activities (i.e., long distance running or cross-country skiing). The increased adiposity exhibited by swimmers has been commented upon previously (171,211) and may be an advantage either related to natural selection or precipitated by a specific training response.

Endurance training, such as the type involved in an intensive swimming program, has been shown to induce metabolic adaptations that include increased mobilization and utilization of free fatty acids during exercise (83,107,108,109,110). Furthermore, an increased adiposity and a concomitant decrease in specific gravity have been hypothesized to be advantageous for swimmers due to the increased bouyancy and reciprocal decrease in energy expenditure necessary to remain afloat (57). In addition, data on channel swimmers (178,179) and untrained subjects (45,134) indicate that swimmers compete in a medium favorable for heat exchange. During high-energy output in swimming, less of the cardiac output may be necessary to dissipate heat and more may be available for oxygen transport (55,69). However, during the prolonged exposure to an aquatic environment that occurs during swim training, even increased metabolic heat production during work is incapable of preventing a decrease in internal body temperature (38,56,134). Several investigators (116,162,165) have demonstrated that subcutaneous fat levels are an important factor in preventing heat loss in water. These subcutaneous fat levels are likely represented by the relatively high body fat content seen in swimmers, which in turn may provide an advantage in thermal regulation. Thus, the metabolic adaptations induced by an intense regimen of swim training, coupled with adaptations to a working environment that eliminates weight-bearing energy expenditure and facilitates bouyancy and thermal regulation, could induce an optimal level of body fat for each individual. Obviously, in the highly competitive swimmer this optimal

level of body fat cannot compromise the lean body mass necessary for the development of muscular strength, endurance and power. However, among adaptations peculiar to elite swimmers due to their working environment may be body fat levels that are higher than those found in other well-trained athletes. In recreational or ultra-distance swimming where velocity is not a major concern, a relatively higher level of adiposity can be tolerated and in some cases may even enhance performance. This possibility has been addressed by Pugh in his work with channel swimmers (178,179).

The metabolic data for the male and female swimmers when expressed in absolute terms (Table 4) follow patterns previously reported for swimmers (16,24,32,68,117,143,189). However, this study presents data collected from a larger, more homogeneous group of male and female swimmers with a higher proficiency and degree of training than has been reported to date. Additionally, this research represents only the second examination of a separate group of female swimmers using a tethered swim ergometer.

The difference between male and female absolute peak oxygen uptake values shown in Table 4 (35%) is within the range of differences (31-56%) previously reported for elite, well-trained swimmers tested by free swimming (143), flume swimming (68,111,117), tethered swimming (24), treadmill running (68,111,117) and cycling (189). In general, when mean values for peak oxygen uptake are compared during upper body exercise (arm-cranking, swimming), whether in absolute or relative terms, the differences between men and women are somewhat smaller than

the average differences reported in the meta-analysis by Sparling (209) for cycle and treadmill exercise. These smaller differences in peak oxygen uptake between men and women may be due to factors that are thought to limit performances in small- versus large-muscle exercise. Large-muscle exercise is thought to be limited to a great degree by "central factors" (e.g., maximal cardiac output); whereas, it has been postulated that dynamic small-muscle exercise is more influenced by peripheral factors (e.g., local blood flow and/or oxidative capacity of the active musculature) (130,155,194). In this light, a definite physiological and anatomical basis would appear to exist for the major differences between males and females reported for peak oxygen uptake measured during large-muscle exercise. One important difference between the sexes in this regard is that maximum oxygen uptake is significantly lower in females than in males due to a smaller maximal stroke volume in females (9). This fact is supported in the present study by the large difference obtained in oxygen pulse between males and females (Table 4). Oxygen pulse has been considered to be a valid indicator of stroke volume (60). The smaller maximal cardiac output combined with the female's approximately 15% lower hemoglobin content (157) would markedly reduce oxygen delivery to skeletal muscle during large-muscle exercise and thus limit peak oxygen uptake in women as compared to men. In contrast, there is no evidence to suggest that there are differences in peripheral factors such as blood flow distribution during exercise, capillary density, or intramuscular oxidative enzyme activities of men and women (5,52,190). Therefore, sex-related differences in peak oxygen uptake should be less in

small-muscle activities than in large-muscle activities such as cycling or running. The inclusion of swimming as a small-muscle exercise is based on evidence that indicates the major portion of the propulsive force in the front crawl is produced by the arms (150). However, a comparison of the present study with others that have investigated differences in arm-cranking for men and women is limited by the advanced state of fitness attained by the females in this study.

When the oxygen uptake data are expressed relative to body weight (Table 5), the difference between the male and female swimmers remains statistically significant ($p < .001$), but it is reduced to 14%. This pattern has been seen in data from other reports involving untrained men and women (209), as well as in the previously mentioned investigations utilizing trained male and female swimmers (24,68,111,117,143,189). Furthermore, when the oxygen uptakes in the current study are expressed relative to LBW (Table 5), the difference between the men and women essentially is eliminated. This was not an unexpected result as previous work with non-swimming ergometers has demonstrated an elimination of sex differences when aerobic capacity is normalized for the skeletal muscle mass actively engaged in the exercise (1,13,39,228). Although peak oxygen uptake has been expressed relative to fat-free mass for male and female swimmers in several reports (165,170,171,210,211,221), to the writer's knowledge it has not been presented previously in a single investigation employing well-trained swimmers of both sexes. However, difficulty arises as one attempts to derive a meaningful interpretation of the observation that the difference in oxygen uptake between the sexes is reduced in

swimming when the data are expressed relative to body weight or LBW. Certainly in weight-bearing activities such as treadmill running, the reduction in the sex difference in oxygen uptake values when expressed relative to body weight is well documented (13,39,209,229,232); and the relative data are thought to more accurately represent the oxidative capacity of the working musculature. However, it is the contention of a few investigators that greater validity can be attained in the estimation of the active tissue oxidative capacity of swimmers by expressing oxygen uptake in either absolute terms (202) or in terms relative to fat-free body mass (13,39). The first contention is supported by the observation that the experienced swimmer, in the free-swimming state, expends little energy to support body weight, therefore, the prime criterion of endurance is absolute aerobic power. In contrast to that position, the possibility exists that in the tethered condition more energy must be expended to maintain proper body alignment due to the lack of laminar water flow which normally facilitates the maintenance of body attitude in the free-swimming state. This may be particularly true at lower work rates, and it is more likely to be a factor in the males than in the females due to differences in the amount and distribution of body fat. Furthermore, the expression of aerobic capacity in absolute terms does not account for differences in body size. Although body weight is not an ideal estimate of muscle mass, the intra-sex variability in body fat within the subjects of the present study was low ($9.5 \pm 0.27\%$ males, $18.8 \pm 0.29\%$ females). With this degree of homogeneity, it seems reasonable to propose that the expression of oxygen uptake in terms relative to

body weight is an acceptable estimate of the whole body aerobic capacity within the context of the present study.

The second contention of expressing aerobic capacity in terms of fat-free body mass is based on the fact that body fat adversely affects continuous, relatively prolonged performance of weight-bearing activities by lowering the peak oxygen uptake (ml/kg/min). This occurs because body fat is essentially dead weight in land-based activities. It adds to the load being carried without contributing to the energy production as estimated by oxygen uptake. Since percentage of fat values generally are higher for women than for men, part of the sex difference in oxygen uptake (ml/kg/min) is due to the difference in adiposity. Thus, when the aerobic capacity in weight-bearing activities is expressed relative to fat-free weight instead of body weight, a portion of the sex difference is eliminated. However, energy expenditure in an aquatic environment by highly skilled swimmers presents a more complicated situation than that encountered during a land-based activity such as running. As previously discussed, intense swim training may produce an optimal level of body fatness as a specific adaptation to the exercise environment as well as to the work overload. The role of fat in thermal regulation and buoyancy suggests the possibility that body fat exerts an important influence on the energy expended while swimming. Additionally, the major resistance encountered in free swimming can be estimated by body drag (114). In theory, the amount of resistance the swimmer must overcome during movement through water is a function of the velocity of the body and

the body profile that is presented while performing the individual strokes (114). Although the contribution of body fat in the formation of body drag is difficult to estimate, it remains to be considered as a contributing component. In this light, body fat may impose yet another influence on energy expenditure while swimming. Therefore, it seems reasonable to account for this influence by the discussion of the metabolic consumption of oxygen primarily in terms of total body weight rather than in terms of fat-free weight.

Further examination of the absolute metabolic variables in Table 4 shows that male swimmers, as compared to female swimmers, have significantly higher values for most variables with a ventilatory component. In addition, Table 5 illustrates a reduction or disappearance of these sex differences when the variables are expressed relative to body weight or fat-free weight (15-min net oxygen debt, 2-min net oxygen debt, \dot{V}_E , \dot{V}_E/resp , O_2 pulse and O_2/resp). The large \dot{V}_E for the male swimmers in the present study was expected and has been reported elsewhere for well-trained swimmers (24,68,111,117,143,189). The reduction in the sex difference for \dot{V}_E and related variables when expressed relative to body weight and lean body weight (Table 5) probably is due to the indirect normalization of the ventilatory data caused by the larger chest cavity and thus the larger total lung and vital capacities found in males than in females of similar age (232).

The peak pulmonary ventilations reported for the present group of swimmers are within the range reported for other elite swimmers tested with a swimming ergometer (24,32,63,68,111,117,122,136,151,153,169) but

are lower than the values obtained from swimmers tested on land-based ergometers as well as values obtained from highly trained athletes of other specialities emphasizing weight-bearing, aerobic activities (15,68,111,117,122,152,189,203,211). Although Dixon and Faulkner (63) reported similar \dot{V}_E values for a highly trained group of swimmers tested both on a treadmill and a tethered swim ergometer, most investigators (11,15,60,111,117,122,153,159,169) have found higher values for similar subjects during land-based ergometry as opposed to swimming in the tethered, flume or free-swimming conditions. The reasons for lower pulmonary ventilations while swimming are based on the specific conditions imposed by the activity. Immersion in water is thought to reduce vital capacity by 10%. The effects of hydrostatic pressure (3,69,119,131,224), increased flow resistance (3), the position of the chest cavity in the prone position (131), and involvement of the respiratory muscles in the arm stroke (42) constitute factors that might contribute to the limitation of ventilation.

Swimming is an activity in which respiration rate normally is synchronized with stroke rate. Even with the introduction of a breathing valve which makes free breathing possible, synchrony of respiration rate and stroke pattern was maintained by the subjects tested in this study. Similar observations have been made by other investigators (118,153,159). In the present study at the lowest work levels, the subjects often inspired on every second or third stroke cycle. Respiratory frequency was escalated to match stroke rate only when the work load approached maximal levels. Although the breathing

mechanics of the subject seemed to be unencumbered by the valve apparatus, the question of whether or not the test equipment modified respiration is completely open. More sophisticated methods are required to analyze the respiratory pattern during natural swimming. It is possible that the breathing valve may actually enhance respiration, thereby increasing oxygen tension in the alveolar air. Another way in which alveolar oxygen tension could be increased is by an increase in tidal volume to a greater percentage of total lung volume in water. Such a change could be achieved by reductions in the expiratory and inspiratory reserve volumes (224). These possibilities are supported by the observation that alveolar ventilation per breath is higher during maximal swimming than during maximal running (118,153). Further support for this hypothesis is provided by the report of Astrand and Saltin (15) in which they demonstrated large variations in pulmonary ventilation in the same subjects during different maximal activities even though the peak oxygen uptakes were similar. These observations seem to indicate that despite the lower pulmonary ventilation during swimming, gas exchange is sufficient to maintain an oxygenation of the arterial blood similar to that observed during running.

Peak respiratory frequency and ventilatory equivalents were the only variables in Table 4 to show no differences between the sexes. When compared to values previously reported, the current breathing rates were slightly higher than the range reported in the literature (29 to 49 breathes/min) for well-trained swimmers tested on a treadmill (63,153,159,169,211), a tethered swim ergometer (63,153,169) and in

free swimming (159). Upon approaching maximal effort, the subjects in the present study were urged to increase the power of the pull phase of the stroke and the turnover of the stroke cycle. Since respiratory rate clearly is synchronized with stroke rate, an increase in stroke rate would be matched by an increased breathing rate at maximal effort. Ventilatory equivalents of the present study were within the range of values (23.8 to 28.9) reported for swimmers tested by flume (68) and free swimming (143) but were lower than the range of values (29.6 to 35.9) obtained for swimmers tested on a bicycle ergometer (152) or during treadmill running (68,171,211). As previously discussed, the lower ventilatory equivalents that are observed in swimming, as compared to land exercise, can be related directly to the lower pulmonary ventilations found during swimming.

The higher peak heart rates recorded for the females than for the males (Table 4, Fig. 2) are in agreement with data reported for trained female and male swimmers tested during both tethered (24) and free swimming (143). In addition, untrained females of approximately the same height as the present sample of women (170-180 cm) were reported to have higher heart rates than males of similar height at a variety of sub-maximal oxygen uptakes (82). However, no differences were demonstrated when the peak heart rates of elite male and female swimmers tested during flume swimming or treadmill running were compared (68,111,117). Also, Drinkwater (131) has reported that maximal heart rate does not differ between the sexes. It is possible that the sex difference in peak heart rate in the present study is due to less than maximal efforts on the part of the males, but this seems

unlikely in light of the patterns of oxygen consumption, heart rate, and RER (Fig. 1-3) which are indicative of maximal effort. Subjective evaluation of the swimmers' efforts at the time of testing also support this observation. Although female resting heart rates are 5 to 10 bpm faster than males (4), it also is unlikely that this can account for the sex difference during maximal work since base and early exercise heart rates are nearly identical in the sexes (Fig. 2). Evidence from both human and animal experimentation has accumulated to indicate that there are intrinsic differences in the mechanical functioning of the male and female myocardium. Human males have been shown to have a greater initial acceleration of blood flow in the aorta (93), as well as higher systolic, diastolic and mean blood pressures than do women of the same age (176). Additionally, sex-related differences have been noted in amino acid composition as well as in total protein and collagen content of the cardiovascular systems of male and female rats (233). Differences in contractility of the isolated papillary muscle (43) and in the intact isolated working heart (198) have been described for male and female rats. Finally, results from a study by Schaible et al. (197) suggest that despite similar skeletal muscle adaptations, hearts of male rats adapt to endurance training with improved intrinsic performance, whereas hearts of female rats do not. Whether this differential response in cardiovascular function in males and females is due to sex hormones or to genetic properties of the myocardium warrants further investigation. The demonstration of specific sex hormone receptors in the myocardium (100,141,218) suggests that the heart is a target organ for gonadal hormones and that the

interrelationships between the sex hormones may contribute to the present peak heart rate difference.

Although the pattern of the heart rate response during exercise and recovery (Fig. 2) appears to be similar to that reported for comparably intense land exercise (114), the magnitude of the heart rate response to maximum effort swimming is less pronounced than in other exercise tests. This lowered heart rate response in swimming is remarkably constant and can be demonstrated in both elite and recreational swimmers. Previous work has demonstrated lower submaximal and maximal heart rates during swimming than during cycling (51,85) and treadmill running (153) at similar oxygen uptakes. In the report by Magel and Faulkner (153), maximal oxygen uptakes were determined during treadmill running as well as during free and tethered swimming for a group of college swimmers. Although the oxygen uptakes did not differ significantly between the tests, maximum heart rates were significantly less during both swim tests (181-186 bpm) than during the treadmill test (197-200 bpm). The range of heart rates obtained by Magel and Faulkner (153) in their swim test is similar to that recorded in the present sample. Further corroboration of the present heart rate data comes from another study by Magel and coworkers (154) who reported that higher peak heart rates were obtained during treadmill running than during free swimming by the same group of varsity swimmers. Also, Holmer and his group (118) found higher peak heart rates in treadmill running than in flume swimming with the same group of swimmers (186 vs. 174 bpm). Peak heart rates in the range of those in the present study

have been reported for well-trained swimmers using flume (111,115,117, 118), free (154,159) and tethered swimming tests (24,63,96,122,151,153, 169). Only Klissouras (136) and Eriksson (68) have presented heart rate data higher than 190 bpm attained during tethered (197 bpm) and flume swimming (192 bpm).

Several pertinent factors must be considered in any attempt to explain the fact that heart rates during maximal work are significantly lower in swimming than in running or cycling. These factors serve to support the contention that the metabolic data obtained in the present study were characteristic of maximal responses elicited by the tethered swim test despite heart rates that generally would be considered sub-maximal in subjects of similar age and training status being tested by running or cycling. Although the relative importance of these various factors remains to be evaluated, the effects of the thermoregulatory demands and the hydrostatic and gravitational influence due to submergence and body position probably are critical. Early experiments on the effects of submergence and water temperature demonstrated that heart rate is decreased when water temperature drops below body temperature (20,21,220,230). Later studies indicated that during exercise in cold water, a subject's heart rate may be depressed at any given level of oxygen uptake (75,116,160,162,165,168). Furthermore, heart rate during maximal work seems to depend on internal body temperature (116,160,165), and skin temperature has been proposed to be an important determinant of thermal and circulatory adjustments to swimming in water at different temperatures (168). Even though most swimmers can maintain an unchanged internal temperature due to the

sustained work of swimming (183), the heart rate-oxygen uptake relationship still shifts toward lower heart rates in cooler water (116). Since cardiac output is constant during swimming at various oxygen uptakes in water temperatures from 18 to 33°C (160), the reduction in heart rate response is compensated for by a proportionate increase in stroke volume. This concept is suggested by the observation that during swimming, hydrostatic pressure and supine body position offset the tendency of blood to pool in the lower portions of the body as happens during vertical land exercise. Central blood volume and venous return increase, presumably resulting in an increased stroke volume (7,142). The cumulative effects of these specific conditions during swimming, in addition to the influence of a smaller contracting active muscle mass (146), provide evidence supporting the assumption that heart rates in the range of the current study (174-183 bpm) are indicative of maximal efforts during exercise in water.

Another indication of maximal effort during an exercise test is the generally accepted criterion of a centrally-limited maximum oxygen uptake (67,202). This criterion is met by the attainment of a plateau in oxygen uptake despite an increasing work load. At the suggestion of Shephard et al. (202), the plateau is attained with increments of oxygen uptake < 0.15 l/min or 2.0 ml/kg/min from the pentultimate to the final work load. A leveling off in oxygen uptake has not been demonstrated during arm ergometry (8,15,28,155,180,205,216,227,228) prompting Magel et al. (155) to suggest that the highest oxygen uptake attained be referred to as "peak" oxygen uptake. The reasons for the lack of a plateau in oxygen uptake seem to be related to factors that

are thought to be limiting in small- versus large-muscle exercise. During small-muscle exercise such as arm cranking, peak oxygen uptake values are limited more by peripheral factors than by central circulatory factors (79,130,155,194,195,205). These limiting peripheral factors include a relatively small muscle mass participating in the exercise (79,155,195), possible restrictions to muscle perfusion (195,205), and higher levels of local muscular fatigue (130,195). In addition, a plateau in oxygen uptake is thought to require generation of energy from anaerobic pathways (180). Gollnick et al. (84) have presented evidence that muscles with relatively low oxygen uptakes also have limited capacities for anaerobic metabolism. The difficulty in obtaining a plateau in oxygen uptake during arm cranking may be due to the relatively low capacity for oxygen uptake in the upper body musculature of the untrained subjects usually employed in arm cranking studies.

Although the active muscle mass engaged during swimming is most likely larger than that used during arm cranking, it undoubtedly is smaller than the mass involved during cycling or running. The maximal oxygen uptake varies with the type of activity that is undertaken (15,202). In accord with these observations, it generally is accepted that, for the moderately trained swimmer, oxygen uptake during swimming is approximately 19% and 8% below values attained during treadmill running and cycling, respectively (11,15,63,111,153,159). These differences are reduced (111,113) or disappear (63,113,169) in well-trained or elite swimmers. The possible explanation for these differences in oxygen uptake during swimming and land exercise seems to

be related to the activation of a relatively smaller, untrained muscle mass. Subjects who are not swim-trained are not likely to display a plateau in oxygen uptake due to the limiting peripheral factors that were discussed for arm cranking. A search of the literature reveals only one report which presents data illustrating a plateau in oxygen uptake during swimming. This study by Holmer and Astrand (115) demonstrates a leveling-off of oxygen consumption during flume swimming in each of two female subjects tested. Magel and Faulkner (153) observed that during tethered swimming, their less skilled subjects appeared to be impaired by local muscular fatigue and/or respiratory distress before peak oxygen uptake was attained. Shephard and coworkers (203) suggested that the difficulty in producing the necessary graded increments of work load in a swimming test is the reason a plateau in oxygen uptake is not readily demonstrated. Visual inspection of the present data (Fig. 1) seems to indicate some leveling off of oxygen uptake for the males and perhaps more for the females. This observation supports the criterion of Shephard et al. (202) of a "centrally-limited" maximum oxygen uptake. Further evidence suggesting a plateau in oxygen uptake in the present study is supplied in Table 4 where values for percentage of steady state $\dot{V}O_2$ of 92.4% and 94.4% are given for the male and female swimmers, respectively. These values indicate that the subjects maintained better than 90% of their peak oxygen uptakes for approximately the final 2.5-min of the 5-min exercise test.

The contention of Shephard et al. (203) regarding the lack of adequate graded loading increments in a swimming test is supported by

various reported test protocols. Loading increments in the tethered swim test seem particularly crucial to the attainment of maximum oxygen consumption values. Magel and Faulkner's (153) observation that their subjects were limited by local muscular fatigue could have been due to the loading sequence employed. The addition of 1.14 kg in an early phase of work would fulfill the intended function of increasing the load on the central factors that limit aerobic capacity. The addition of the same weight at the penultimate stage of work may be sufficient to surpass the working muscles' ability to produce the tension needed to support the load before exhausting the central and peripheral factors contributing to the consumption of oxygen. The protocol of the present study (Appendix A) attempts to avoid this overloading by utilizing decreasing load increments as the test progresses. For this reason, it is felt that a true maximum oxygen uptake was attained as demonstrated by the leveling off in oxygen consumption in Figures 1, 4, 5, 10, 11.

The present protocol also may serve to approximate an actual swimming race. With the exception of the sprint events, competitive swimming generally involves a pre-race warm-up, followed by the initiation of competition. The swimmer then rapidly attains a high level of sub-maximal work ("race pace") that, it could be postulated, involves a large portion of the individual's maximal aerobic capacity (80-90% of peak oxygen uptake). This level of energy expenditure is sustained until approximately the final minute of the race when an attempt is made to increase velocity (theoretically to the maximal work level) in an effort to complete the distance in the shortest possible

time. It is felt that the tethered swim protocol employed in the present study roughly reflects this progression of work intensity. The decreasing magnitude of the loading increments as the test progresses simulates a sustained effort by the swimmer involving a substantial portion of the individual's maximum oxygen uptake (approximately 92%) for nearly 50% of the total work time (final 2.5-min). This sustained effort is confirmed by visual inspection of the plateau in oxygen uptake evident in Figures 1, 4, 5, 10 and 11 which is substantiated by the criteria of Shephard et al. (202), as well as the data for the percentage of peak steady state $\dot{V}O_2$ found in Tables 4, 6, 8, 10, and 12. The maintenance of a large percentage of peak oxygen uptake for the final 2.5-min of the exercise test can be compared to a sustained "race pace" that would be reached in actual competition.

As with heart rate and oxygen uptake, the pattern of the respiratory exchange ratio (RER) response to exercise and recovery (Figures 3, 8, 9, 14 and 15) appears similar to that observed for equivalent land exercise. However, the magnitude of the response during exercise is slightly less than would be expected during maximal work on land-based ergometers (123,124). In general, previous reports comparing RER values of trained swimmers tested on swimming tests and land-based ergometers have found lower RER values during swimming (11,68,117,151,153,159). This finding could indicate less ability to expire CO_2 during swimming than during running or cycling. That is, the difference might be due to a lower alveolar ventilation during swimming which could then result in a higher alveolar P_{CO_2} . However, this does not appear to be the case because the compensatory

RER increase early in recovery is no larger in swimming than it is in other activities. Consequently, it is tempting to account for the lower RER values during work in terms of a shift in the carbon source for the intramuscular energy metabolism required while swimming. Endurance training of high intensity is known to enhance lipid metabolism while concomitantly reducing the rate of glycogen utilization in exercising skeletal muscle (129,191). At the same absolute and relative work loads, subjects show a reduction in RER values after endurance training due to the modification of substrate mobilization and utilization (83,107,110). It is safe to assume that the current sample of swimmers underwent training of sufficient intensity and duration to illicit these adaptations. However, a definite interpretation of the obtained RER values in a metabolic context is impossible due to the lack of a steady-state work load during the exercise phase of the test (123,124,126). Constant-load work from 3 to 5 min duration is necessary for a steady-state energy exchange to be established (104). The present exercise protocol does not meet this criterion.

The RER values at peak oxygen uptake for the male and female swimmers (Table 4, Fig. 3), although low, are within the range of values (.88-1.08) reported for similarly trained swimmers tested in a swimming flume (68,117), free swimming (32,143) and tethered swimming (32,153). Only Klissouras (136) reports a tethered peak value that is much higher (1.23), and that was obtained early in recovery. In comparison to the females, the males of the present study achieved significantly higher RER values at peak oxygen uptake (Table 4) and

tended to have higher values during recovery (Fig. 3). Higher peak RER values for male swimmers have been reported previously during free swimming (143), but other investigators have found no differences between the sexes during flume swimming (68,117). Assuming a maximal effort by both sexes, a potential explanation for the higher peak RER values for the male swimmers can be found in a possible sex-related difference in training intensity and specificity. Although there were nearly equal proportions of male and female sprint swimmers in the study (less than 200 yards) (Table 2), the possibility exists that the male sprint swimmers trained specifically to enhance the anaerobic metabolic pathways whereas some female sprinters, despite their specialty, trained more aerobically with long-duration endurance swimming. If this were the case, the male sprinters could have reached higher levels of anaerobic metabolism during the test which, in turn, could have increased the concentrations of acid metabolites over those found in the females. That is, the higher RER values for the males may be the result of excess CO_2 released from the bicarbonate which is used to buffer acid metabolites produced during intense exercise (124). This possibility of a sex difference in training regimen will be discussed further in a later section.

The patterns of the oxygen consumption (Fig. 1) and RER values (Fig. 3) during recovery are similar for male and female swimmers. The males maintained approximately a 25% higher oxygen uptake than did the females throughout the 15-min recovery period. In general, the males also tended to maintain higher RER values during recovery with the difference reaching marginal statistical significance at several time

points. Both sexes returned to oxygen uptake and RER values at or below baseline values by the 10th minute of recovery. In addition, the RER values show a sharp increase upon cessation of exercise for both sexes (Fig. 3). This might be the result of the uptake of oxygen being reduced faster than the exhalation of carbon dioxide (186). Further interpretation is limited by the lack of blood lactate values and the lack of a true steady-state period which is necessary to produce information on metabolic substrate usage through the RER values. Even a resting recovery period cannot be considered a steady-state condition (74) due to the fact that the body's internal environment is in a constant state of flux while returning to "baseline" levels following the general metabolic disturbance caused by exercise. The use of a sub-maximal "working" baseline in the present study further limits the interpretation of recovery data. Although Royce (186) found no differences between active and passive recoveries from aerobic work, other investigators have demonstrated that there is an increased lactate clearance (22,31,54,59,77,99,167,213,231) and a reduced oxygen debt (54,77) during working recovery. However, it has been pointed out that the effectiveness of exercise during recovery is influenced by the baseline blood lactate concentration (214) and that this and other conditions that are critical for interpretive purposes do not remain constant throughout the recovery period (212). Continued activity must preclude some of the components of recovery, especially those related to ion and metabolite replacement. In the present study, a working recovery seemed to be the prudent choice given the nature of recovery following an actual competitive swimming event (easy swimming) and the problem of thermoregulation during emersion. However, further

experimentation is warranted concerning the differences in recovery metabolism measured using various baselines.

Although a discussion of the relationship between lactic acid metabolism and recovery oxygen uptake is beyond the scope of this paper, a brief review of the contemporary explanation for the elevation in metabolic rate after exercise is in order to provide background for speculation as to the meaning of the present recovery data. The classical "oxygen debt" hypothesis formulated by Hill and associates (101,102,103,104) was an attempt to link the metabolism of lactic acid with oxygen consumed in excess of resting that occurs after exercise. At the root of this classical theory is the assertion that the major portion of lactate (80%) formed during exercise is reconverted to glycogen in the immediate post-exercise period, while the remainder is oxidized to carbon dioxide and water and provides the energy necessary for glycogenesis (104). This hypothesis was modified by Margaria et al. (156) who partitioned the oxygen debt into separate fast, initial ("alactacid"), and slow, secondary ("lactacid"), components. Current literature, however, shows a strong indication that this original explanation of the oxygen debt was too simplistic. Numerous studies on several species have provided evidence demonstrating a dissociation between the kinetics of lactate removal and the "lactacid" component of the post-exercise oxygen uptake (26,73,81,91,133,138,201). Furthermore, the bulk of the literature concerning the fate of lactate in the recovering mammal indicates that the major portion of lactate produced during exercise is oxidized (33,34,64,66,73,125,187,226). The elevated concentration of lactate at the completion of exercise has been

characterized as a "reservoir of carbon" (74) which, besides serving as a source of carbon skeletons for the synthesis of glucose (50,71,185), glycogen repletion (25,81,161), amino acids (34) and TCA cycle intermediates (34,145), eventually serves as a source of oxidative ATP production. Further confounding the issue of the fate of lactate after exercise, in light of the working recovery, are reports that lactate production can occur during muscular contractions even when the muscle is well oxygenated (49,86,127,128,135). In fact, Issekutz and associates (125) have reported that lactate is not only produced but is utilized by the working muscle during exercise. A logical explanation for this observation, which is suggested by the authors, concerns the heterogeneity of fiber types in mammalian skeletal muscle (125).

Several investigators have reported that fast-twitch muscle fibers of rats have the capacity for synthesizing glycogen from lactate, but that slow-twitch fibers do not due to an extremely low level of fructose-1,6 diphosphatase activity (161,164,174). In contrast, Hintz et al. (105) reported that slow-twitch muscle fibers in one human subject had considerable levels of fructose-1,6 diphosphatase activity, and Bonen et al. (31) demonstrated a positive correlation between lactate removal and the percentage of slow-twitch muscle fibers in humans. As a consequence, the metabolic production and removal of lactate after exercise appears to depend in part on the biochemical profile of the muscle fibers involved which may vary considerably both between and within species. Although no complete explanation of the metabolic basis for excess post-exercise oxygen uptake exists, it may eventually

be understood in terms of those factors which directly or indirectly influence mitochondrial oxygen consumption and energy production. Included among these factors are creatine phosphate concentration (92,139), catecholamines (18,19,40,41,46,78), thyroxine (120), glucocorticoids (120), fatty acids (106), calcium ions (44), muscle fiber type (31,161,164,174), and temperature (35,36,37,89).

In light of the preceding discussion, further speculation is possible regarding the present recovery data of the male and female swimmers. Some researchers consider temperature to be the most influential factor contributing to the elevated post-exercise oxygen uptake (74). Increased muscle temperatures in humans have been associated with elevated post-exercise oxygen consumption (48,89). The relatively low oxygen debts in the present study (Tables 4, 6, 8, 10, and 12), as compared to those reported in previous studies on exercising humans (102,182,222), might be attributed to the efficacy of water in conducting heat away from the working skeletal musculature. However, if any sex difference exists in this regard due to subcutaneous body fat, it is masked by the anatomical and physiological factors that account for the higher oxygen uptakes in the males at each level of work and recovery (Fig. 1). The small differences in recovery RER values between the males and females (Fig. 3) are not likely due to intramuscular oxidative enzyme activities for carbohydrates and lipids since several investigators have reported no differences between men and women in either the trained or the untrained state (52,53,190). On the contrary, the slight differences in RER values in the present samples might be explained best by differences in training status

between the sexes. If the assumption that a higher proportion of the males than the females underwent a sprint training program is accepted, then metabolic adaptations related to substrate utilization and the fate of lactate in skeletal muscle may explain the lower RER values for the females during recovery. In this context, a sprint training program would consist of short to medium duration work intervals at maximal or near maximal speeds with relatively long rest periods interspersed. The purpose of such a training program would be to increase the flux of substrates through the glycolytic reactions and to maintain optimal metabolic accommodation of accumulated glycolytic products. Several training adaptations could influence substrate oxidation during recovery thus increasing metabolic production of carbon dioxide. Intense exercise training has been shown to increase the level of activity of glutamate-pyruvate transaminase (GTP) in gastrocnemius muscles of rats (163). This enzymatic reaction, besides providing for a larger percentage of pyruvate being converted to alanine than to lactate, also makes available α -ketoglutarate for oxidation in the Krebs cycle. The reaction plays an important role in maintaining levels of the Krebs cycle intermediates in muscle mitochondria (149). The enzymes of the malate-aspartate shuttle also are increased during intense training (107,108,109,110,149). This shuttle functions in skeletal muscle to transport reducing equivalents (NADH) generated in glycolysis into the mitochondria for oxidation. Finally, the oxidation of lactate in skeletal muscle may be enhanced by intense exercise training. A report by York et al. (234) has examined the effects of intense training on the subunits of lactate

dehydrogenase (LDH). The M subunit is predominant in skeletal muscle and catalyzes the conversion of pyruvate to lactate. The H subunit, the predominate form in cardiac muscle, catalyzes the reaction responsible for the oxidation of lactate. York et al. (234) have demonstrated a decrease in M subunit LDH activity while the H subunit activity remains unchanged with intense aerobic/anaerobic training. This finding suggests that an anaerobic training program could enhance the capacity of the H subunit LDH in skeletal muscle to oxidize lactate during and following exercise. The combination of these metabolic adaptations to intense training may function to increase the oxidation of lactate, to enhance NADH and Krebs cycle intermediates, and thus to increase the production of metabolic carbon dioxide which could be reflected in the higher RER values for the males than for the females throughout recovery (Fig. 3).

A final possibility exists to explain differences in the RER values during work and recovery between male and female swimmers. Several investigators, using both rats (6,166) and humans (193), have observed that, despite similar enzymatic adaptations in skeletal muscles, greater body weight and fat reductions occur following training in males than in females. This suggests the possibility that females are hormonally more resistant to some exercise regimens than are males. In the present study, the possibility exists that both sexes were trained with similar intensity but that the females responded with slightly altered or reduced adaptations.

Clear resolution of a possible sexual dimorphism in the metabolic adaptation to exercise awaits further experimentation. Undoubtly,

hormonal and behavioral differences exist and may exert their influences in a variety of ways.

Comparisons by Distance

The ages, heights and weights of the present sample of male and female sprint and middle-distance swimmers (Table 2) are comparable to those previously reported (29,121,173,203,219). The percentages of body fat were slightly lower and the LBW values were somewhat higher in the present group than in the sprint and middle-distance swimmers studied by Thorland et al. (219). These differences could be the result of the high caliber of swimmers included in the present investigation. No other reports of these variables for male or female sprint and middle-distance swimmers were found. Within the present sample, there were no differences between the female sprint and middle-distance swimmers for any of the physical characteristics presented in Table 2. The physical characteristics of the male sprinters were nearly identical to those of the middle-distance swimmers with the exception of percentage of body fat in which the male sprinters had significantly less body fat than did the middle-distance swimmers (8.6 ± 0.29 vs. $10.2 \pm 0.51\%$).

The lack of difference in the percentage of fat between female sprint and middle-distance swimmers is compatible with subjective evaluations by ourselves and others concerning the relatively high body fat content of top-caliber female swimmers as compared to other athletes of both sexes. This observation might serve as additional support for the previously discussed possibility of a sexual dimorphism in the adaptation to training. Under the assumption that both sexes

had participated in similar training regimens, the female sprint swimmers may have exhibited a resistance to anaerobic training which is partially reflected in the lack of body composition differences between the sprint and middle-distance female swimmers. Another possible differential response to training may be inferred from the RER value responses during work and recovery of the male and female sprint and middle-distance swimmers (Figures 8 and 9). Several studies have reported larger body weight and fat reductions following training in male than in female rats (6,166), and Savard et al. (193) have reported large reductions in the fatness levels of human males while no changes were recorded for females following the same training regimen. The present group, however, was highly trained and continually involved in swim training. The major training difference between the sprint and middle-distance swimmers would be the higher intensity but lesser amount of exercise that is presumably present in a sprint-training regimen. Further study is needed to identify differences in physical characteristics between sprint and middle-distance swimmers particularly in light of the fact that no other investigations have been able to distinguish between such characteristics in either sex (29,121,219).

The physiological variables for the male sprint and middle-distance swimmers are presented in Table 6 as absolute values and in Table 7 as values relative to body weight and lean body weight. Comparable values are found for the female and middle-distance subjects in Tables 8 and 9. For the males, absolute peak oxygen uptake (Table 6) was significantly higher ($p < .10$) in the middle-distance swimmers

than in their sprint counterparts. This finding is consistent with the hypothesis that, due to a specific training response and/or to a genetic predisposition to outstanding intramuscular oxidative capacity, the swimmers specializing in the longer events should have higher peak aerobic capacities. This difference in peak oxygen uptake is enhanced when the data are expressed relative to both body weight and lean body weight (Table 7) which further establishes the difference in whole body oxygen consumption between male sprint and middle-distance swimmers. Ohkuwa et al. (173), using a cycle ergometer test, also found higher peak oxygen uptake values in male distance swimmers than in male sprint swimmers. The peak oxygen uptake values in Ohkuwa's report were considerably less than those in the current study, an observation which is consistent with the fact that the swimmers in the present investigation were all of at least national caliber.

Shephard and coworkers (203) used treadmill running to demonstrate higher peak oxygen uptake values in male distance swimmers than in sprint or middle-distance swimmers. Although statistical analyses were not presented in the report, values expressed in absolute terms show marginal differences (4.37 vs. 4.89 l/min), while values expressed relative to body weight indicate more pronounced differences (58.3 vs. 65.4 ml/kg). Additional examination of Shephard's oxygen uptake data reveals no differences between his "sprint" and "middle" groups. Shephard's "middle" group would have been classified with the sprint group (200 yards or less) in the current study which seems justified in light of their absolute oxygen uptake values (4.37 vs. 4.35 l/min). The patterns of exercise and recovery oxygen uptakes for the male

sprint and middle-distance swimmers (Figure 4) are similar, with the exception that the magnitude of the response was higher in the middle-distance swimmers during the last 2.5-min of exercise and the first 30-s of recovery. Both groups reached a plateau in oxygen consumption as estimated by the criterion of a "centrally-limited" maximum (202).

In contrast to those of the males, the female absolute peak oxygen uptakes (Table 8) did not differ between the sprint and middle-distance swimmers. However, when the peak oxygen uptakes for the females are expressed in relative terms (Table 9), the middle-distance swimmers have significantly higher values than do the sprinters ($p = .027$ relative to body weight and $p = .022$ relative to LBW). Slightly lower body weights and lean body weights for the middle-distance swimmers (Table 2) can account for these differences in relative peak oxygen uptake. The patterns of the oxygen uptakes during exercise and recovery for the female sprint and middle-distance swimmers (Figure 5) approximate the patterns shown for the males in Figure 4 including the attainment of an oxygen uptake plateau in each group. The differences in uptake occurring between the female sprint and middle-distance swimmers in the final 2.5-min of exercise, although similar to those found in the male groups, were more pronounced ($p < .05$). However, when expressed in absolute terms the female differences in uptake disappear during this 2.5-min of exercise while such differences remain between the male sprint and middle-distance groups (data not shown).

Although several investigators have reported higher vital capacities for distance than for sprint swimmers (29,203), the

differences in oxygen uptake in the present study for both males and females were demonstrated without significant differences in ventilation, O_2 pulse or heart rate (Tables 6 and 8). Surprisingly, there also were no differences for either sex between sprinters and middle-distance swimmers in their absolute oxygen debts (Tables 6 and 8, Figures 4 and 5). These data confirm the few previous reports attempting to estimate anaerobic metabolic capacity in swimmers (62,203,223) and indicate a relatively weak relationship between oxygen debt and performance in sprint and middle-distance swimming events. One possible explanation for these findings can be offered in light of the dissociation between the rate of lactate production and removal and the recovery oxygen uptake (74). Whereas the excess post-exercise oxygen uptake is the result of a myriad of metabolic disturbances caused by strenuous work, the sprint swimmer may produce and tolerate high levels of lactate that are not even reflected in the oxygen consumption following exercise. Clearly the relationship between the respiratory oxygen debt and anaerobic metabolic capacity warrants further investigation.

Peak heart rate responses were not different between the distance groups for either the males (Table 6) or the females (Table 8). Heart rate responses during work and recovery were essentially the same for the males (Figure 6) and females (Figure 7). However, as compared to the sprinters, both male and female middle-distance swimmers maintained significantly lower heart rates during recovery. In addition, the female middle-distance swimmers had lower heart rates during the initial portion of work (Figure 7). No comparisons between sprint and

middle-distance swimmers are made in the literature concerning peak working or recovery heart rates. Lower resting heart rates were reported for male middle-distance swimmers than for sprinters (29), while no difference between resting heart rates was found in another study (203). Physical training in animals and humans frequently has resulted in lower heart rates during submaximal work (199). In view of the results of the present study, the possibility exists that the typical training program for distance swimming causes an increased stroke volume (184) which might manifest itself as a lowered heart rate response during recovery. Possibly this adaptation was not achieved by the sprinters. However, this explanation is tenuous at best, given the fact that, despite the specificity of a "sprint" training program, sprint swimmers undoubtedly train a sufficient volume (duration x frequency) to stimulate major adaptations in the cardio-respiratory system. Other research concerning the bradycardia of training suggests, as a potential mechanism, increases in parasympathetic activity of the heart with a concomitant reduction in resting sympathetic activity (199). The determination of whether or not differences in this regard correlate with differences in training intensity and volume awaits further investigation.

The peak RER values in Table 6 for male sprint and middle-distance swimmers were marginally different ($p = .053$). However, throughout exercise and recovery, the RER values presented in Figure 8 were consistently higher for the male sprinters, with the difference being statistically significant during work and the final four minutes of the recovery. In contrast, the RER values were not different between the

female sprint and middle-distance swimmers (Table 8, Figure 9). As previously discussed, the RER values obtained in the present study must be interpreted cautiously due to the lack of steady-state conditions during the test. However, the difference shown in Figure 8 between male sprint and middle-distance swimmers and the lack of difference in RER values between the female groups have at least two possible explanations. As a consequence of a "sprint" training program, several metabolic adaptations may occur which alter the oxidation of lactate, NADH, and Krebs cycle intermediates and which may be reflected by an increased production of carbon dioxide and thus higher RER values in the male sprint swimmers than in male middle-distance swimmers (Figure 8). The lack of difference in Figure 9 suggests the possibility that the majority of the female sprinters were not subjected to as intense a sprint training as were their male counterparts. A second possibility for the lack of RER value differences between the female groups (Figure 9) involves the suggestion of a sexual dimorphism in training response. In an earlier portion of this discussion, evidence was presented from the work of others which supports this suggestion as do the present data which demonstrate different RER responses during work and recovery for male and female swimmers (Figure 3). In reference to Figures 8 and 9, if both male and female sprinters underwent similar "sprint" training regimens, then their different responses in the RER values may indicate the possibility of a resistance to training in the female swimmers. The current data indicate that it might be possible to differentiate between "sprint" and "distance" trained swimmers. However, the question as to whether the female swimmers are actually

trained differently or if they undergo a differential response to the same training program is unresolved.

Comparisons by Rank

Although comparisons have been made between the metabolic responses to work tests of recreational and untrained swimmers (47,111,115,118,152), no investigation has attempted to distinguish between swimmers of differing performance capacities within a group of highly trained, national-caliber swimmers. In the present study, the performance time of each swimmer in his/her best event was used to rank the subjects within their respective sexes. The physical characteristics of the upper and lower 20% of each sex are given in Table 3. Within the females, there were no differences between the upper and lower 20% of the swimmers. The male swimmers ranked in the upper 20% were older and consequently taller and heavier. They also had higher lean body mass values than did the males ranked in the lower 20% (Table 3). Despite these differences, there is little to distinguish the males ranked in the upper 20% from those ranked in the lower 20% when considering physiological parameters expressed absolutely (Table 10) or in relative terms (Table 11). Similarly, the selected peak absolute and relative metabolic variables were not different between the females ranked in the upper and lower 20% of their group (Tables 12 and 13).

In contrast to the data in Tables 10 through 13, the data in Figures 10 through 15 (oxygen uptake, heart rate, and RER values during work and recovery) suggest the possibility that differences do exist between the upper and lower 20% of both the male and female swimmers.

The differences between the male groups, however, are quite unlike the differences between the female groups.

The oxygen uptake responses to work and recovery for male swimmers ranked in the upper and lower 20% are shown in Figure 10. According to the original hypothesis, swimmers ranked in the upper 20% might be expected to consume less oxygen than swimmers ranked in the lower 20% during the early and middle stages of exercise (i.e., up to a work load eliciting approximately 60% of peak oxygen uptake). At later more strenuous stages of work, the upper 20% group might be expected to surpass the lower group and reach higher levels of oxygen consumption. Recovery patterns for the two groups should be similar until oxygen uptake levels off near baseline values when the upper 20% group should again record lower values for the remainder of the recovery period. The patterns of oxygen uptake for the male swimmers (Figure 10) are in agreement with this hypothesis except that the values near the peak oxygen uptake for the lower 20% group remained higher than those of the upper 20% group. In contrast, the patterns of oxygen uptake for the females were reversed (Figure 11). Swimmers ranked in the lower 20% of the group recorded lower oxygen uptake values during work and recovery than did their upper 20% counterparts.

Heart rate values during work and recovery for the males and females (Figures 12 and 13) exhibited the same reversal of pattern as was seen in oxygen uptake. The males followed the expected pattern of similar heart rates during exercise and the first 2 min of recovery in both groups. However, once the heart rates returned to near baseline values (at approximately 40% of peak HR), the upper 20% group recorded

consistently lower heart rates than did the lower 20% group for the remainder of the recovery (Figure 12). Female heart rates (Figure 13) showed no differences between groups during work and a pattern opposite that of the males during recovery (i.e., lower 20% group with lower heart rates).

The pattern of RER values during work and recovery for the male and female swimmers show the same reversal of pattern as was seen in oxygen uptake and heart rate. Male swimmers ranked in the upper 20% have consistently lower RER values during work and the final 10 min of recovery than do the lower 20% males (Figure 14). In contrast, the pattern in the females was reversed from what was seen in the males (Figure 15). No differences were observed between the female groups during exercise.

The expected patterns of oxygen uptake, heart rate, and RER involve lower values for these parameters in swimmers ranked in the upper 20% during the early stages of work and the majority of the later stages of recovery. This hypothesis is based on information which indicates that endurance training enhances lipid metabolism while decreasing the rate of glycogen utilization in exercising skeletal muscle (83). A whole-body metabolic parameter that is thought to reflect these intracellular adaptations is a lowering of the RER values during steady-state work after training. Other information exists which predicts a lowered heart rate response during steady-state submaximal work following a training period (90,94,215). As indicated earlier, limitations to the interpretation of the present data include the fact that true steady-state work conditions were not achieved

during the tethered swim test despite a constant work load during recovery. However, inspection of Figures 10 through 15 reveals that all three parameters (oxygen uptake, heart rate and RER) had returned to near baseline levels by the midpoint of the recovery period. For the purpose of this discussion then, this leveling-off will be considered to satisfy steady-state work conditions despite its occurrence during recovery from maximal exercise. Another limitation to the interpretation of the data compared by rank within each sex is the difficulty of delineating between upper and lower 20% groups which are, in fact, parts of a relatively homologous sample that has been trained to perform at high levels of physical capacity. However, the present method of classifying a swimmer by relating his/her best performance time to the American record in that event does appear to create a workable dichotomy of upper and lower 20% groups. Further confounding the matter is the fact that even a sprint training program has more than an adequate volume of swimming to enhance aerobic capacity. In swimming, the difference in training between sprint and middle-distance competitors is sometimes obscure, so the classification of a swimmer as a sprinter may be based as much on natural sprinting ability as on the training protocol of the individual. However, at the highest levels of swimming competition, the vast majority of sprint swimmers do undergo a reasonable amount of high-intensity, sprint training. In the present sample, both the male and female upper and lower 20% groups consisted of similar proportions of sprint and middle-distance swimmers. Therefore, despite the aforementioned interpretive limitations, it is possible to state that the different

patterns of oxygen uptake, heart rate and RER values for male and female swimmers compared by rank within sexes might result from differential adaptations to training by males and females. Note that differences between the sexes are evident in the comparisons by distance as well as by rank and sex.

Several possibilities exist as explanations for the suggested sex difference in responses to the tethered swim test. Some have been discussed previously and will be only briefly reviewed here.

It is well known that the mitochondria of skeletal muscle undergo major adaptations to physical training. These adaptations are thought to be partially responsible for the enhanced capacity of trained muscle to extract oxygen during exercise. Although Costill et al. (52) have reported that there are no differences between trained men and women in regard to muscle fiber distribution or intramuscular enzymatic activities, a later report from the same laboratory (53) suggests that female muscle may adapt to a lesser degree than male muscle under similar training programs. An additional report by Savard et al. (193) indicates that the adipose tissue response to training is more efficient in males than in females which suggests that females may be resistant to some training programs. The results of the present study could be interpreted to support this observation and raise the possibility that the differential responses observed between men and women swimmers is at least partially due to a sexual dimorphism in the metabolic adaptations to training.

Another possibility discussed earlier is based upon the sex difference observed in cardiac function that exists apparently at the

gross anatomical and cellular levels. Human males have been shown to have larger maximal stroke volumes (9) and higher initial blood flows in the aorta (93) than do females. Also, male hearts have demonstrated greater intrinsic cardiac function than female hearts in both trained (197) and untrained rats (4,198). The possibility exists then that these sex differences are contributing to the alterations in patterns observed in the present study for the heart rate response of the upper- and lower-ranked swimmers (Figures 12 and 13). The influence of hormonal status on cardiac function has been suggested by several investigators (17,100,140,141,196,218). Hormonal status also is known to influence appetite (87), and since the daily energy intake and expenditure were not controlled in the present study, it is possible that differences in consumption and expenditure between the various comparison groups may have affected oxygen uptake and/or the RER values during exercise and recovery.

Another potential contributing factor to the possible sex differences in metabolic responses that was previously discussed is the fate of the lactic acid produced by the working musculature. Although no sex differences have been reported in the ability to oxidize lactate in liver or skeletal muscle, or in hepatic blood flow during or after exercise, differences between the sexes may be due partly to alterations in training programs. As discussed, if more males than females underwent an intensive sprint training program, RER values might be elevated due to increased CO_2 production as a result of more lactate being oxidized in male than in female skeletal muscle.

Further influence on the performances of men and women swimmers could be the typical sex differences in adipose tissue distribution. Though it has been suggested that females may be more effective than males as swimmers due to reduced body drag and increased buoyancy, this hypothesis has yet to be supported by scientific investigation. However, the combination of increased levels of subcutaneous adiposity and a possible alteration in motor unit recruitment patterns could effectively produce an increased work efficiency in the female swimmer and subsequently alter the metabolic characteristics of the female to work tests. Even though further investigation is required, it seems likely that differences exist between the sexes in the efficiency of work performed in water.

A final consideration is the possibility that the lower-ranked female swimmers were less talented, but reached high levels of performance by attaining higher levels of training. This would explain the pattern seen in Figure 11 in which the lower-ranked females attained a higher peak oxygen uptake value with lower oxygen consumption during recovery. However, this possibility does not explain the pattern seen in Figure 10 for the males in which the lower-ranked group attained higher oxygen uptakes for the final 2.5-min of exercise.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Summary

The intent of this study was to examine selected metabolic responses of national-caliber swimmers to a maximum-effort tethered swim test which employs a unique, continually adjusted loading protocol. Sixty-five females and 55 males participated in the testing. The major purposes of the investigation were to: (a) provide information concerning the physiological responses of well-trained female swimmers and contrast their responses with those of a similar group of male subjects; and (b) to differentiate, within each sex, between the metabolic responses of swimmers specializing in sprint and distance events and between the responses of swimmers ranked by performance in the upper and lower 20% of each sex group.

Analysis of variance indicated that the male swimmers had significantly higher absolute metabolic values than did the females with the exception of heart rate. These significant differences persisted but were reduced when the data were expressed relative to body weight and lean body mass.

Male distance swimmers were found to have significantly higher peak oxygen uptakes than did their sprint counterparts. This difference was apparent in data expressed in both absolute and relative terms. There was no difference in the metabolic data of the female swimmers categorized by distance speciality when expressed in absolute

terms. However, when expressed relative to body weight or lean body weight, female distance swimmers had significantly higher peak oxygen uptake values than did the sprint swimmers. Work/recovery curves indicate more efficient performances by both male and female distance swimmers when compared to sprinters.

Male swimmers ranked in the top 20% of their group had significantly higher peak absolute oxygen uptakes than did those males ranked in the bottom 20%. Those differences disappeared when the data are expressed relative to body weight or lean body weight. Peak absolute and relative metabolic values for female swimmers ranked in the upper and lower 20% of their group were not different. Work/recovery curves for the male swimmers indicate that the swimmers ranked in the upper 20% were more efficient than those ranked in the lower 20%. In general, this pattern was reversed when the females ranked in the upper and lower 20% were compared.

Finally, the loading protocol employed in the tethered swim test of the present study was capable of inducing centrally-limited maximum oxygen uptake in all comparison groups. This attainment of a plateau in oxygen uptake despite an increasing work load has not been demonstrated previously using other tethered swim protocols.

Conclusions

The results of this study warrant the following conclusions:

1. Elite male swimmers have higher peak absolute metabolic capacities than elite female swimmers. These differences, although reduced, persist when the data are expressed relative to body weight or lean body weight.

2. In both sexes, elite sprint and distance swimmers can be metabolically distinguished.
3. As indicated by the work/recovery curves, successful elite male swimmers perform more efficiently than less successful elite male swimmers. This pattern is reversed in similarly ranked elite female swimmers. A possible sexual dimorphism in training methodology and/or adaptations to training is suggested.
4. The demonstration of a plateau in oxygen consumption, indicating the attainment of a centrally-limited maximum performance on the tethered swim ergometer, indicates the importance of proper loading increments.

Recommendations

Following are suggestions for future investigation of the metabolic responses of swimmers to a tethered swim test.

The loading increments are of prime importance in determining maximum metabolic responses of swimmers by means of a tethered swim ergometer. Initial loading should be relative to the individual's capacity and training. Loading should be continuously adjusted to avoid test termination due to local fatigue.

Levels of physical training should be specified before comparison of groups can be made. Specific training regimens can be distinguished and should be included in the data analysis. Performance criteria can be used to dichotomize even a homogenous group of swimmers and may be useful in the interpretation of results.

Male and female data cannot be pooled for analysis because they represent separate populations. Sex differences also must be accounted for when subjects are distinguished by other criteria (distance speciality, rank). Further research is needed to identify factors contributing to success in elite swimmers. The possibility of a sexual dimorphism in training response warrants further investigation.

Appendix A

Appendix A

Method used to calculate standard load progressions for Est. Max. loads ≥ 4.00 kg.

<u>At Time</u>	<u>Work Load Calculated as Follows</u>
B 0:00	Base work load = 0.25 (Est. Max.) All values rounded to nearest 1/4 kg with values ending in exactly 1/8, 3/8, 5/8, or 7/8 kg rounded to next higher 1/4 kg.
E 0:00	Work load for bag E1 = 0.50 (Est. Max.) All values rounded to nearest 1/4 kg with values in exactly 1/8, 3/8, 5/8, or 7/8 kg rounded to next higher 1/4 kg.
E 0:30	Work load for bag E2 = work load for bag E1. Let Δ = difference between work loads for bags E1 and E6.
E 1:00	Work load for bag E3 = work load for bag E1 plus 35% of Δ .*
E 1:30	Work load for bag E4 = work load for bag E3 plus 28% of Δ .*
E 2:00	Work load for bag E5 = work load for bag E4 plus 22% of Δ .*
E 2:30	Work load for bag E6 = (Est. Max.) - 1.00 kg
E 3:00	Work load increased by 1/4 kg each subsequent exercise bag until exhaustion.

*Cumulative rounding errors occasionally resulted in a situation in which one of these work loads had to be altered subjectively by $\pm 1/4$ kg. Alterations were based upon: (a) smoothing progressions within corresponding bag numbers across Est. Max. loads, and (b) smoothing the progression within the given Est. Max. load across bags E2 . . . E6.

REFERENCES

REFERENCES

1. Adams, W. C. Influence of age, sex, and body weight on the energy expenditure of bicycle riding. J. Appl. Physiol. 22:539-545, 1967.
2. Adrian, M., M. Singh, and P. V. Karpovich. Energy cost of leg kick, arm stroke, and whole crawl stroke. J. Appl. Physiol. 21:1763-1766, 1966.
3. Agostoni, E., G. Gurtner, G. Torri, and H. Rahn. Respiratory mechanisms during submersion and negative pressure breathing. J. Appl. Physiol. 21:251-258, 1966.
4. Altmann, P. L. Respiration and Circulation. P. L. Altmann and D. S. Dittmar (Eds.), Fed. Amer. Soc. Exp. Biol., Bethesda, Md., 1971, p. 337.
5. Anderson, P. Capillary density of man. Acta Physiol. Scand. 95: 203-205, 1975.
6. Applegate, E. A., D. E. Upton, and J. S. Stern. Food intake, body composition and blood lipids following treadmill exercise in male and female rats. Physiol. Behav. 28:917-920, 1982.
7. Aborelius, M., Jr., U. I. Balldin, D. Lilja, and C. E. G. Lundgren. Hemodynamic changes in man during immersion with head above water. Aerospace Med. 43:592-598, 1972.
8. Asmussen, E. and I. Hemmingsen. Determination of maximum working capacity at different ages in work with the legs or with the arms. Scand. J. Clin. Lab. Invest. 10:67-71, 1958.
9. Astrand, P. O., T. E. Cuddy, B. Saltin, and J. Stenberg. Cardiac output during submaximal and maximal work. J. Appl. Physiol. 19:268-274, 1964.
10. Astrand, P. O. and S. Englesson. A swimming flume. J. Appl. Physiol. 33:514, 1972.
11. Astrand, P. O., L. Engstrom, B. O. Eriksson, P. Karlberg, I. Nylander, B. Saltin, and C. Thoren. Girl swimmers. With special reference to respiratory circulatory adaptation and gynecological and psychiatric aspects. Acta Paediat. Suppl. 147:43-75, 1963.
12. Astrand, P. O. and K. Rodahl. Textbook of Work Physiology. New York: McGraw-Hill, 1977.

13. Astrand, P. O. and I. Ryhming. A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during submaximal work. J. Appl. Physiol. 7:218-221, 1954
14. Astrand, P. O. and B. Saltin. Oxygen uptake during the first minutes of heavy muscular exercise. J. Appl. Physiol. 16: 971-976, 1961.
15. Astrand, P. O. and B. Saltin. Maximal oxygen uptake and heart rate in various types of muscular activity. J. Appl. Physiol. 16:977-981, 1961.
16. Bagnall, K. M. and D. W. Kellett. A study of potential Olympic swimmers: I. The starting point. Brit. J. Sports Med. 11:127-132, 1977.
17. Baker, P. J., E. R. Raman, and P. W. Ramwell. Androgen mediated sex-differences of cardiovascular responses in rats. Am. J. Physiol. 235:H242-H246, 1978.
18. Barnard, R. J. and M. L. Foss. Oxygen debt: Effect of beta-adrenergic blockade on the lactacid and alactacid components. J. Appl. Physiol. 27:813-816, 1969.
19. Barnard, R. H., M. L. Foss and C. M. Tipton. Oxygen debt: Involvement of the Cori cycle. Intern. Z. angew. Physiol. 28:105-119, 1970.
20. Bazett, H. C. Studies on effects of baths on man: Relationships between effects produced and temperature of bath. Am. J. Physiol. 70:412-429, 1924.
21. Bazett, H. C. Studies on effects of baths on man: Diuresis caused by warm baths, together with some observations on urinal tides. Am. J. Physiol. 70:430-542, 1924.
22. Belcastro, A. N. and A. Bonen. Lactic acid removal rates during controlled and uncontrolled recovery exercise. J. Appl. Physiol. 39:932-936, 1975.
23. Bell, G. H. The effects of two breathing patterns on selected physiological parameters during a 200-yard simulated freestyle swim in male swimmers. J. Sports Med. 21:271-278, 1981.
24. Bell, G. H. and P. M. Ribisl. Maximal oxygen uptake during swimming of young competitive swimmers 9 to 17 years of age. Res. Quart. 50:574-582, 1979.
25. Bendall, J. R. and A. A. Taylor. The Meyerhof quotient and the synthesis of glycogen from lactate in frog and rabbit muscle. Biochem. J. 118:887-893, 1970.

26. Bennett, A. F. Activity metabolism of the lower vertebrates. Ann. Rev. Physiol. 400:447-469, 1978.
27. Berniuk, M. J. E., W. B. M. Erich, A. L. Peltenburg, M. L. Zonderland, and I. A. Huisveld. Height, body composition, biological maturation and training in relation to socio-economic status in girl gymnasts, swimmers, and controls. Growth 47:1-12, 1983.
28. Bevegard, B. S., V. Freyschuss, and T. Strandell. Circulatory adaptation to arm and leg exercise in supine and sitting position. J. Appl. Physiol. 21:37-46, 1966.
29. Bloomfield, J. and P. O. Sigersth. Anatomical and physiological differences between sprint and middle distance swimmers at the University level. J. Sports Med. Phys. Fitness 5:76-81, 1965.
30. Bonen, A. and A. N. Belcastro. Comparison of self-selected recovery methods on lactic acid removal rates. Med. Sci. Sports 8:176-178, 1976.
31. Bonen, A., C. J. Campbell, R. L. Kirby, and A. N. Belcastro. Relationship between slow-twitch muscle fibres and lactic acid removal. Can. J. Appl. Sport Sci. 3:160-162, 1978.
32. Bonen, A., B. A. Wilson, M. Yarkony, and A. N. Belcastro. Maximal oxygen uptake during free, tethered, and flume swimming. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 48:232-235, 1980.
33. Brooks, G. A., K. E. Brauner, and R. G. Cassens. Glycogen synthesis and metabolism of lactic acid after exercise. Am. J. Physiol. 224:1162-1166, 1973.
34. Brooks, G. A. and B. A. Gaesser. End points of lactate and glucose metabolism after exhausting exercise. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 49:1057-1069, 1980.
35. Brooks, G. A., K. J. Hittelman, J. A. Faulkner, and R. E. Beyer. Temperature, liver mitochondrial respiratory functions, and oxygen debt. Med. Sci. Sports 2:72-74, 1971.
36. Brooks, G. A., K. J. Hittelman, J. A. Faulkner, and R. E. Beyer. Temperature, skeletal muscle mitochondrial functions, and oxygen debt. Am. J. Physiol. 220:1053-1059, 1971.
37. Brooks, G. A., K. J. Hittelman, J. A. Faulkner, and R. E. Beyer. Tissue temperatures and whole-animal oxygen consumption after exercise. Am. J. Physiol. 221:427-431, 1971.

38. Bullard, R. W. and G. M. Rapp. Problems of body heat loss in water immersion. Aerospace Med. 41:1269-1277, 1970.
39. Buskirk, E. and H. L. Taylor. Maximal oxygen uptake and its relation to body composition. J. Appl. Physiol. 11:72-77, 1957.
40. Cain, S. M. Exercise O₂ debts of dogs at ground level at altitude with and without β -block. J. Appl. Physiol. 30:838-843, 1971.
41. Cain, S. M. and C. K. Chapler. Effects of norepinephrine and β -block on O₂ uptake and blood flow in dog hindlimb. J. Appl. Physiol. 51:1245-1250, 1981.
42. Campbell, E. J. M. The Respiratory Muscles and the Mechanics of Breathing. Chicago: Year Book, 1958.
43. Capasso, J. M., R. M. Remily, R. H. Smith, and E. H. Sonnenblick. Sex differences in myocardial contractility in the rat. Basic Res. Cardiol. 78:156-171, 1983.
44. Carafoli, E. and A. L. Lehninger. A survey of the interaction of calcium ions with mitochondria from different tissues and species. Biochem. J. 122:681-690, 1971.
45. Carlson, L. D., A. C. L. Hsieh, F. Fullington, and R. W. Busner. Immersion in cold water and body tissue insulation. J. Aviation Med. 29:145-152, 1958.
46. Chapler, C. K., W. N. Stainsby, and L. B. Gladden. Effect of changes in blood flow, norepinephrine, and pH on oxygen uptake by resting skeletal muscle. Can. J. Physiol. Pharmacol. 58:93-96, 1980.
47. Charbonnier, J. P., J. R. Lacour, J. Riffat, and R. Flandrois. Experimental study of the performance of competition swimmers. Europ. J. Appl. Physiol. 34:157-167, 1975.
48. Claremont, A. D., F. Nagle, W. D. Reddan, and G. A. Brooks. Comparison of metabolic, temperature, heart rate and ventilatory responses to exercise at extreme ambient temperatures (0° C and 35° C). Med. Sci. Sports 7: 150-157, 1975.
49. Connett, R. J., T. E. J. Gayeski, and C. R. Honig. Lactate accumulation in fully aerobic, working dog gracilis muscle. Am. J. Physiol.: Heart Circ. Physiol. 15:H120-H128, 1984.
50. Cori, C. F. Mammalian carbohydrate metabolism. Physiol. Rev. 11:143-275, 1931.

51. Costill, D. L., P. J. Cahill, and D. Eddy. Metabolic response to submaximal exercise in three water temperatures. J. Appl. Physiol. 22:628-632, 1967.
52. Costill, D. L., J. Daniels, W. Evans, W. Fink, G. Krahenbuhl, and B. Saltin. Skeletal muscle enzymes and fiber composition in male and female track athletes. J. Appl. Physiol. 40:149-154, 1976.
53. Costill, D. L., W. J. Fink, L. H. Getchell, J. L. Ivy, and F. A. Witzmann. Lipid metabolism in skeletal muscle of endurance-trained males and females. J. Appl. Physiol. : Respirat. Environ. Exerc. Physiol. 47:787-791, 1979.
54. Cowan, C. R. and O. M. Solandt. The duration of the recovery period following strenuous muscular exercise, measured to a base line of steady, mild exercise. J. Physiol. (London) 89:462-466, 1937.
55. Craig, A. B. Influence of exercise and O₂ on breath holding. J. Appl. Physiol. 17:225-227, 1962.
56. Craig, A. B. and M. Dvorak. Thermal regulation of man exercising during water immersion. J. Appl. Physiol. 25:28-35, 1968.
57. Cureton, T. K. Physical Fitness Appraisal and Guidance. St. Louis: C. V. Mosby and Company, 1947, p. 262-266.
58. Daniels, J. Portable respiratory gas collection equipment. J. Appl. Physiol. 31:164-167, 1971.
59. Davies, C. T. M., A. V. Knibbs, and J. Musgrove. The rate of lactic acid removal in relation to different baselines of recovery exercise. Int. Z. angew. Physiol. 28:155-161, 1970.
60. deVries, H. A. Physiology of Exercise. Dubuque, Iowa: Wm. C. Brown Co. Publishers, 1980.
61. Dicker, S. G., G. K. Lofthus, N. W. Thornton, and G. A. Brooks. Respiratory and heart rate responses to tethered controlled frequency breathing swimming. Med. Sci. Sports Exerc. 12:20-23, 1980.
62. DiPrampo, P. E., F. P. Limas, and G. Sassi. Maximal muscular power, aerobic and anaerobic, in 116 athletes performing at the XIXth Olympic Games in Mexico. Ergonomics 13:665-674, 1970.
63. Dixon, R. W. and J. A. Faulkner. Cardiac outputs during maximum effort running and swimming. J. Appl. Physiol. 30:653-656, 1971.

64. Donovan, C. M. and G. A. Brooks. Endurance training affects lactate clearance, not lactate production. Am. J. Physiol.: Endocrinol. Metab. 224:E83-E92, 1983.
65. Drinkwater, B. Physiological responses of women in exercise. In Exercise and Sport Science Review, Vol. 1, J. H. Wilmore (Ed.), New York: Academic Press, 1973.
66. Drury, D.R. and A. N. Wick. Metabolism of lactic acid in the intact rabbit. Am. J. Physiol. 184:304-308, 1956.
67. Ekblom, B. Effect of physical training on oxygen transport system in man. Acta Physiol. Scand. Suppl. 328:11, 1969.
68. Eriksson, B. O., I. Holmer, and A. Lundin. Physiological effects of training in elite swimmers. In Swimming Medicine IV. International Series on Sport Sciences, Vol. 6, B. Eriksson and B. Furberg (Eds.), Baltimore, MD: University Park Press, 1978, p. 177-187.
69. Faulkner, J. A. Physiology of swimming. Res. Quart. 37:41-54, 1966.
70. Faulkner, J. Physiology of swimming and diving. In Exercise Physiology, H. Z. Falls (Ed.), New York: Academic Press, 1968, p. 415-446.
71. Freminet, A., E. Bursaux, and C. F. Poyast. Effect of elevated lactataemia on the rates of lactate turnover and oxidation in rats. Pflugers Arch. 346:75-86, 1974.
72. Froelicher, V. F., H. Brammell, G. Davis, I. Noguera, A. Stewart, and M. C. Lancaster. A comparison of three maximal treadmill exercise protocols. J. Appl. Physiol. 36:720-725, 1974.
73. Gaesser, G. A. and G. A. Brooks. Glycogen repletion following continuous and intermittent exercise to exhaustion. J. Appl. Physiol. 49:722-728, 1980.
74. Gaesser, G. A. and G. A. Brooks. Metabolic bases of excess post-exercise oxygen consumption: A review. Med. Sci. Sports Exerc. 16:29-43, 1984.
75. Galbo, H., M. Houston, N. J. Christensen, J. J. Holst, B. Nielsen, E. Nygaard, and J. Suzuki. The effect of water temperature on the hormonal response to prolonged swimming. Acta Physiol. Scand. 105:326-337, 1979.
76. Gergley, T. J., W. D. McArdle, P. DeJesus, M. M. Toner, S. Jacobowitz, and R. J. Spina. Specificity of arm training on aerobic power during swimming and running. Med. Sci. Sports Exerc. 16:349-354, 1984.

77. Gisolfi, C., S. Robinson, and E. S. Turrell. Effects of aerobic work performed during recovery from exhausting work. J. Appl. Physiol. 21:1767-1772, 1966.
78. Gladden, L., W. Stainsby, and B. MacIntosh. Norepinephrine increases canine skeletal muscle $\dot{V}O_2$ during recovery. Med. Sci. Sports Exerc. 14:471-476, 1982.
79. Glaser, R. M., M. N. Sawka, M. F. Brune, and S. W. Wilde. Physiological responses to maximal effort wheelchair and arm crank ergometry. J. Appl. Physiol. : Respirat. Environ. Exerc. Physiol. 48:1060-1064, 1980.
80. Gleeson, T. Metabolic recovery from exhaustive activity by a large lizard. J. Appl. Physiol. 48:689-694, 1980.
81. Gleeson, T. Lactate and glycogen metabolism during and after exercise in the lizard *Sceleoporus occidentalis*. J. Comp. Physiol. 147:79-84, 1982.
82. Godfrey, S. The growth and development of the cardio-pulmonary response to exercise. In Scientific Foundations of Paediatrics, J. A. Davis and J. Dobbing (Eds.), Philadelphia, PA: Saunders, 1974, p. 271-280.
83. Gollnick, P. D. Free fatty acid turnover and the availability of substrates as a limiting factor in prolonged exercise. N. Y. Acad. Sci. 301:64-71, 1977.
84. Gollnick, P. D., R. B. Armstrong, C. W. Saubert, IV, K. Piehl, and B. Saltin. Enzyme activity and fiber composition in skeletal muscle of untrained and trained men. J. Appl. Physiol. 33:312-319, 1972.
85. Goodwin, B. P. E. and G. R. Cumming. Radiotelemetry of the electrocardiogram, fitness tests, and oxygen uptake of water-polo players. Can. Med. Assoc. J. 95:402-406, 1966.
86. Graham, T. E., D. G. Sinclair, and C. K. Chapler. Metabolic intermediates and lactate diffusion in active dog skeletal muscle. Am. J. Physiol. 231:766-771, 1976.
87. Gray, J. M. and M. R. C. Greenwood. Time course of effects of ovarian hormones on food intake and metabolism. Am. J. Physiol. : Endocrinol. Metab. 243:E203-E211, 1981.
88. Green, H. J., I. G. Fraser, and D. A. Ranney. Male and female differences in enzyme activities of energy metabolism in vastus lateralis muscle. J. Neurol. Sci. 65:323-331, 1984.
89. Hagberg, J. M., J. P. Mullin, and F. J. Nagle. Effect of work intensity and duration on recovery O_2 . J. Appl. Physiol. : Respirat. Environ. Exerc. Physiol. 48:540-544, 1980.

90. Hanson, J. S. and B. S. Tabakin. Comparison of the circulatory response to upright exercise in 25 normal men and 9 distance runners. Brit. Heart J. 27:211-219, 1965.
91. Harris, P., M. Bateman, T. J. Bayley, K. W. Donald, J. Gloster, and T. Whitehead. Observations on the course of the metabolic events accompanying mild exercise. Q. J. Exp. Physiol. 53:43-64, 1968.
92. Harris, R. R., R. Edwards, E. Hultman, L. O. Nordesjo, B. Nyland, and K. Sahliu. The time course of phosphorylcreatine resynthesis during recovery of the quadriceps muscle in man. Pflugers Arch. 367:137-142, 1976.
93. Harrison, W. K. and J. E. Smith. Sex differences in cardiac function of a group of young adults. Cardiology 66:74-84, 1980.
94. Hartley, L. H., G. Grimby, A. Kilbom, N. J. Nilsson, I. Astrand, J. Bjure, B. Ekblom, and B. Saltin. Physical training in sedentary middle-aged and older men. Scand. J. Clin. Lab. Invest. 24:335-344, 1969.
95. Heigenhauser, G. J. F., D. Boulet, B. Miller, and J. A. Faulkner. Cardiac outputs of post-myocardial infarction patients during swimming and cycling. Med. Sci. Sports 9:143-147, 1977.
96. Heigenhauser, G. J. F. and J. A. Faulkner. Estimation of cardiac output by the CO₂ rebreathing method during tethered swimming. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 44:821-824, 1978.
97. Heigenhauser, G. J. F., N. B. Oldridge, and N. L. Jones. The CO₂ responsiveness and ventilatory response to leg and arm exercise in female swimmers. Respir. Physiol. 53:263-272, 1983.
98. Hermansen, K. and B. Saltin. Oxygen uptake during maximal treadmill and bicycle exercise. J. Appl. Physiol. 26:31-37, 1969.
99. Hermansen, K. and I. Stensvold. Production and removal of lactate during exercise in man. Acta Physiol. Scand. 86:191-201, 1972.
100. Hickson, R. C., T. M. Galassi, T. T. Kurowski, D. G. Daniels, and R. T. Chatterton, Jr. Androgen and glucocorticoid mechanisms in exercise-induced cardiac hypertrophy. Am. J. Physiol.: Heart Circ. Physiol. 246:H761-H767, 1984.
101. Hill, A. V., C. N. H. Long, and H. Lupton. Muscular exercise, lactic acid and the supply and utilization of oxygen. Pt. I-III. Proc. Roy. Soc. B. 96:438-475, 1924.

102. Hill, A. V., C. N. H. Long, and H. Lupton. Muscular exercise, lactic acid and the supply and utilization of oxygen. Pt. IV-VI Proc. Roy. Soc. B. 97:84-138, 1924.
103. Hill, A. V., C. N. H. Long, and H. Lupton. Muscular exercise, lactic acid and the supply and utilization of oxygen. Pt. VII-VIII Proc. Roy. Soc. B. 97:155-176, 1924.
104. Hill, A. V., C. N. H. Long, and H. Lupton. Muscular exercise, lactic acid and the supply and utilization of oxygen. Quart. J. Med. 16:135-171, 1923.
105. Hintz, C. S., C. V. Lowry, K. K. Kaiser, D. McKee, and O. H. Lowry. Enzyme levels in individual rat muscle fibers. Am. J. Physiol.: Cell Physiol. 239:C58-C65, 1980.
106. Hittelman, K. J., O. Lindberg, and B. Cannon. Oxidative phosphorylation and compartmentation of fatty acid metabolism in brown fat mitochondria. Europ. J. Biochem. 11:183-192, 1969.
107. Holloszy, J. O. and F. W. Booth. Biochemical adaptation to endurance exercise in muscle. Ann. Rev. Physiol. 38:273-291, 1976.
108. Holloszy, J. O., F. W. Booth, W. W. Winder, and R. H. Fitts. Biochemical adaptations of skeletal muscle to prolonged physical exercise. In Metabolic Adaptation to Prolonged Physical Exercise, H. Howard and J. R. Poortmans (Eds.), Proceedings of the 2nd International Symposium of Biochemistry of Exercise, 1973, p. 438-447.
109. Holloszy, J. O. and E. F. Coyle. Adaptations of skeletal muscle to endurance exercise and their metabolic consequences. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 56:831-838, 1984.
110. Holloszy, J. O., M. J. Rennie, R. C. Hickson, R. K. Conlee, and J. M. Hageberg. Physiological consequences of the biochemical adaptations to endurance exercise. Ann. N.Y. Acad. Sci. 301:440-450, 1977.
111. Holmer, I. Oxygen uptake during swimming in man. J. Appl. Physiol. 33:502-509, 1972.
112. Holmer, I. Energy cost of arm stroke, leg kick, and the whole stroke in competitive swimming styles. Europ. J. Appl. Physiol. 33:105-118, 1974.
113. Holmer, I. Physiology of swimming man. Acta Physiol. Scand. Suppl. 407:6-55, 1974.

114. Holmer, I. Physiology of swimming man. In Exercise and Sport Sciences Reviews, Vol. 7, R. S. Hutton and D. I. Miller (Eds.), Philadelphia, PA: The Franklin Press Inst., 1979, p. 87-124.
115. Holmer, I. and P. O. Astrand. Swimming training and maximal oxygen uptake. J. Appl. Physiol. 33:510-513, 1972.
116. Holmer, I. and U. Bergh. Metabolic and thermal response to swimming in water at varying temperatures. J. Appl. Physiol. 37:702-705, 1974.
117. Holmer, I., A. Lundin, and B. O. Eriksson. Maximum oxygen uptake during swimming and running by elite swimmers. J. Appl. Physiol. 36:711-714, 1974.
118. Holmer, I., E. M. Stein, B. Saltin, B. Ekblom, and P. O. Astrand. Hemodynamic and respiratory responses compared in swimming and running. J. Appl. Physiol. 37:49-54, 1974.
119. Hong, S. K., P. Cerretilli, J. C. Cruz, and H. Rahn. Mechanics of respiration during submersion in water. J. Appl. Physiol. 27:535-538, 1969.
120. Horwitz, B. A. Metabolic aspects of thermogenesis: Neuronal and hormonal control. Fed. Proc. 38:2147-2149, 1979.
121. Hough, T. J., W. G. Thorland, G. O. Johnson, G. D. Tharp, C. J. Cisar, M. J. Refsell, and C. J. Ansorge. Body composition variables as discriminators of sports participation of elite adolescent female athletes. Res. Quart. 55:302-304, 1984.
122. Houston, M. E., D. M. Wilson, H. J. Green, J. A. Thomson and D. A. Ranney. Physiological and muscle enzyme adaptation to two different intensities of swim training. Europ. J. Appl. Physiol. 46:283-291, 1981.
123. Issekutz, B., N. C. Birkhead, and K. Rodahl. Use of respiratory quotients in assessment of aerobic work capacity. J. Appl. Physiol. 17:47-50, 1962.
124. Issekutz, B. and K. Rodahl. Respiratory quotient during exercise. J. Appl. Physiol. 16:606-610, 1961.
125. Issekutz, B., W. A. S. Shaw, and A. C. Issekutz. Lactate metabolism in resting and exercising dogs. J. Appl. Physiol. 40:312-319, 1976.
126. Jansson, E. On the significance of the respiratory exchange ratio after different diets during exercise in man. Acta Physiol. Scand. 114:103-110, 1982.

127. Jobsis, F. F. Spectrophotometric studies on intact muscle. II. Recovery from contractile activity. J. Gen. Physiol. 46:929-969, 1963.
128. Jobsis, F. F. and W. N. Stainsby. Oxidation of NADH during contraction of circulated mammalian skeletal muscle. Respirat. Physiol. 4:292-300, 1968.
129. Johnson, R. H., J. L. Walton, H. A. Krebs, and R. H. Williamson. Metabolic fuels during and after severe exercise in athletes and non-athletes. Lancet 2:452-455, 1969.
130. Kamon, E. and K. B. Pandolf. Maximal aerobic power during laddermill climbing, uphill running and cycling. J. Appl. Physiol. 32:467-473, 1972.
131. Karpovich, P. V. Respiration in swimming and diving. Res. Quart. 10:3-14, 1939.
132. Karpovich, P. V. and H. LeMaistre. Prediction of time in swimming the breaststroke based on oxygen consumption. Res. Quart. 11:40-44, 1940.
133. Kayne, H. L. and N. R. Alpert. Oxygen consumption following exercise in the anesthetized dog. Am. J. Physiol. 206:51-56, 1964.
134. Keatinge, W. R. The effect of work and clothing on the maintenance of body temperature in water. Quart. J. Exp. Physiol. 46:69-82, 1961.
135. Keul, J., D. Doll, and D. Keppler. The substrate supply of the human skeletal muscle at rest, during and after work. Experientia 23:974-979, 1967.
136. Klissouras, V. and W. S. Sinning. Metabolic prediction of swimming performance. In Swimming Medicine IV. International Series on Sport Sciences, Vol. 6, B. Eriksson and B. Furberg (Eds.), Baltimore, MD: University Park Press, 1978, p. 262-273.
137. Knowlton, R. G., M. N. Sawka, and D. T. Deutsch. Varied intensity treadmill protocols for the measurement of maximal oxygen uptake. J. Sports Med. 17:262-268, 1977.
138. Knuttgen, H. G. Oxygen debt after submaximal physical exercise. J. Appl. Physiol. 29:651-657, 1970.
139. Knuttgen, H. G. and B. Saltin. Muscle metabolites and oxygen uptake in short-term submaximal exercise in man. J. Appl. Physiol. 32:690-694, 1972.

140. Koenig, H., A. Goldstone, and C. Y. Lu. Testosterone-mediated sexual dimorphism of the rodent heart. Circ. Res. 50:782-787, 1982.
141. Krieg, M., K. Smith, and W. Bartsch. Demonstration of a specific androgen receptor in rat heart muscle: Relationship between binding, metabolism, and tissue levels of androgens. Endocrinology 103:1686-1694, 1978.
142. Lange, L., S. Lange, M. Echt, and O. H. Gaver. Heart volume in relation to body posture and immersion in a thermo-neutral bath. Pfluegers Archiv. 352:219-226, 1974.
143. Lavoie, J. M., A. W. Taylor, and R. R. Montpetit. Physiological effects of training in elite swimmers as measured by a free swimming test. J. Sports Med. 21:38-42, 1981.
144. Lavoie, J. M. and G. Thibault. Specificity of swim training on maximal oxygen uptake: An inter-sex comparison. Med. Sci. Sports Exerc. 14:112-118, 1981.
145. Lee, S. H. and E. J. Davis. Carboxylation and decarboxylation reactions. J. Biol. Chem. 254:420-430, 1979.
146. Lewis, S. F., P. G. Snell, W. F. Taylor, M. Hamra, R. M. Graham, W. A. Pettinger, and C. G. Blomquist. Role of muscle mass and mode of contraction in circulatory responses to exercise. J. Appl. Physiol. 58:146-151, 1985.
147. Liljestrang, G. and J. Lindhard. Uber das Minutevolumen des Herzens beim Schwimmen. Skand. Arch. Physiol. 39:64-77, 1919.
148. Liljestrang, G. and N. Strenstrom. Studien uber die Physiologie des Schwimmens. Skand. Arch. Physiol. 39:1-63, 1919.
149. Lowenstein, J. M. Ammonia production in muscle and other tissues: The purine nucleotide cycle. Physiol. Rev. 52:382-414, 1972.
150. Magel, J. R. Propelling force measured during tethered swimming in the four competitive swimming styles. Res. Quart. 41:68-74, 1970.
151. Magel, J. R. Comparison of the physiologic response to varying intensities of submaximal work in tethered swimming and treadmill running. J. Sports Med. Phys. Fitness 11:203-212, 1971.
152. Magel, J. R. and K. L. Andersen. Pulmonary diffusing capacity and cardiac output in young trained Norwegian swimmers and untrained subjects. Med. Sci. Sports 1:131-139, 1969.

153. Magel, J. R. and J. A. Faulkner. Maximum oxygen uptakes of college swimmers. J. Appl. Physiol. 22:929-938, 1967.
154. Magel, J. R., W. D. McArdle, and R. M. Glaser. Telemetered heart rate response to selected competitive swimming events. J. Appl. Physiol. 26:764-770, 1969.
155. Magel, J. R., W. D. McArdle, M. Toner, and D. J. Delio. Metabolic and cardiovascular adjustment to arm training. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 45:75-79, 1978.
156. Margaria, R., H. T. Edwards, and D. B. Dill. The possible mechanisms of contracting and paying the oxygen debt and the role of lactic acid in muscular contraction. Am. J. Physiol. 106:689-715, 1933.
157. Mathews, D. K. and E. L. Fox. The Physiological Basis of Physical Education and Athletics. Philadelphia, PA: Saunders, 1976, p. 449-460.
158. McArdle, W. D., G. F. Foglia, and A. V. Patti. Telemetered cardiac response to selected running events. J. Appl. Physiol. 23:566-570, 1967.
159. McArdle, W. D., R. M. Glaser, and J. R. Magel. Metabolic and cardio-respiratory response during free swimming and treadmill walking. J. Appl. Physiol. 30:733-738, 1971.
160. McArdle, W. D., J. R. Magel, G. R. Lesmes, and G. S. Pechar. Metabolic and cardiovascular adjustment to work in air and water at 18, 25 and 33° C. J. Appl. Physiol. 40:85-90, 1976.
161. McLane, J. A. and J. O. Holloszy. Glycogen synthesis from lactate in the three types of skeletal muscle. J. Biol. Chem. 254:6548-6553, 1979.
162. McMurray, R. G. and S. M. Horvath. Thermoregulation in swimmers and runners. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 46: 1086-1092, 1979.
163. Mole, P. A., K. M. Baldwin, R. L. Terjung, and J. O. Holloszy. Enzymatic pathways of pyruvate metabolism in skeletal muscle: Adaptations to exercise. Am. J. Physiol. 224:50-54, 1973.
164. Moorthy, K. A. and M. K. Gould. Synthesis of glycogen from glucose and lactate in isolated rat soleus muscle. Arch. Biochem. Biophys. 130:399-407, 1969.
165. Nadel, E. R., I. Holmer, U. Bergh, P. O. Astrand, and J. A. J. Stolwijk. Energy exchanges of swimming man. J. Appl. Physiol. 36:465-471, 1974.

166. Nance, D. M., B. Bromley, and L. M. Krusak. Detailed body composition analysis of female rats subjected to a program of swimming. J. Nutr. 103:412-418, 1973.
167. Newman, E. V., D. B. Dill, H. T. Edwards, and F. A. Webster. The rate of lactic acid removal in exercise. Am. J. Physiol. 118:457-462, 1937.
168. Nielsen, B. Metabolic reactions to changes in core and skin temperatures in man. Acta Physiol. Scand. 97:129-138, 1976.
169. Normura, T. Maximal oxygen uptake of age group swimmers. Jap. J. Phys. Educ. 22:301-309, 1978.
170. Novak, L. P., M. Bierbaum, and H. Mellerowicz. Maximal oxygen consumption, pulmonary function, body composition, and anthropometry of adolescent female athletes. Int. Z. angew. Physiol. 21:103-119, 1973.
171. Novak, L. P., R. E. Hyatt, and J. F. Alexander. Body composition and physiologic function of athletes. J. Am. Med. Assoc. 205:764-770, 1968.
172. Novak, L. P., W. A. Woodward, C. Bestit, and H. Mellerowicz. Working capacity, body composition and anthropometry of Olympic female athletes. J. Sports Med. Phys. Fitness 17:275-285, 1977.
173. Ohkuwa, T., N. Fujitsuka, T. Utsuno, and M. Miyamura. Ventilatory response to hypercapnia in sprint and long-distance swimmers. Europ. J. Appl. Physiol. 43:235-241, 1980.
174. Pearce, F. and R. Connett. Effect of lactate and palmitate on substrate utilization of isolated rat soleus. Am. J. Physiol.: Cell Physiol. 238:C149-C159, 1980.
175. Peter, J. B., R. J. Barnard, V. R. Edgerton, C. A. Gillespie, and K. E. Stempel. Metabolic profiles of three fiber types of skeletal muscle in guinea pigs and rabbits. Biochemistry 14:2627-2633, 1972.
176. Pickering, G. W. Hypertension: Causes, Consequences and Management. Edinburgh: Churchill Livingstone, 1974.
177. Pollock, M. L., C. Foster, D. Schmidt, C. Hellman, A. C. Linnerud, and A. Ward. Comparative analysis of physiologic responses to three different maximal graded exercise test protocols in healthy women. Am. Heart J. 103:363-373, 1982.
178. Pugh, L. G. L. and O. G. Edholm. The physiology of channel swimmers. Lancet 2:761-768, 1955.

179. Pugh, L. G. L., O. G. Edholm, R. H. Fox, H. S. Wolff, G. R. Hervey, W. H. Hammond, J. M. Tanners, and R. H. Whitehouse. A physiological study of channel swimming. Clin. Sci. 19:257-273, 1960.
180. Reybrouck, T. G., F. Heigenhauser, and J. A. Faulkner. Limitations to maximum oxygen uptake in arm, leg and combined arm-leg ergometry. J. Appl. Physiol. 38:774-779, 1975.
181. Roberts, J. A. and J. W. Alspaugh. Specificity of training effects resulting from programs of treadmill running and bicycle ergometer riding. Med. Sci. Sports 4:6-10, 1972.
182. Robinson, S., D. L. Robinson, R. J. Mountjoy, and R. W. Bullard. Influence of fatigue on the efficiency of men during exhausting runs. J. Appl. Physiol. 12:197-201, 1958.
183. Robinson, S. and A. Somers. Temperature regulation in swimming. J. Physiol. (Paris) 63:406-409, 1971.
184. Rowell, L. B. Human cardiovascular adjustments to exercise and thermal stress. Physiol. Rev. 54:75-159, 1974.
185. Rowell, L. B., K. K. Kraning II, T. O. Evans, J. W. Kennedy, J. R. Blackmon, and F. Kusumi. Splanchnic removal of lactate and pyruvate during prolonged exercise in man. J. Appl. Physiol. 21:1773-1783, 1966.
186. Royce, J. Active and passive recovery from maximal aerobic capacity work. Int. Z. angew. Physiol. 28:1-8, 1969.
187. Sacks, J. and W. C. Sacks. Carbohydrate changes during recovery from muscular contraction. Am. J. Physiol. 112:565-572, 1935.
188. Saltin, B. Oxygen transport by the circulatory system during exercise in man. In Limiting Factors of Physical Performance, J. Keul (Ed.), Stuttgart: Thieme, 1973, p. 240.
189. Saltin, B. and P. O. Astrand. Maximal oxygen uptake in athletes. J. Appl. Physiol. 23:353-358, 1967.
190. Saltin, B., J. Henriksson, E. Nygaard, and P. Anderson. Fiber types and metabolic potentials of skeletal muscles in sedentary man and endurance runners. Ann. N. Y. Acad. Sci. 301:3-29, 1977.
191. Saltin, B. and J. Karlsson. Muscle glycogen utilization during work of different intensity. In Muscle Metabolism During Exercise, B. Pernow and B. Saltin (Eds.), New York: Plenum, 1971, p. 289-299.

192. Sargent, R. M. Relation between oxygen requirement and speed in running. Proc. Roy. Soc. B. London 100:10, 1926.
193. Savard, R., J. P. Despres, M. Marcotte , and C. Bouchard. Endurance training and glucose conversion into triglycerides in human fat cells. J. Appl. Physiol. 58:230-235, 1985.
194. Sawka, M. N., M. E. Foley, N. A. Pimental, M. M. Toner, and K. B. Pandolf. Determination of maximal aerobic power during upper-body exercise. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 47:514-521, 1979.
195. Sawka, M. N., D. S. Miles, J. S. Petrofsky, S. W. Wilde, and R. M. Glaser. Ventilation and acid-base equilibrium for upper and lower body exercise. Aviat. Space Environ. Med. 53:354-359, 1982.
196. Schaible, T. F., A. Malhotra, C. Ciambrone, and J. Scheuer. The effects of gonadectomy on left ventricular function and cardiac contractile proteins in male and female rats. Circ. Res. 54:38-49, 1984.
197. Schaible, T. F., S. Penpargkul, and J. Scheuer. Cardiac responses to exercise training in male and female rats. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 50:112-117, 1981.
198. Schaible, T. F. and J. Scheuer. Comparison of heart function in male and female rats. Basic Res. Cardiol. 79:402-412, 1984.
199. Scheuer, J. and C. M. Tipton. Cardiovascular adaptations to physical training. Ann. Rev. Physiol. 39:221-251, 1977.
200. Secher, N. H., N. Ruberg-Larsen, R. A. Binkhorst, and F. Bonde-Petersen. Maximal oxygen uptake during arm cranking and combined arm plus leg exercise. J. Appl. Physiol. 36:515-518, 1974.
201. Segal, S. S. and G. A. Brooks. Effects of glycogen depletion and work load on post exercise oxygen consumption and blood lactate. J. Appl. Physiol: Respirat. Environ. Exerc. Physiol. 47:514-521, 1979.
202. Shephard, R. J., C. Allen, A. J. S. Benade, C. T. M. Davies, P. E. diPrampo, R. Hedman, J. E. Merriman, K. Myhre, and R. Simmons. The maximum oxygen intake: An international reference standard of cardio-respiratory fitness. Bull. World Health Org. 38:757-764, 1968.
203. Shephard, R. J., G. Godin, and R. Campbell. Characteristics of sprint, medium and long-distance swimmers. Europ. J. Appl. Physiol. 32:99-116, 1974.

204. Siebers, L. S. and R. G. McMurray. Effects of swimming and walking on exercise recovery and subsequent swim performance. Res. Quart. 52:68-75, 1981.
205. Simmons, R. and R. J. Shephard. Measurements of cardiac output in maximum exercise. Application of an acetylene rebreathing method to arm and leg exercise. Intern. Z. angew. Physiol. 29:159-172, 1971.
206. Simmon, R. and R. J. Shephard. Effects of physical conditioning upon the central and peripheral circulatory responses to arm work. Int. Z. angew. Physiol. Enschl. Arbeit. Physiol. 30:73-84, 1971.
207. Skubic, V. and J. Hilgendorf. Anticipatory, exercise and recovery heart rates of girls as affected by four running events. J. Appl. Physiol. 19:853-856, 1964.
208. Sloan, A. and J. Weir. Nomograms for prediction of body density and total body fat from skinfold measurements. J. Appl. Physiol. 28:221-222, 1970.
209. Sparling, P. B. A meta-analysis of studies comparing maximal oxygen uptake in men and women. Res. Quart. Exerc. Sports 51:542-552.
210. Sprynarova, S. and J. Parizkova. Comparison of the functional circulatory, and respiratory capacity in girl gymnasts and swimmers. J. Sports Med. Phys. Fitness 9:165-172, 1969.
211. Spyrnarova, S. and J. Parizkova. Functional capacity and body composition in top weight lifters, swimmers, runners and skiers. Int. Z. angew. Physiol. 29:184-194, 1971.
212. Stainsby, W. N., L. B. Gladden, J. K. Barclay, and B. A. Wilson. Exercise efficiency: Validity of baseline substractions. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 48:518-522, 1980.
213. Stamford, B. A., R. J. Moffatt, A. Weltman, C. Maldonada, and M. Curtis. Blood lactate disappearance after supramaximal one-legged exercise. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 45:244-248, 1978.
214. Stamford, B. A., A. Weltman, R. J. Moffatt, and S. Sady. Exercise recovery above and below anaerobic threshold following maximal work. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 51:840-844, 1981.
215. Steinhaus, A. H. Chronic effects of exercise. Physiol. Rev. 12:103-147, 1933.

216. Stenberg, J. P., P. O. Astrand, B. Ekblom, J. Royce, and B. Saltin. Hemodynamic response to work with different muscle groups, sitting and supine. J. Appl. Physiol. 22:61-70, 1967.
217. Stromme, S. B., F. Ingjer, and H. D. Meen. Assessment of maximal aerobic power in specifically trained athletes. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 42:833-837, 1977.
218. Stumpf, W. E., M. Sar, and G. Aumuller. The heart: A target organ for estradiol. Science 196:319-321, 1977.
219. Thorland, W. G., G. O. Johnson, T. J. Hough, and M. J. Refsell. Anthropometric characteristics of elite adolescent competitive swimmers. Human Biology 55:735-748, 1983.
220. Tuttle, W. W. and J. F. Corleaux. The response of the heart to water of swimming pool temperature. Res. Quart. 6:24-26, 1935.
221. Vaccaro, P., D. H. Clarke, and A. F. Morris. Physiological characteristics of young well-trained swimmers. Europ. J. Appl. Physiol. 44:61-66, 1980.
222. Van Huss, W. D. Specific responses to heavy exercise stress. Osteopath. Ann. 5:53-62, 1977.
223. Van Huss, W. D. and T. K. Cureton. Relationship of selected tests with energy metabolism and swimming performance. Res. Quart. 26:205-221, 1955.
224. Von Dohlen, W. and I. Holmer. Body composition, sinking force and oxygen uptake of man during water treading. J. Appl. Physiol. 37:55-59, 1974.
225. Vrijens, J., P. Hoekstra, J. Bouckaert, and P. Van Uytvanck. Effects of training on maximal working capacity and hemodynamic response during arm and leg-exercise in a group of paddlers. Europ. J. Appl. Physiol. Occup. Physiol. 34:113-119, 1975.
226. Warnock, L. G., R. E. Keoppe, N. F. Inciardi, and W. E. Wilson. L(+) and D(-) lactate as precursors of muscle glycogen. Ann. N. Y. Acad. Sci. 119:1048-1060, 1965.
227. Washburn, R. A. and D. R. Seals. Comparison of continuous and discontinuous protocols for the determination of peak oxygen uptake in arm cranking. Europ. J. Appl. Physiol. Occup. Physiol. 51:3-6, 1983.
228. Washburn, R. A. and D. R. Seals. Peak oxygen uptake during arm cranking for men and women. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 56:954-957, 1984.

229. Wells, C. L., L. H. Hecht, and G. S. Krahenbuhl. Physical characteristics and oxygen utilization of male and female marathon runners. Res. Quart. 52:281-285, 1981.
230. Wells, G. The effect of external temperature changes on heart rate, blood pressure, physical efficiency, respiration and body temperature. Res. Quart. 3:108-121, 1932.
231. Weltman, A., B. A. Stamford, and C. Fulco. Recovery from maximal effort exercise: Lactate disappearance and subsequent performance. J. Appl. Physiol.: Respirat. Environ. Exerc. Physiol. 47:677-682, 1979.
232. Wilmore, J. H. and P. O. Sigerseth. Physical work capacity of young girls, 7-13 years of age. J. Appl. Physiol. 22:923-928, 1967.
233. Wolinsky, H. Effects of hypertension and its reversal on the thoracic aorta of male and female rats. Morphological and chemical studies. Circ. Res. 28:622-637, 1971.
234. York, J. W., L. B. Oscai, and D. G. Penney. Alterations in skeletal muscle lactate dehydrogenase isozymes following exercise training. Biochem. Biophys. Res. Commun. 61:1387-1393, 1974.

MICHIGAN STATE UNIVERSITY LIBRARIES



3 1293 03145 1358