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ABSTRACT

This booklet is designed to make research findings about swimming available with interpretations for practical application. Chapter 1, "Physical Characteristics of Swimmers," discusses somatotyping, body composition, and growth. Chapter 2, "Physiological Characteristics of Swimmers," discusses resting rate, vital capacity, effects of water immersion, pulmonary ventilation, aerobic capacity, temperature regulation, warmup and swimming performance, underwater swimming, and muscle strength and endurance. Chapter 3, "Water Resistance and Energy Expenditure," concludes that comprehensive data are needed on the caloric and heart rate cost of different interval training procedures and of distance swimming to provide more accurate estimates of what swimmers can and are doing physiologically. Chapter 4, "Sociological and Psychological Aspects of Swimming," discusses psychological characteristics, social factors, psychology of coaching, motivation, and level of anticipation. Chapter 5, "Evaluation of Performance," presents information regarding Craig's velocity-duration curve, pulse rate after repeats or races, pulse rate and velocity, propulsive force, energy expenditure and efficiency, and caloric cost of swimming practices. A bibliography is included at the end of each chapter. (PD)

SWIMMING

WHAT RESEARCH TELLS THE COACH ABOUT

SWIMMING

Prepared by
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Ann Arbor

In cooperation with the
American Swimming Coaches Association
and the
College Swimming Coaches Association of America

AMERICAN ASSOCIATION FOR HEALTH, PHYSICAL EDUCATION, AND RECREATION
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FOREWORD

This is the second publication in the series of books about specific sports under the title of "What Research Tells the Coach." It was prepared under the direct supervision of the Research Council of the American Association for Health, Physical Education, and Recreation. The purpose of this series is to make available to coaches pertinent research findings with interpretations for practical application.

John A. Faulkner, the author of this book, *What Research Tells the Coach About Swimming*, is a renowned researcher. Dr. Faulkner's area of specialty is the physiology of exercise, and he has done work in connection with altitude physiology. He has been a competitive swimmer as well as a coach of swimming, and many of his researches have been conducted with swimmers as his subjects. We are indeed fortunate to have him as the author of this book.

There has been no attempt made here to do more than let the coaches know what has been found out about swimming. This is followed by an interpretation of the findings. A valuable list of research references in swimming is included, along with indications as to the areas in which research is needed. It is hoped that the modern coach is familiar with research techniques and terminology. However, a minimal use of technical language has been made.

It is hoped that this publication may open new doors and suggest new ideas to the swimming coach of today. We are proud to be a part of this worthy undertaking.

JOHN M. COOPER

PREFACE

Historically, swimming was practiced by civilized peoples in ancient times. The earliest records are two Egyptian hieroglyphs dated 3000 B.C. and 2500 B.C. A number of early societies recognized the recreational and wartime values of swimming. However, competitive swimming as it is known began just over one hundred years ago, and most records date from the 1870's. Major developments were the introduction of the trudgen stroke in the 1880's, the Australian crawl at the turn of the century, and the gradual evolution of the four competitive strokes since 1900.

Improvements in swimming times have been phenomenal, except for brief regressions during each World War. The rapid improvements may be attributed to regular international competition, the age group program, the improved physical endowment of swimmers, greater motivation, more rigorous training, a 12 month season based on an indoor and an outdoor program, and improved stroke mechanics.

A gradual standardization of stroke technique has been noticeable since the 1956 Olympics, probably because of the widespread use of filmstrips, loop films, and picture sequences of champions. The present technique has developed empirically and few objective data are available on the mechanics of swimming.

As for recreational swimming, 90 percent of college freshmen and approximately 80 percent of the total adult population can swim. Unfortunately, the criterion of swimming is usually a minimum distance of 25 to 50 yards. In reality, tew Americans can swim well. The drownproofing technique, devised by Fred Lanoue at the Georgia Institute of

Technology, and the development of skin and scuba diving have been major innovations in recreational swimming.

Much research data on swimming have been published in professional journals not readily available to coaches. Several review articles have summarized selected portions of this literature. This monograph will be limited to research data pertinent to competitive and recreational swimming. In testing highly trained swimmers in the laboratory and the pool, the specificity of training for a particular task and distance has been clearly evidenced. Consequently, only data collected on swimmers or pertaining directly to swimmers will be included. When no data on swimmers are available, procedures for the collection of appropriate data will be suggested. Within this framework, an attempt has been made to organize and interpret research findings which are of practical value to the coach. Arbitrarily, the topics of kinesiology, biomechanics, nutrition, and all aspects of skin and scuba diving have been considered beyond the scope of this monograph.

The coaching of swimming is still more of an art than a science. A scientific approach to swimming has been slow to evolve because of the complexity of taking most measurements in the water. Fortunately, this has not deterred some investigators. Their names appear in the reference lists. However, it is the performance of the practitioner that ultimately determines the progress of a discipline or a sport. Swimming has had and continues to have great coaches. If this monograph aids coaches in the development of better swimmers, it will have served its purpose.

JOHN A. FAULKNER

1. PHYSICAL CHARACTERISTICS OF SWIMMERS

Human physique may be assessed as to size, form, and/or composition (9). Each assessment has implications for the coaching of swimming through its effect on buoyancy, resistance, and/or propulsion (Figure 1).

Simple measurements of height and weight provide reasonable estimates of body size (2) and can be used to evaluate growth (2, 3). Height alone is an imperfect predictor of weight (9). Weight can be predicted from height, shoulder width, and hip width (10). Body fatness may be estimated by dividing observed weight by predicted weight (10).

The somatotyping system developed by William Sheldon and his associates (11) has been widely used for the past quarter century to assess body form. Subsequently, the term *somatotype* has been used for body build ratings based on widely differing techniques of assessment (7, 11).

From a metabolic, nutritional, or performance viewpoint, the objective of body composition analysis is a division between metabolically active and relatively inactive constituents. The method has evolved into estimates of fat-free body weight and the percentage of the body weight that is fat. The percent fat is predicted from body density and the fat-free weight is calculated from this estimate.

Underwater weighing has been the most widely used method of determining body density (9). Total body volume is determined by subtracting the weight in water from the weight in air (Archimedes' principle) with an additional correction for the residual air in the lungs and air passages. Body density is then the weight in air divided by the body volume.

A simple and economical measurement of fatness is the skinfold test. A double thickness of skin and subcutaneous fat is lifted and measured by a caliper. The skinfold technique has become useful with the development of standardized skinfold calipers (9). When observers are well trained in selection of site, lifting the skinfold, applying the caliper, and reading the caliper, objective and highly reliable data are obtainable. Skinfold measures have been validated against roentgenograms and underwater weighing and have been found to give accurate predictions of total body fat.

Somatotyping

Somatotyping, body density, and skinfold measures have all been used to evaluate the body build of swimmers. Cureton (7) used a modifica-

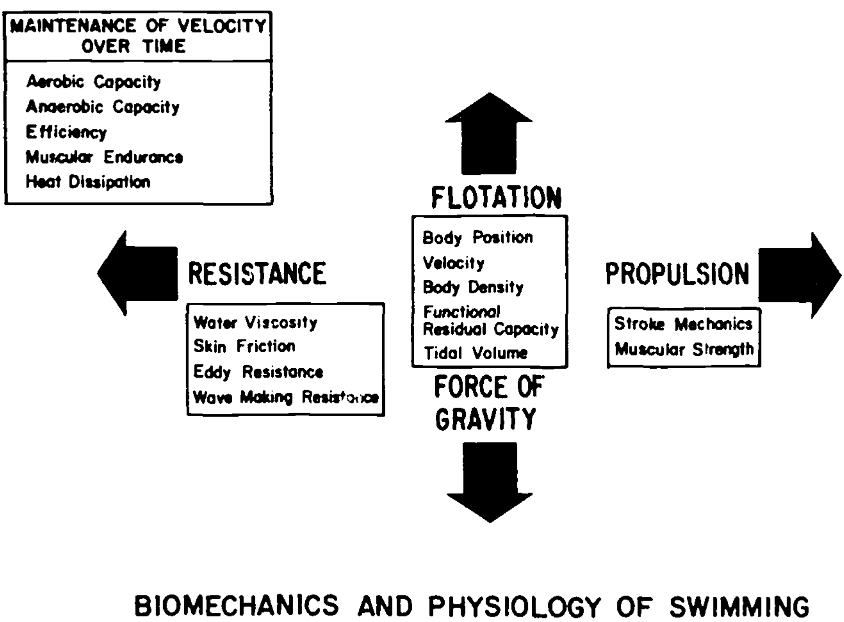

FIGURE 1. The interaction of flotation, force of gravity, propulsion, and resistance in swimming.

tion of the Sheldon-Stevens-Tucker somatotype technique to assess the body build of American Olympic swimming champions. The average somatotype rating for ten champions was 3½–5–3½. Cureton concludes that swimmers of top ability "represent the mesomorphic ideal in body build." Among the champion swimmers, the sprint swimmers tended to have higher ratings on mesomorphy and the 400- and 1500-meter swimmers higher ratings on endomorphy (7). Cureton notes that the distance swimmers were more buoyant and floated closer to the horizontal than the sprinters. Since a linear relationship exists between endomorphy and body density, at least part of the increased buoyancy would be attributed to a decreased body density.

The specific gravity data of Bloomfield and Sigerseth (4) and unpublished data on skinfold measurements add further support to a difference in the body composition of sprinters (s.g.=1.0786) and middle distance swimmers (s.g.=1.0729). Considerable overlap exists between the two groups in all studies. Bloomfield and Sigerseth (4) concluded that contemporary distance swimmers have smaller fat depots than their predecessors. They attribute the "reduction of fat depots" to the increased tempo of interval training and the increased relative speed of the distance swimmers. Although plausible, both the assumption of a reduction and the hypothesis as to its cause are not substantiated by data (4).

The laborious somatotyping technique of Sheldon and his associates (11) is not likely to become a practical tool for coaches. On the other hand, Cureton's fairly gross assignment of ratings by subjective assessment is quick and yet useful to both swimmer and coach (Appendix A). The estimate of the somatotype, however rough, focuses attention on the strengths and weaknesses of a particular body build for swimming. Successful varsity swimmers tend toward an ecto-mesomorphic somatotype.

Body Composition

Male swimmers are taller, heavier, and less fat than college students of the same age (Table 1). Although girl swimmers have lower skinfold measurements than the average for their age, they have greater body weight, probably because of greater muscle development (Table 2). Compared to age-matched norms, girl swimmers tend to be taller throughout the teens (2). Because of their greater body weight, there is no significant change in the weight/height ratio (2). From ages 12 to 17 years, there is a significant increase in the subcutaneous fat thickness of girl swimmers. This could be due to maturational factors, to a reduced training load with increasing age, or to a combination of the two.

TABLE 1. MEAN BODY BUILD DATA FOR MALE SWIMMERS AND MEN FROM THE TOTAL POPULATION

Source	Age (yr.)	Height (cm)	Weight (kg)	Skinfolds (mm, sum of 4)	Percent[b] Fat	Reference
Young college men (N = 158)	20	176	72	56	14	
College swimmers (N = 22)	20	182	77	31	10	
Sprint swimmers (N = 24)	21	181	75	19[a]	8	(4)
Middle distance swimmers (N = 24)	21	180	74	35[a]	10	(4)

[a] Skinfold measurement was calculated from body density (Appendix B).
[b] Percent fat was estimated from 5.783 + (0.153 × sum 4 fat measures).

TABLE 2. AVERAGE BODY BUILD DATA FOR GIRL SWIMMERS AND GIRLS FROM THE TOTAL POPULATION

Source	Age (yr.)	Height (cm)	Weight (kg)	Skinfolds (mm) Triceps	Infrascapular	Sum 4	Reference
American girls (N = 189)	13	156	48.4	13.8	9.2	—	(10)
American girl swimmers (N = 24)	13	163	50.4	11.9	8.9	41	
Swedish girl swimmers (N = 30)	14	165	54.2	—	—	—	(2)
American girl swimmers (N = 24)	14	164	55.1	13.6	10.4	45	
American girls (N = 188)	17	164	55.0	16.9	12.3	—	(10)
Girl swimmers (N = 21)	17	166	59.9	15.8	11.9	53	

Note: Age, height, and weight are means. Skinfold measurements are medians.

Daily tabulations of weight and monthly determinations of fatness and percent fat (Appendix B) provide valuable information on the variability of the body composition of swimmers. Mature swimmers. with a total of 25 to 35 mm of subcutaneous fat over the four sites (Appendix B) should hold a constant body weight while training (5, 12).

Vigorous training should result in a loss of weight and fat for overly fat swimmers (over 50 mm for males and over 60 mm for females). The maintenance of a high percentage of body fat during training is rare. Such a swimmer should be referred to a private physician who will advise him concerning a reduction in food intake.

Growth

In programs where growing children are trained intensively, care should be taken that normal growth curves are maintained (2, 3). Height, weight, and skinfolds should be measured monthly and data should be compared to normal growth curves (2, 3). All available data indicate that the physiologic response to strenuous training programs is similar regardless of age (1, 2). Although no detrimental effects have been reported, growth places an added stress on the organism, and its interaction with the training process should be carefully evaluated (2). Significant deviations from normal gains in height and weight (3) should be referred to a physician.

Summary

Height, weight, fatness, and gross estimates of somatotype can provide important data for a more scientific approach to the training and event placement of swimmers. Male swimmers with over 35 mm fat (four sites) and female swimmers with over 50 mm fat (four sites) should probably be encouraged to reduce. Coaches should evaluate the growth of age group swimmers regularly. Swimmers who require weight reduction programs or age group swimmers who do not make normal gains in height and weight should be referred to a physician.

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2. PHYSIOLOGICAL CHARACTERISTICS OF SWIMMERS

The only comprehensive physiological investigations of swimming have been of channel swimmers and Swedish girl swimmers. It is unfortunate that in a sport in which the times have improved so rapidly (Figure 2), data are not available to evaluate the changes physiologically.

The highly trained swimmer has the low resting heart rate, large vital capacity, and large maximum oxygen uptake typical of the endurance athlete. The physiological response to swimming compared to the physiological response to other sports activities is complicated by the effects of immersion, the horizontal body position, and the predominant arm work.

Resting Heart Rate

Bloomfield and Sigerseth (3) report a mean resting heart rate of 57 beats/min. for 24 male sprint swimmers and 53 beats/min. for 24 male distance swimmers. Carlile and Carlile (6) observed a mean resting heart rate of 67 beats/min. and a range of 51 to 75 among 20 male Australian swimmers trying out for the 1956 Olympic team. For Swedish girl swimmers, Astrand and others (1) recorded a mean of 72 beats/min. and a range of 60 to 84 beats/min. Seventy-five beats/min. is an average heart rate for young adult men and about 85 beats/min. for young women.

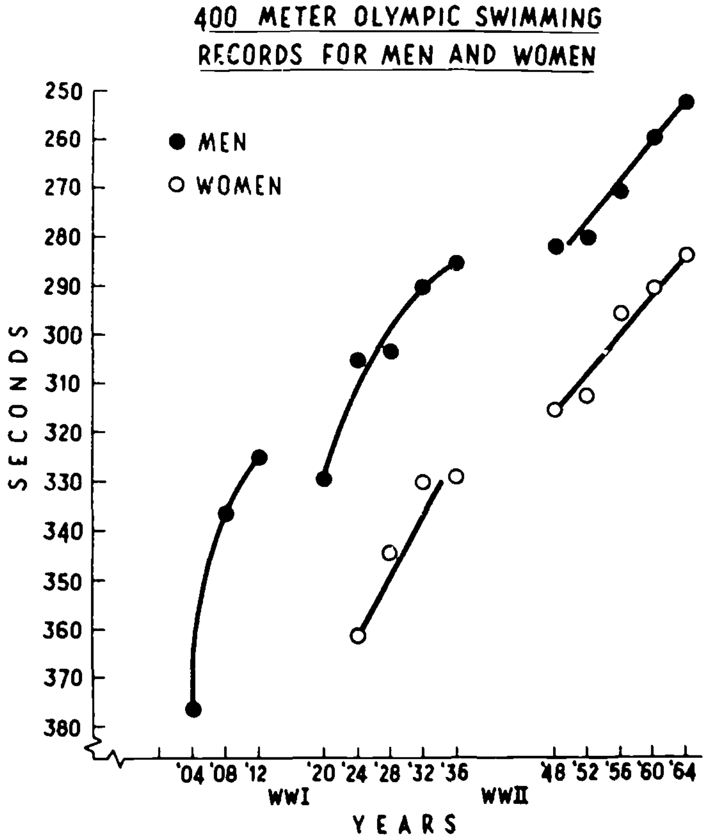

FIGURE 2. 400-meter Olympic swimming records for men and women.

Vital Capacity

The large vital capacities of swimmers have been noted by many investigators. For male swimmers, mean vital capacities (BTPS) are 5.32 liters * (3), 5.86 liters (24), 5.90 liters (26), and 6.28 liters * (12). For female swimmers, mean vital capacities (BTPS) are 4.00 liters (1) and 4.55 liters * (26). The mean values are from 6 to 13 percent higher than the predicted values for age, height, and sex (1, 23).

Astrand and his associates (1) have compared the lung function of 30 girl swimmers to predicted values based on age and height cubed. The girl swimmers showed 10 to 13 percent greater than predicted values

* Not indicated whether ATPS or BTPS.

for each of functional residual capacity, total lung capacity, vital capacity, and 1-second forced expiratory capacity. The residual volume did not vary from the predicted value. The larger than predicted value for total lung capacity (Figure 3) was achieved by an enhanced expiratory reserve volume (20 percent) and an enhanced inspiratory capacity (13 percent). Compared to controls, the greater vital capacity of the Korean *amas* was due entirely to a greater inspiratory capacity (30).

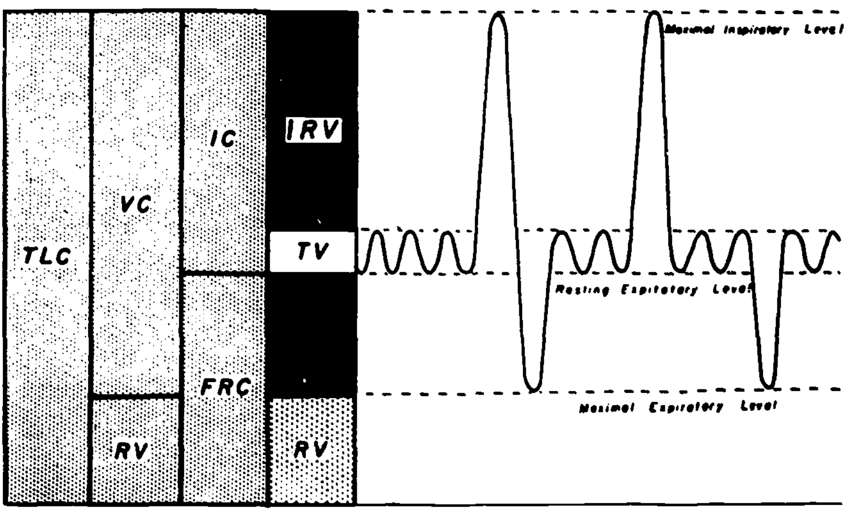

FIGURE 3. The lung volumes and capacities.

TV (tidal volume, or depth of breathing)—the volume of gas inspired during each respiratory cycle.

IRV (inspiratory reserve volume)—the maximal amount of gas that can be inspired from the end-inspiratory position.

ERV (expiratory reserve volume)—the maximal amount of gas that can be expired from the end-expiratory level.

RV (residual volume)—the volume of gas remaining in the lungs at the end of a maximal expiration.

TLC—total lung capacity, VC—vital capacity, IC—inspiratory capacity, FRC—functional residual capacity.

(From *Physiology of Respiration*, by Julius H. Comroe, Jr. Copyright 1965, Year Book Medical Publishers, Inc. Used by permission of Year Book Medical Publishers.)

Significant increases in vital capacity have been observed after escape tank training in underwater diving and "free ascents" from depths up to 32 m (4). Similar data have not been published on swimmers. However, it appears that the large vital capacities were developed during swimming training rather than through self-selection of competitive swimming careers by persons with large inherited vital capacities.

Longitudinal data on pretraining and post-training values for vital capacity, inspiratory capacity, functional residual volume, forced expiratory velocity, and maximum breathing capacity of swimmers would do much to clarify the effects of competitive swimming on lung function. Tidal volumes and respiratory rates during training and time trials would aid in the understanding of the respiratory load induced by swimming. At present the data are not sufficient to make a definitive statement.

Effects of Water Immersion

Immersion in water of swimming pool temperature (27-32 C) results in a decreased heart rate (32). The decrease is directly related to the resting heart rate (33). In swimming classes, participants with resting heart rates in the 70's had an average drop of 5 beats due to immersion; heart rates in the 80's, a drop of 11 beats; heart rates in the 90's, a drop of 14 beats; and heart rates over 100, a drop of 16 beats. The water temperature, which was not well controlled, ranged from 18 to 30 C. On observing no difference between varsity swimmers and nonswimmers, Tuttle and Corleaux (32) concluded that the response was not affected by training. Keatinge and Evans (22) found 12 subjects did condition to immersion in 15 C water. After eight immersions, the initial tachycardia and overbreathing were reduced or abolished. The changes were attributed to central nervous system conditioning rather than peripheral factors.

Approximately 5 percent of the more than 100 subjects tested failed to respond to immersion with a drop in heart rate (50). The abnormal response was attributed to a fear of immersion. Three out of seven of these subjects developed a normal response after six class hours of swimming instruction. A failure to display a normal response after conditioning was described as a "submersion syndrome" and attributed to a "sensitivity to water" (33). Horton and Gabrielson (20) in the description of a similar response pattern cite a "hypersensitivity to cold" as the cause. Goff and others (18) would apparently concur with the focus on the response to temperature change. They conclude that "The heart rate is more directly influenced by average skin temperature than by immersion per se." However, all of their subjects were trained divers. They also conclude that divers who do not display a normal reduction in heart rate on immersion in water below 37 C may be unfit for underwater tasks.

The oxygen consumption of four subjects resting supine on a slatted "duck board" were not affected significantly on immersion in water of 29.5 to 36.5 C (18). Probably because of the neutral buoyancy, average sitting and standing oxygen consumptions of "booted" divers submerged at a depth of 3.66 m are 10 to 30 ml min. less than normal resting consumptions (15).

Vital capacity is reduced approximately 9 percent by vertical immersion to the neck in water. The hydrostatic pressure results in a 5 percent loss due to the displacement of blood into the thorax and a 4 percent loss due to impedance of the respiratory muscles.

Pulmonary Ventilation

In most activities man simply breathes as needed. Freestyle swimming requires the unusual coordination of inspiration with stroke mechanics. The energy cost of breathing is increased by the extra work required in inspiration caused by water pressure and by the horizontal body position.

Tidal volumes of 2 to 3 liters have been recorded on channel swimmers stroking at 42 to 73 strokes per minute (28). Similar tidal volumes have been observed during tethered swimming by 17 highly trained college swimmers (24). The average pulmonary ventilation (BTPS) at maximum load was 110 liters/min. with 42 stroke cycles/min. and one breath per stroke cycle. In the backstroke, swimmers had a pulmonary ventilation (BTPS) of 132 liters/min. with 38 stroke cycles and 67 breaths/min. The tidal volume was 2 liters for the backstrokers and 2.6 liters for swimmers using other strokes (24).

At sea level, pulmonary ventilation is seldom the factor that limits maximum performance in land sports. In aquatics, breathlessness may become a significant factor early in work, particularly in the untrained. Trained swimmers become acclimatized to a reduced pulmonary ventilation and extract a large percentage of oxygen from a given volume of air. The inability of untrained swimmers to tolerate the increased carbon dioxide and increase the oxygen extraction greatly limits their work capacity in swimming.

In competitive swimming, hyperventilation is advocated prior to the start (25). Tracings of swimmers indicate the breath is held after a normal inspiration at the command "Take your marks," and a short deep inhalation is taken at the takeoff. The hyperventilation would appear to be of little value since total body oxygen stores cannot be significantly increased (10). Hyperventilation does increase breath holding time by reducing the partial pressure of CO_2. However, swimmers will begin their normal breathing within the stroke cadence before maximum breath holding time is reached. The only exception to breath holding is the 50-yard sprint, when as few as two breaths may be taken. Breath holding does allow for a steadier set prior to the start, and the full inhalation after the gun increases buoyancy during the glide.

Maximum Oxygen Uptake (Aerobic Capacity)

Maximum oxygen uptake appears to be the best measure of man's ability to perform long-term work of high intensity. Maximum oxygen uptake is attained during sustained aerobic work of from 5 to 10 minutes duration which approximates maximum performance or during all-out interval work with short rest intervals. The clearest criterion for the attainment of maximum oxygen uptake is when the oxygen uptake plateaus or peaks and then declines during the last minutes of the test.

In bicycle ergometer or treadmill tests of physical work capacity, highly trained swimmers have approximately the same maximum oxygen uptake (4.41 liters/min.) as distance runners (4.45 liters/min.). However, when these data are converted to ml/kg/min. the swimmers have much lower values because of their greater body weight. Highly trained male college swimmers average 56 ml/kg/min. (range—50 to 70 ml/kg/min.) and distance runners average 66 ml/kg/min. (range—60-80 ml/kg/min.).

Highly trained male and female swimmers attain higher heart rates, higher pulmonary ventilations, and a lower oxygen extraction at maximum work capacity when bicycling or running as compared to swimming (1, 24). The maximum oxygen uptakes of girl swimmers were slightly lower when swimming (2.60 liters/min.) compared to bicycling (2.80 liters/min.), whereas no significant difference was observed between the maximum oxygen uptakes of male swimmers when swimming (4.14 liters/min.) and running (4.20 liters/min.). Apparently, highly trained swimmers are able to obtain equally high maximum oxygen uptakes when swimming, bicycling, or running (1, 24).

Less well trained swimmers may evidence reductions of 15 to 25 percent or more in maximum oxygen uptake while swimming compared to running (24) or bicycling (2). The reduction may be due to (a) an inability to activate sufficient muscle mass, (b) the attainment of respiratory limitations, and/or (c) the development of local muscular fatigue.

Even though a maximum oxygen uptake may be obtained by swimmers in other activities, it is advisable to measure their aerobic capacity during swimming. The relationship between oxygen uptake and speed or force provides important information for the coach on individual differences and improvements or regressions in skill and efficiency over time. During the competitive season coaches and swimmers are far more receptive to swimming tests than to running or bicycling tests, particularly if they require maximum effort. The best test procedure is a tethered or a free-swimming test (Appendix C).

The relationship between maximum oxygen uptake and maximum running velocity over the longer distances has been well established. Distance runners must have an aerobic capacity in excess of 70 ml/kg/min. if they are to attain world class. Very little is known of the maximum oxygen uptakes of world class swimmers. Two Olympic medalists in the 1500-meter had 4.85 liter/min. or 59 ml/kg/min. uptakes. Because the body weight is not supported while swimming, uptake in liters/min. may provide a more appropriate evaluation than uptake in ml/kg/min. At present, the data are insufficient to make a reasonable assessment of the relationship.

Temperature Regulation

The human body at rest (not basal) generates approximately 50 kcal/m^2/hr. of heat, yet a more or less constant body temperature is maintained. Consequently, interaction is constantly taking place between the body and its environment. In this interaction, two temperature gradients exist—an internal physiologic gradient, and an external physical gradient. Variations in deep body temperature are minimized or prevented by complex mechanisms of tissue conductivity (22). In spite of effective control mechanisms, rectal temperature may vary from 25 to 43 C (28).

In water, heat is lost approximately twice as rapidly as in air because of the greater effective surface area for heat loss and the high specific heat of water, which results in quicker transfer. The heat loss from the deep tissues depends on the thermal gradient and the tissue conductivity. The internal gradient is taken as rectal temperature (Tr) minus skin temperature (Ts). In water, skin temperature and water temperature are assumed to be the same. Swimming invariably increases tissue conductivity.

Swimming, except in water over 30 C, presents the opposite thermal stress to that of running. Running two miles at near record time can raise the rectal temperature to 41 C. Although rectal temperatures have not been reported following competitive swimming races, the data on channel swimmers (28) and laboratory subjects (27) indicate that swimmers are competing in a medium favorable to heat exchange. Rectal temperatures of as low as 35.5 C have been observed after prolonged swims in cold water (27).

During high energy output in swimming, less of the cardiac output is necessary to dissipate heat and more is available for oxygen transport than in running (1[illegible]). Consequently, swimmers can maintain 75 percent of maximum velocity for 4 minutes and 65 percent for an hour, compared to 68 percent and 55 percent for runners (11).

Further investigations are necessary to isolate the effects of training and fatness on body insulation and the optimum levels of energy expenditure to maintain body temperature in waters of different temperature. Optimum water temperatures for maximum performance, particularly in the distance events, also need to be determined.

Warm-Up and Swimming Performance

Warm-up procedures of swimming, calisthenics, hot showers, and massage have been evaluated by the performance criterion of swimming time (5, 14). Different investigators have obtained contrary results using the same techniques. There is some suggestion that different warm-up procedures have different effects depending on the stroke and possibly the distance (14). The psychological biases of the subjects are also difficult to control. The conflicting and insufficient data make a clear evaluation of the effect of warm-up on swimming performance impossible. At present, a definitive investigation has not been published.

Underwater Swimming

Underwater swimming is as useful an aquatic skill as surface swimming. In certain boat and car accidents, it is necessary for water safety. The professional work of the *amas* of Japan and Korea (19) and the Torres Straits islanders (29) depends on this skill. The challenge of underwater swimming for distance has universal appeal.

Unfortunately, a number of case histories of fatal and near fatal submersions (10, 13, 16) indicate inherent dangers in this sport. Of the survivors, all had hyperventilated vigorously on the pool deck, attempted a maximum swim underwater, and lost consciousness with little or no warning, because of anoxia. The interactions of hyperventilation, breath holding, and exercise produce hypoxia under unique conditions.

The hyperventilation reduces alveolar PCO_2 from 40 mm Hg to 15 mm Hg and increases alveolar PO_2 tension from 100 mm Hg to 140 mm Hg (19). The reduced PCO_2 can cause up to a 50 percent reduction in cerebral oxygen tension due to vasoconstriction (29). The increased metabolism of swimming may decrease the PO_2 to a dangerous degree before the reduced PCO_2 reaches the "breaking point" of breath holding (10, 16). Underwater swimmers routinely use swallowing and pumping against a closed glottis (16), and these maneuvers are augmented by an increased tolerance to hypercapnia during exercise. The changes in thoracic pressure associated with breath holding and its related phenomena also interfere with circulation.

Although underwater swimming at depth greatly increases the possibility of anoxia, particularly during ascent, the *amas* of Japan and Korea do not appear to encounter the hazard.

The Korean *ama* does hyperventilate in the water prior to each dive (19). A loud whistle with lips pursed accompanies each exhalation. Just before submergence, an inhalation is made of approximately 85 percent of their vital capacity. The average drop in alveolar PCO_2 from 37 to 26 mm Hg and the increase in alveolar PO_2 from 102 to 120 mm Hg indicates a relatively mild degree of hyperventilation.

Since the key to underwater safety is the sensitivity of the respiratory center to CO_2, apparently the degree of hyperventilation is not severe enough to compromise this mechanism. Obviously, hyperventilation prior to underwater swimming should be used with caution. Underwater swimmers should also be informed of the factors contributing to anoxia and the danger of ignoring the urge to breathe.

Bradycardia is demonstrated by every diving animal that has been studied. The bradycardia is reflexively initiated and is affected by psychological factors. It may be superimposed upon the tachycardia of swimming. A decrease from 110 beats to 36 beats has been recorded in human subjects by direct EKG leads (21). The maintenance of systolic and diastolic blood pressure in spite of excessive bradycardia suggests extensive vasoconstriction. The mechanisms of bradycardia and associated phenomena are an important adaptation to diving. These phenomena are undoubtedly mediated by the motor cortical centers of cardiovascular control. Previous studies (17) have indicated that these mechanisms can be improved by conditioning; however, the techniques have not been adopted in the coaching or teaching of swimming.

Muscle Strength and Muscle Endurance

Little data have been published on the strength of swimmers, and a definitive study on the strength requirements of swimming has not been made. A swimmer of 76 kg averages 136 kg on a 90° bent arm pull or 1.78 kg per kilogram of body weight. This is greater than the pull of the average college freshman (96 kg and 1.37 kg per kilogram of body weight) and compares favorably with the limited data on other athletes. In a test of "strength of arm flexion at the scapulo-humeral joint," Bloomfield and Sigerseth (3) obtained mean scores of 74 kg for sprinters and 67 kg for middle distance swimmers. The best prediction of maximum endurance appears to be the percentage of maximum strength involved in each contraction. Such a relationship has been determined between strength per pound of body weight and muscular endurance in a sample of 30 physical education majors. The 90° bent arm pull score divided by body weight correlated .90 with the maximum number of pull-ups performed.

The percentage of maximum strength involved in each pull varies from a sprinter with a velocity of 120 m/min. to a channel swimmer with a velocity of 54 m/min. If arm pull is taken as 70 percent of total propelling force (7), the force for each pull is approximately 9 kg sprinting and 1.7 kg swimming distance. A swimmer who can pull 68 kg with each arm pulls 13 percent of his maximum strength each sprint stroke and 2.5 percent each distance stroke compared to a greater than 50 percent effort for each pull-up (see Appendix D for calculations).

A major issue to be resolved is how much strength and muscle endurance is optimum for different strokes and at different distances. The second question is how this level of performance can be attained and maintained most effectively and efficiently. At present, the training programs recommended for the development of muscular strength and muscular endurance vary greatly among different coaches (8, 31). None has been validated by objective analysis.

Summary

Swimmers compare to other endurance athletes in heart rate, maximum oxygen uptake, and pulmonary ventilation, with the exception of some deviations caused by body build. Heart rate, oxygen uptake, and pulmonary ventilation in swimming are influenced by body position and water immersion. There are not sufficient data to evaluate the relationship of warm-up or muscular strength to swimming performance.

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3. WATER RESISTANCE AND ENERGY EXPENDITURE

While swimming at constant velocity, water resistance exactly equals the propulsive force. Any change in either the resistance or the force will result in acceleration or deceleration. Water resistance and force increase approximately with the square of the velocity. Consequently, energy expenditure is linearly related to propelling force and curvilinearly related to velocity.

Water Resistance

The measurement of water resistance and propulsion in swimming has involved (a) towing swimmers prone and supine and determining the drag (7, 10), (b) pulling against a measurement device while swimming at zero velocity (10, 11, 12), (c) pulling against a measurement device while swimming at different velocities (1, 5), and (d) theoretical determinations based on principles of fluid mechanics (10).

Alley's (1) and Karpovich's (7, 10) data on resistance in the prone position are in excellent agreement from velocities of 18 m/min. to 120 m/min. The data of Counsilman (5) are considerably lower at velocities above 54 m/min. The use of effective propulsive force * indicates the greatest force, approximately 14 kg, is exerted at zero velocity (1, 5). There is a steady decrease in effective propulsive force with increasing velocity up to 50 m/min. Effective propulsive force at 50 m/min. is

* The force exerted on the restraining device plus the resistance at the velocity the swimmer is being let out by the restraining device.

approximately 75 percent of the force at zero velocity. The decrease is probably due to the reduced relative speed of the arm to the water (5). The graph of the velocity resistance relationship (1) indicates a planing action between 36 and 90 m/min. and an increasing resistance above 100 m/min. due to the development of a bow wave.

The most useful formulas for the calculation of force or work in swimming are:

$$f = kv^2$$

$$w = fs = rs$$

$$w = kv^2s = k\left(\frac{s}{t}\right)^2 s$$

where w = work, f = force, r = resistance, s = distance, v = velocity, t = time.

Karpovich (7) has determined values of k for the front and back crawl strokes (Table 3). The formulas assume constant velocity and do not account for changes in acceleration due to starts, turns, planing, and bow wave. In spite of inconsistencies in velocity because of these factors, Karpovich's constants and these formulas provide a reasonable estimate of resistance and work throughout the usual range of swimming velocities.

TABLE 3. WATER RESISTANCE IN SWIMMING CRAWL AND BACK STROKE

Source	Skin surface area in square meters	Water resistance in kg Prone guide	Back glide
Men	2.23 — 1.77	3.17 v^2	3.66 v^2
Men and Women	1.77 — 1.53	2.68 v^2	2.93 v^2

Adapted from Karpovich (7) with the permission of the author.

Note: v is speed in meters per second and the constant k is in $\frac{kg \cdot sec^2}{m^2}$

The propelling force of each of the four competitive strokes has been analyzed in the tethered position by Mosterd and Jongbloed (12). The swimmer is attached by a harness and nonstretchable nylon cord to a dynamometer. The movements of the dynamometer spring are recorded on a kymograph.

The data in Table 4 show the average propelling force and swimming time of the two fastest male and female swimmers in each stroke in the Mosterd and Jongbloed study (12). Each stroke has a characteristic kymograph pattern, and within strokes, individual patterns of timing, acceleration, and deceleration are discernible.

TABLE 4. MEAN PROPELLING FORCE IN KG DURING 20-SECOND AND 60-SECOND SWIMS

Source	Subjects	20 sec.	60 sec.	Time 100-m race
Front crawl	Males (N = 2)	14.4	10.6	:58.0
	Females (N = 2)	10.6	8.8	1:03.6
Back crawl	Males (N = 2)	14.0	10.8	1:06.0
	Females (N = 2)	9.8	8.7	1:11.4
Butterfly stroke	Males (N = 1)	13.1	9.9	1:03.2
	Females (N = 2)	6.4	5.8	1:10.6
Breaststroke	Males (N = 2)	22.3	17.0	1:15.2
	Females (N = 2)	14.4	10.8	1:21.8

From Mosterd and Jongbloed (12) with permission of the publisher.

The greatest force tethered is attained by swimmers using the breaststroke, although in free swimming this is the slowest stroke. The discrepancy results from the development of relatively greater resistance in free breaststroke swimming because of the underwater recovery of the arms, the recovery of the upper and lower limbs against the water flow, and the discontinuity of the propulsive force.

Energy Expenditure

Energy expenditure data in swimming are necessary to assess (a) the physiologic stress, (b) the caloric cost, and (c) the efficiency of swimming different strokes at different velocities. Swimmers at different levels of skill and training may also be compared.

Heart rate (6), oxygen uptake (2, 13), and strokes per minute (13) are reasonably linear functions of swimming velocity between 20 and 70 m/min. Andersen (2) found a linear relationship between oxygen consumption and swimming velocities between 20 and 50 m/min. in each of five breaststroke swimmers. Pugh and others (13) observed a similar relationship in two channel swimmers swimming the front crawl at velocities between 40 and 70 m/min. Astrand and others (3) have presented maximum oxygen uptakes on girl swimmers; however, neither swimming velocity, the stroke, nor the speed of stroking were reported.

Karpovich and Millman (9) provide the most complete data on energy expenditure in swimming. The caloric cost–velocity relationships * were determined for front crawl, back crawl, breast and butterfly, and sidestroke. The range of velocities was from 36 m/min. to maximum in

* Caloric cost is approximately 5 times the oxygen uptake.

each stroke. The swimmers held their breath during the swim and until they could expire into a Douglas bag. The expired gas was then collected for the next 20 to 40 minutes. The collection of expired gas over this time period tends to give higher energy expenditures than collections made during the swim, particularly at sprint velocities. Strenuous exercise may raise the resting metabolism for many hours after the exercise has ceased (14). After the cessation of exercise there is a fast and then a slow repayment of the oxygen debt that was incurred during the exercise (14). An unresolved question in exercise physiology is how much, if any, of the slow repayment should be included in oxygen debt measurements.

Therefore, the true oxygen consumption–velocity relationship is still unresolved. The most complete data which indicate a curvilinear relationship are apparently based on an overly long collection period for oxygen debt. A more linear relationship results from the data based on collection of expired gas during swimming. Unfortunately, these data are neither complete for a full range of velocities within a stroke nor for all strokes. It is possible that the relationship might become curvilinear at lower velocities as other variables plateau and velocity continues to decrease, and at maximum velocity as the physiologic variables increase with no commensurate increase in velocity. Additional data are needed to clarify the interactions of water resistance, velocity, and energy expenditure.

Skilled and/or trained swimmers swim the same speed with lower heart rates (6) and lower oxygen uptakes (2, 9, 13) than do less skilled and/or less well trained swimmers. Differences occur in both the intercept and the slope of the oxygen uptake–velocity relationship (13).

The caloric cost of swimming is high even at low speed. A swimmer uses approximately 170 kcal to swim 400 m and 500 kcal to swim 1500 m (Table 5). A channel swimmer expends 10,000 kcal in a 12-hour channel crossing (13).

The efficiency of swimming may be calculated from the formula:

$$\%\ \text{efficiency} = \frac{kv^2s \times .0004686}{\text{oxygen uptake (liters/min.)}} \times 100 \qquad (10)$$

Where k = constant (Table 3), v = velocity in m/sec.

s = distance in m, and 1 kg-m of work = .0004686 liters of oxygen.

(Note: Distance and oxygen uptake measurements must be for the same time period.)

The range in the efficiency of swimming has been reported by Karpovich and Pestrecov (10) as 0.5 to 2.2 percent and Karpovich and others (9) as 1.71 and 3.99 percent. When the efficiency of channel swimmers

TABLE 5. ANALYSIS OF THE EFFICIENCY OF SWIMMING THE FRONT CRAWL AT DIFFERENT VELOCITIES

Distance	Time	Velocity (m/sec.)	Strokes per min.	Force (kg)	Average oxygen cost * (liters/min)	Efficiency (percent)
50 m	:24	2.08	112	13.7	26.0	3.23
100 m	:54	1.85	100	10.8	12.8	4.60
200 m	1:59	1.68	85	8.9	8.4	4.63
400 m	4:50	1.58	72	7.9	6.3	5.76
1,500 m	17:50	1.44	69	6.6	5.0	5.40
38,620 m	11 hr. 40 min.	.92	57	2.7	3.2	2.32

* Average oxygen cost for an event is taken as the sum of aerobic and anaerobic metabolism. A maximum oxygen uptake of 4.80 liters/min. and a maximum oxygen debt capacity of 7.2 liters (1.5 × 4.8 liters/min.) was assumed for the 50- to 1500-meter events. Since 4.80 liters/min. is a conservative estimate for a world record holder, the aerobic capacity during an event was taken as event time in seconds divided by 60 × 4.8. The last example was based on data collected on a chunnel swimmer during a long swim. No debt measurement was used in this calculation.

was calculated from the data of Pugh and others (13) the range was from 1.6 to 7.2 percent. Compared to the 25 to 30 percent efficiency of runners, these efficiencies appear very low. However, the efficiency of arm ergometry is approximately 6 percent, and motorboats have an efficiency of about the same magnitude.

The energy cost of propulsion by the legs alone is 2 to 4 times greater than the energy cost of the same propulsive force by the arms alone or the whole stroke (9). The range in the efficiency of the leg kick was .05 to 1.23 percent and of the arm pull .56 to 6.93 percent. The means were .49 percent for the legs and 2.16 percent for the arms. These results support the de-emphasis of the kick in distance swimming.

Trained swimmers have higher efficiencies than the untrained at any given velocity (2, 9, 13). For the same swimmer performing the same stroke, efficiency is lowest at low and high speed. The loss in efficiency at low speed is primarily due to the lack of a planing action and at high speed to the development of a bow wave.

Efficiencies can be calculated for existing swimming records or for an individual's performance by assuming values for the oxygen uptake swimming and the oxygen debt in recovery. A value of 4.80 liters/min. was assumed for the oxygen uptake. A procedure for the accurate measurement of oxygen debt is not available. The maximum oxygen debt capacity appears to be a function of the maximum oxygen uptake. A reasonable estimate of oxygen debt may be obtained by multiplying the maximum oxygen uptake by 1.5. In this case a debt of 7.2 liters is obtained (1.5 × 4.8). Efficiencies were calculated on the basis of these data in Table 5.

The last estimate in Table 5 was based on the oxygen uptake and velocity of a channel swimmer over a period of hours (13). Oxygen debt was not used in this calculation since the oxygen debt, even if maximum, contributes less than 1 percent of the energy, whereas in the 50 m sprint, 70 to 90 percent of the total energy is attributable to the oxygen debt mechanism.

The strokes, in order of their efficiency, are the front crawl, back crawl, breaststroke, and sidestroke (9). The relative efficiency of the butterfly stroke varies with velocity. It is the least efficient stroke at slow speed and more efficient than the side stroke or breaststroke above 55 m/min.

Swimmers with the same efficiency who swim the same distance in a practice could have much different workouts. Both the kg-m of work and the caloric cost of swimming increase approximately with the square of the velocity. Therefore, swimming practices are more accurately evaluated in these terms than in distance or lengths swum. Coaches traditionally have made this adjustment subjectively by assessing the amount of "speed work" and the amount of "distance work" separately. The work done may be calculated from kv^2s (Appendix E). To determine the caloric cost, the efficiency of the swimmer must be estimated either by measurement or by assuming the values in Table 5. The caloric cost is then determined by converting the work done into calories and dividing by the efficiency.

Summary

The tremendous improvement in world records indicates that new investigations of stroking efficiency are necessary. Comprehensive data are also needed on the caloric and heart rate cost of different interval training procedures and of distance swimming. These data would provide more accurate estimates of what swimmers can and are doing physiologically. Since world class swimmers are presently training the maximum number of hours possible per day, a requirement is the assessment of the relative effectiveness and efficiency of training programs of different intensity and duration.

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4. SOCIOLOGICAL AND PSYCHOLOGICAL ASPECTS OF SWIMMING

The concept of a holistic approach to the coaching of swimmers is accepted (3). In holistic training, all aspects of an individual's life that relate to his swimming performance are considered (Figure 4). Effective coaching is the development and/or reinforcement of the positive factors and the restriction and/or elimination of the negative factors. No other approach appears defensible. A child grows up in a specific cultural context. If he joins an age group swimming program, it is because of attitudes developed in his family and in his community. The swimming program also interacts with the culture. Well organized programs result in better swimmers and the better swimmers progress to national and international competition. The improved caliber of the swimming meets attracts larger crowds and greater publicity, which enables coaches to recruit boys and girls with greater physical endowment.

Psychological Characteristics

The psychological characteristics of swimmers have not been determined. Historically, the measurement of personality factors has been plagued by problems of reliability and validity. Based on the Cattell sixteen personality factor test, 41 leading American and British champions in the 1952 Olympics displayed personality profiles significantly high on factors of dominance and aggressiveness, casualness and undependability, adventurousness and "thick skinnedness," and confidence (8).

At present, extensive personality testing of swimmers by coaches is neither feasible nor justifiable. However, many challenging problems exist in the psychology of spo nd the appropriate professional personnel should be encouraged to undertake investigations. Research is needed to determine the enduring and/or necessary personality traits of champion athletes and whether or not swimmers have the same personality profiles as other athletes.

Social Factors

The phenomenon of family involvement in successful age group programs and the attraction of athletes with greater physical endowment

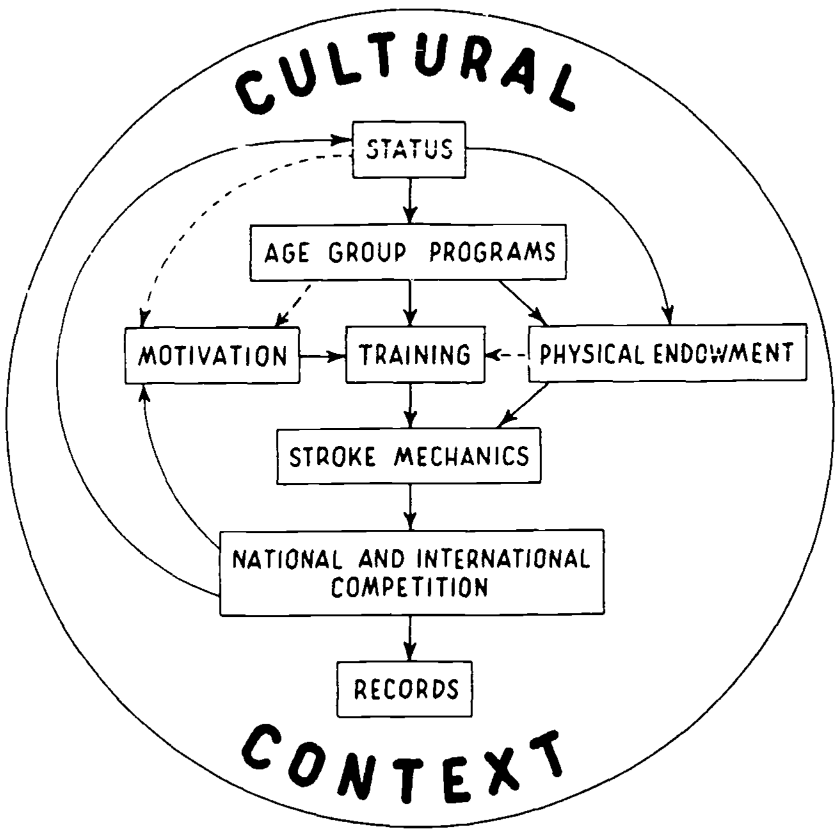

FIGURE 4. A holistic approa h to swimming records.

to swimming with the advent of greater cultural support indicate important sociological factors at work. A glance at the international scene also discloses radically different procedures in the selection and development of international caliber swimmers in different cultures. Astrand and his associates (1) have made a beginning in this field with their treatment of the family background of Swedish girl swimmers. The majority of their parents had been active in sports and competitive athletics themselves; they had taken time to devote themselves to their children's upbringing and to companionship with them; they had a positive attitude to competitive swimming for girls; and they were personally involved in the activities of the swimming club. The similarity to the American age group program is obvious. That additional sociological data are not available is unfortunate.

Psychology of Coaching

The psychology of coaching is still in its infancy. Many coaches through intuitive and trial-and-error procedures have developed highly successful techniques in the handling of swimmers with divergent personalities. Other more aggressive and domineering coaches simply apply an authoritative regime that swimmers either conform to or quit. Many potentially great swimmers have been lost by the latter procedure. Yet an overly permissive approach may be equally damaging. The coach should not be expected to cater to the whim of every swimmer; however, he should have sufficient rapport with his swimmers so that some flexibility within the bounds of sound training practices is possible.

Psychiatrists and psychologists have made clinical observations of the process of identification, the mechanism of sibling rivalry, and the importance of psychological insight in coaching. Since data are not presented, conclusions cannot be drawn as to the extent to which these are operative or need to be operative in successful coaching. A high level of motivation and realistic goal-setting are crucial if a swimmer is to attain his potential, yet no scientific investigations have been made of motivation or level of achievement in the context of sport (2).

Motivation

Why does man swim? Man is definitely not readily adaptable to an aquatic environment either in control of body temperature, in respiration, or in effective propulsion. For children, swimming is a novelty and for both young and old there is the physical invigoration from swimming in the summer. Age group programs appear to have capitalized particularly on the novelty of swimming.

The appeal of competitive swimming is even more of an enigma. Practices are often in the early morning and the highly competitive indoor season is in winter. Swimmers are motivated to spend a surprising portion of their waking hours training. Astrand and his co-workers (1) reported a Swedish girl's club that trained 30 hours a week, during which club members swam from 60,000 to 70,000 m. Many American clubs surpass this mark. Obviously, swimmers who adhere to such an intensive training regime are highly motivated. For many years swimming appeared to attract boys who could not make other more popular athletic teams, although this has not been documented. Recently, athletes with considerable physical prowess have been recruited into competitive swimming careers. Family and personal considerations are undoubtedly involved, and clarification would contribute to an understanding of the motivational structure of world class swimmers.

Level of Anticipation

The control of the cardiovascular system by the motor cortex has been well documented by careful experimentation (10). Motor cortical control of circulation enables a swimmer conditioned to an event to make appropriate cardiovascular adjustments before he begins the race (5, 10, 12). A swimmer poorly prepared for an event may conversely display inappropriate responses.

Muscle action potentials, sweating (psychogalvanic skin response), blood pressure, and heart rate all have been used to assess the level of anticipation (4, 5, 6). Of these, the heart rate is the most useful measure of anticipation and the most accessible (6).

Two types of performances are required in competitive swimming—distance events require maximum efficiency (ratio between useful work and energy expenditure), and sprint events require maximum power (work done per unit time). The efficient response requires mental and physical relaxation before the event. Through practice, muscular relaxation can be mastered with the virtual disappearance of tonus (9, 11). Due to the brief time period involved in a sprint, maximum power is increased by a high level of anticipation. The increased heart rate and increased blood pressure indicate a greater cardiac output. As a result of autonomically conditioned shunting, the increased blood supply is made available to the appropriate muscles before the event actually begins (12).

Just what constitutes the optimum level of anticipation or motivation appears to vary from athlete to athlete and from event to event. It may even vary within a given athlete on different occasions. Distance runners do have lower heart rates prior to and during an unknown work task than do sprint runners (4, 5). The difference persists even after a series of conditioning trials, particularly in the anticipatory heart rate. The high anticipatory heart rates of sprinters may be due to an innate "sprint personality" and/or prior conditioning to a maximum response that is resistant to reconditioning. There is the possibility that even in sprint events an inverted U relationship exists between the level of anticipation and performance.

Summary

A holistic approach to coaching is recommended. The personality characteristics of swimmers have not been determined and tests useful to a coach are not available. The level of anticipation may affect performance. A coach can discern overly anxious swimmers by careful subjective appraisal. Pre-event pulse rates are also easily obtained. Swimmers can be trained to relax before an event. Referral of talented swimmers who are healthy and asymptomatic yet not performing up to their potential also appears warranted. The referral may be made to a school or university psychologist for diagnosis and guidance.

Clinical and experimental psychologists with an interest in sports should be encouraged by coaches to study the motivational structure of swimmers. Research is needed to describe the world class swimmer, to differentiate among specific categories of swimmers, to determine why people swim competitively and why they stop swimming competitively. Longitudinal studies of the effect of long-term swim training programs on the personality and other psychological characteristics of the participants are of the utmost importance.

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5. EVALUATION OF PERFORMANCE

In competitive swimming, the ultimate criterion of performance is the time required to swim a prescribed event. The elapsed time is dependent, however, on the interaction of such factors as cardiovascular-respiratory condition, the distance swum, percentage of maximum velocity involved, and the efficiency of stroke mechanics. The isolation of a specific item as the limiting factor can be most valuable for the coach and the swimmer.

Velocity-Duration Curve

Craig (3) has developed velocity-duration curves for men's freestyle swimming records. He has suggested comparing the velocity-duration curve of individuals to that of world record holders. The technique has possibilities in the separation of speed and endurance as factors limiting performance. In Figure 5, freestyle swimming Olympic records are compared to Craig's 1910 velocity-duration curve (3). An individual swimmer's time for each distance could be plotted in exactly the same way. Each velocity-duration curve is drawn through the 100-meter plot. In 1928, the 400-meter time was slower and the 1500-meter time faster than predicted from the 100-meter time and the velocity-duration curve. The 400-meter and 1500-meter times were right in line in 1960, but much faster than predicted from the 100-meter time. Devitt and Larson's time of 54.2 was slow relative to other swimming performances and a time of 53.8 was to be expected.

The 1964 times were very close to the curve. The position of the 200-, 400-, and 1500-meter plots in 1960 suggest that a change may have occurred in the shape of the curve. Through improvements in training and stroke efficiency swimmers may now maintain a greater percentage of their maximum velocity over a longer distance. An alternative hypothesis is that swimmers are approaching the maximum velocity possible at shorter distances and further major improvements in the sprints are not to be expected.

Pulse Rate After Repeats or Races

In anticipation of an event, the pulse rate is influenced primarily by psychologic factors. After a maximum or near maximum effort, the physiologic influences predominate. Carlile and Carlile (2), Faulkner (5), and Gavreesky (6) have all proposed techniques for evaluating performance on the basis of the pulse rate at the end of a maximum effort

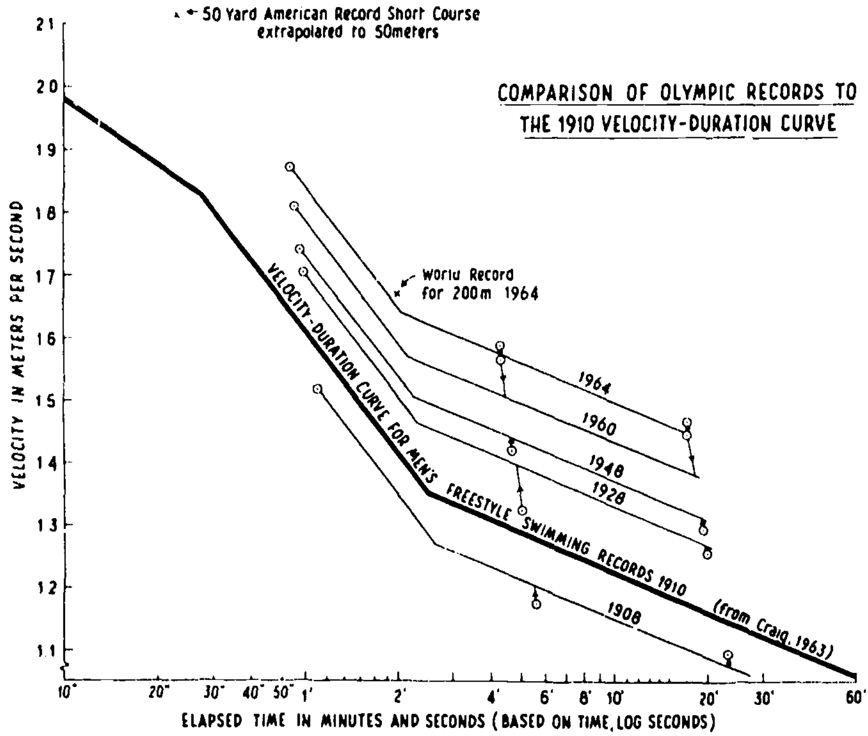

FIGURE 5. Comparison of Olympic swimming records to the 1910 velocity-duration curve. (Modified from Craig, A. B. Evaluation and predictions of world running and swimming records. *J. sports Med. & phys. Fit.* 3:14-21, 1963. With permission of the publisher.)

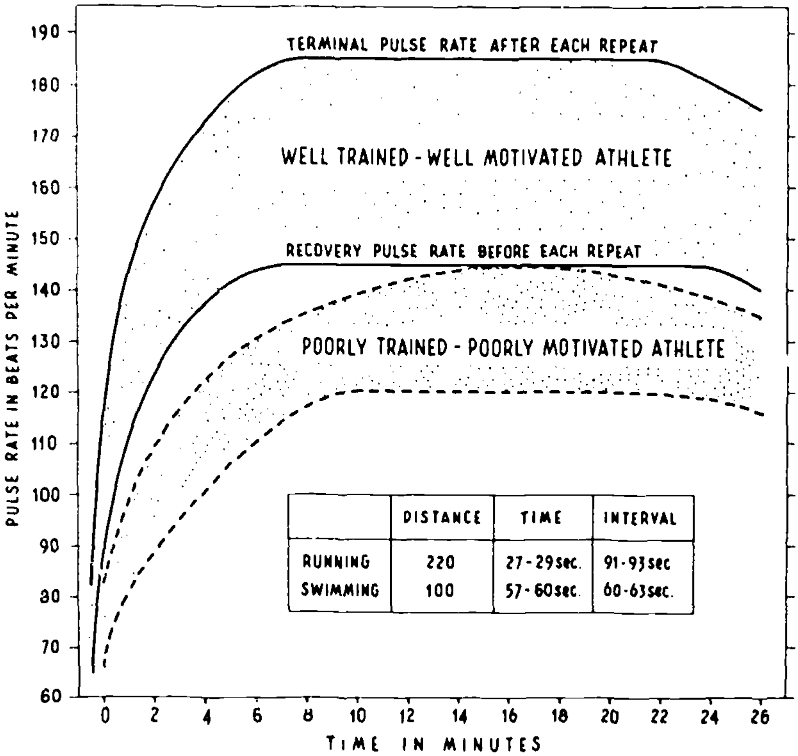

FIGURE 6. Terminal and recovery pulse rates after repeated 100-yard sprints. (From Faulkner, J. A. Motivation and athletic performance. *Coaching Review* 1:3-5, 1963. With permission of the publisher.)

(race or time trial) or after each repeat in interval training. The problem in a strenuous training program is to determine the maximum performance level of different competitors. Because of the linearity of pulse rate and work output, a pulse rate reading immediately after the event is an excellent indicator of the intensity of the swimmer's effort. Regardless of the resting level, a pulse rate of 175 to 200 is maximum for most young adults. World class swimmers perform sets of repeats at maximum effort with pulse rates in this range. Children have higher maximum pulse rates than adults and rates over 200 are not unusual for age group swimmers after a maximum effort.

The smoothed pulse rate curves in Figure 6 are composites based on data collected on male varsity swimmers during the past five years (4). The swimmers were doing repeat freestyle 100-yard swims with starts every two minutes. The well trained, highly motivated swimmer averaged 185 beats per minute after each repeat and recovered to approximately 145 beats during the rest period. The poorly trained, poorly motivated swimmer either did not have the muscular strength and/or endurance to stress his cardiovascular-respiratory systems by swimming, or he was not willing to stress himself maximally.

Some swimmers believe they are working maximally at pulse rates of 140 to 150. The pulse rate data aid the coach in convincing them that they can push themselves harder. However, such data should be used with discretion and should be supplemented with additional data to ensure that the swimmer really is capable of a better performance.

Most trained swimmers will reach pulse rates in excess of 170 if they are working maximally. During repeats, maximum pulse rates are usually attained by the third repeat. If a competitor gives a truly maximum performance his times may slow, and his pulse rate may drop during the last two or three repeats.

If times are checked for each repeat, pulse rates need be taken only after the third, sixth, and ninth repeats. The times indicate that a constant pace is being maintained, and the average of the three pulse rates is a reliable estimate of the degree of stress.

Pulse Rate and Velocity

Graphs of oxygen uptake (8) and pulse rate (5) with swimming velocity provide excellent comparisons of the stroke efficiency of different swimmers (Figure 7).

A practical technique is to have the competitors swim 50 yards from a push-off at approximately "25, 50, 75, and 100 percent" of maximum speed. The specific percentage is merely conceptual and the terms *slow*, *moderate*, *fast*, and *all-out* would be equally appropriate. The elapsed time from push-off to touch is recorded to the nearest tenth of a second. The time for the distance is then transferred into meters per second. The pulse rate is counted for 15 sec. from 5 to 20 sec. after the touch (Appendix C). A velocity-pulse rate relationship is then plotted and a best fit line drawn. The velocity-pulse rate relationship is reasonably linear throughout the mid-range of swimming velocities in the front crawl, backstroke, and breaststroke. The relationship is more curvilinear in the butterfly stroke.

The velocity-pulse rate curve may be used to compare the stroke efficiency of different swimmers or the changes in stroke efficiency of individual swimmers during training or detraining.

Propulsive Force

The measurement of force and the analysis of stroke pattern during tethered swimming are practical aids to coaching. Tethered swimming is a widely used training technique. Swimmers are fastened at the waist with a broad web belt and a shock cord. A simple dynamometer or spring scale can be placed in a tethered swimming rig to measure the force exerted for different time periods. The addition of a kymograph provides a record of the timing and magnitude of the accelerations and decelerations which occur during a stroke cycle. The tracings provide a basis for the comparison of stroke mechanics (7).

The propulsive force generated in free swimming may be determined by reference to equations in Appendix D. The calculations of force tethered and swimming free enables a coach to evaluate the stroke mechanics of swimmers under conditions of increasing velocity. A

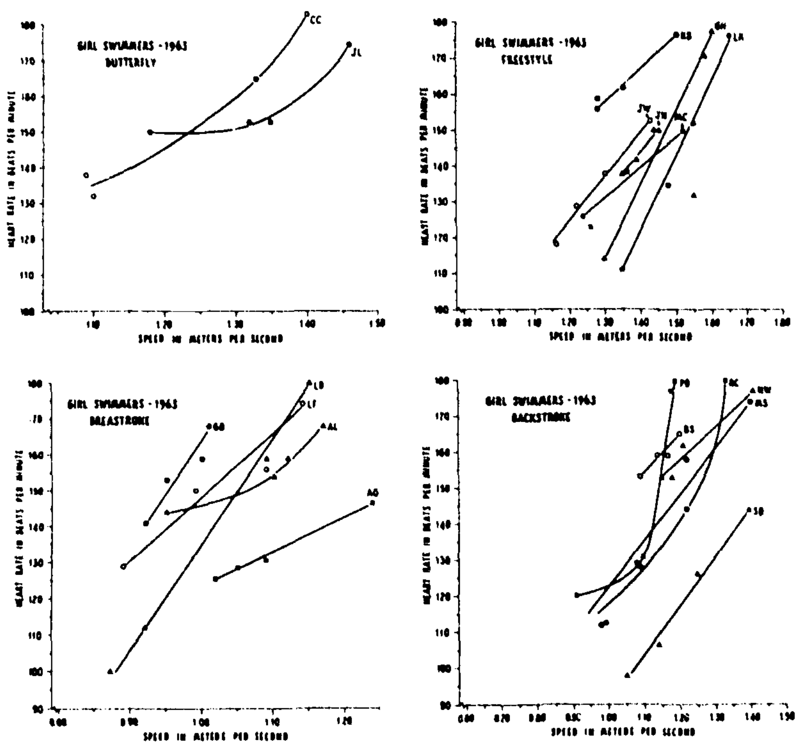

FIGURE 7. Velocity-heart rate relationship in the four competitive strokes. (From Faulkner, J. A., and Dawson, R. M. Pulse rate after 50-meter swims. *Res. Quart.* 37:282-84, 1966.)

swimmer who can develop great force at zero velocity but cannot develop high velocity is likely to have problems in recovery or in body position since he is developing a disproportionately high resistance with movement.

The provision of a force measurement in tethered swimming provides data feedback so important to the motivation of athletes. The addition of a small length of cable in each of a series of tethered swimming rigs would enable the coach to intermittently sample the propulsive force of 10 to 15 tethered swimmers with a cable tensiometer.

Energy Expenditure and Efficiency

An exercise physiology laboratory is necessary for the determination of maximum oxygen uptake—one of the most important physiologic variables. Determination of maximum oxygen uptake during either tethered or free swimming (Appendix C) provides the best estimate of the energy that can be developed by swimming and the data necessary to calculate the efficiency of the swimmer over different distances. The velocity-oxygen uptake graph clarifies the relationship of velocity and energy expenditure. It is unfortunate that so little data on swimmers are available. From the data available, oxygen uptakes in swimming range from 1.2 to 5 liters/min. and efficiency in trained swimmers from 2 to 7 percent. The interactions of maximum oxygen uptake and stroke efficiency are unquestionably the major considerations in swimming performance.

Efficiency may be calculated for a swimmer on the basis of his maximum oxygen uptake, his maximum oxygen debt, and his maximum velocity at different distances (Table 5 and Appendix F). When oxygen uptake cannot be measured directly, a rough estimate can be obtained from the Astrand-Ryhming nomogram (Appendix H). The assumption of an oxygen debt 1.5 times the maximum predicted oxygen uptake provides the necessary data for the calculation of efficiency.

The decreased bow wave and the increased use of aerobic rather than anaerobic energy should result in greater efficiency when maximum velocity is held over greater distances (Table 5, p. 23). If estimates of total oxygen cost are used, a decreased efficiency in the longer distances is usually due to the swimmer not swimming hard enough to engage his maximum oxygen uptake. The overestimation of oxygen uptake in the denominator of the efficiency equation results in a reduced estimate of efficiency. This may also be checked by the velocity duration curve (Figure 5, p. 33). Through the calculation or estimation of maximum oxygen uptake and efficiency, comparisons may be made among swimmers or of the same swimmer at different times.

Caloric Cost of Swimming Practices

Most training programs are currently evaluated in terms of the number of lengths swum. Such an evaluation does not take into account the increase in work with the square of the velocity. Much more energy is expended swimming at high speed as compared to swimming the same distance at slower speed.

The measurement or prediction of maximum oxygen uptake and oxygen debt and the calculation of the efficiency of swimmers at different speeds enables the coach to estimate the caloric cost of different types of swimming practices or of the same practice for different swimmers. By developing graphs of the speed–caloric cost relationship for swimmers of different efficiencies, practices could be evaluated quickly and effectively.

Summary

The biomechanics and physiology of swimming are continually interacting (Figure 1, p. 2). The swimmer has a body density that may be changed by training, diet, or growth and a functional residual capacity (Figure 3, p. 9) that may be increased by training or growth. Within limits, his tidal volume can be controlled. When the swimmer is immersed in water, the combination of body density, functional residual capacity, and tidal volume will provide a certain buoyancy. Buoyancy is directly proportional to functional residual capacity and tidal volume and inversely proportional to body density.

As the swimmer begins to stroke, the propulsion depends on the effectiveness of the stroke mechanics and, to an undetermined degree, on muscular strength. The swimmer will accelerate until the propulsive force equals the water resistance. The velocity at which a given propulsive force equals water resistance will depend on the initial buoyancy, the flotation provided by the water flow "lifting" the body, and the eddy and wave-making resistance created by the stroke mechanics.

The ability of a swimmer to maintain a high velocity over time is a function of his muscle endurance, efficiency, and total capacity for energy expenditure. If local muscular endurance is adequate, the energy cost of swimming at a given velocity (efficiency) and the capacity to do aerobic work interact to limit the velocity that can be maintained over a fixed distance. The anaerobic capacity may account for 80 to 90 percent of the energy expenditure in a 50-m sprint and as little as 8 to 10 percent in a 1500-m swim. Heat dissipation is rarely a problem except for high

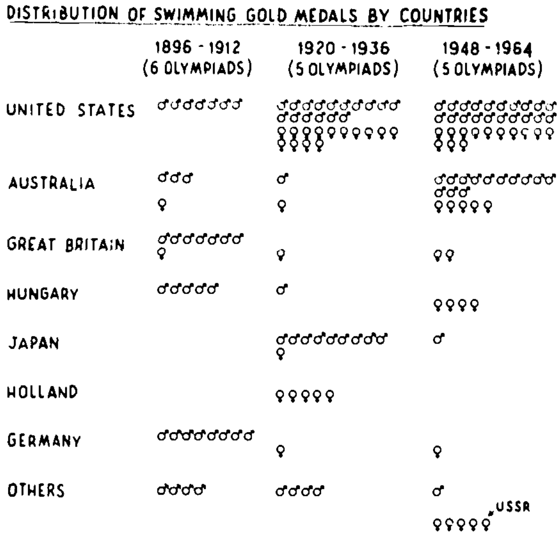

FIGURE 8. Distribution of swimming gold medals by countries.

intensity swimming in water over 30 C. The success of a swimmer depends on the development of (a) muscle strength and endurance, (b) large aerobic and anaerobic capacities, and (c) efficient stroke mechanics.

Americans currently have more world class swimmers in both men's and women's events than any other nation (Figure 8). The age group, public school, and college swimming programs are flourishing. Competition, both national and international, is improving, and more and more talented athletes are being attracted to the sport. The time is opportune for bridging the gap between the theory and practice of swim coaching. Much is known of the physiology, biomechanics, and psychology of swimming that has immediate application. Much that remains to be learned will require the cooperation of scientists, coaches, and swimmers. The experience can be challenging and rewarding for all three participants.

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APPENDIXES

APPENDIX A

Body Build Rating Scale

A. Scale for rating fat status (endomorphy)

1 2	3 4	5 6 7
Extremely low in adipose tissue and relatively small anteroposterior dimensions of the lower trunk.	Average tissue and physical build of lower trunk.	Extremely obese with large quantities of adipose tissue and unproportionately thick abdominal region.

B. Scale for rating muscular status (mesomorphy)

1 2	3 4	5 6 7
Extremely underdeveloped and poorly conditioned muscles squeezed or pushed in the contracted status (biceps, abdominals, thighs, calves).	Average in skeletal muscular development and condition.	Extremely developed with large and hard muscles in the contracted state; firm under forceful squeezing.

C. Scale for rating skeletal status (ectomorphy)

1 2	3 4	5 6 7
Extremely thick and heavy bones, short and ponderous skeleton with relatively great cross-section of ankle, knee, and elbow joints.	Average size bones and joints in cross-section and length.	Extremely thin frail bones; tall linear skeleton with relatively small cross-section of ankle, knee, and elbow joints.

Note: After one rating is selected from each of A, B, and C, the digits are combined into one rating, for example, 2-5-4. The sum of the three digits should equal 11.

(From Cureton, T. K. *Physical Fitness Appraisal and Guidance*. St. Louis: The C. V. Mosby Co., 1947. With permission of the publishers.)

APPENDIX B

Measurement of Body Composition

The method of determining body density is fully described by Goldman and Buskirk.[1] The equipment needed is too expensive and the experimental procedure too complicated for use other than in the laboratory. Ten simpler methods for determining percent body weight that is fat and body density have been evaluated by Damon and Goldman.[2] Body fat as determined by densitometry was best predicted by averaging the multiple regression equations based on the triceps and infrascapular skinfolds.

The skinfold measurement technique is quick and relatively simple. The only equipment necessary is a pair of skinfold calipers. Rather than use the average of the two equations, two additional skinfold measurements are taken and values for percent fat are read directly from Table 6.

The regression equation of Yuhasz,[3] as follows

$$\% \text{ fat} = 4.98 + (0.107 \times \text{sum 6 fat measures})$$

requires measurements of triceps, back, hip, stomach, chest, and thigh fat sites. Since the sum of four measurements (triceps, back, hip, and stomach) correlates 0.96 with the sum of the six measurements, the chest and thigh sites have been eliminated. The equation then becomes

$$\% \text{ fat} = 5.783 + (0.153 \times \text{sum 4 fat measures})$$

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[1] Goldman, R. F., and Buskirk, E. R. Body volume measurement by underwater weighing: Description of a method. In *Conference on techniques for measuring body composition*, Brozek, J., and Henschel, A. (eds.). Washington, D. C.: National Academy of Sciences–National Research Council, 1961.

[2] Damon, A., and Goldman, R. F. Predicting fat from body measurements: Densitometric validation of ten anthropometric equations. *Human Biol.* 36:32-44, 1964.

[3] Yuhasz, M. S. *The effects of sports training on body fat in man with predictions of optimal body weight.* Unpublished doctoral dissertation, University of Illinois, 1962.

Skinfold Measurements

Each of the skinfold measurements is obtained by lifting the skin and underlying fat firmly between the thumb and fingers. The calipers are placed around and at right angles to the raised skinfold. The caliper is gradually released and allowed to compress the skinfold about 1 cm from the point where the skinfold is lifted. The reading is made to the nearest millimeter.

Measurements are made at the following sites:

1. *Arm (triceps).* This measurement is taken at a level halfway between tip of acromion process and tip of elbow. Arm should be hanging freely at subject's side. Skinfold is lifted on back of the right arm parallel to the long axis of the arm about 1 cm above the site.

2. *Abdominal skinfold.* The skinfold is lifted about 1 cm to the right of the umbilicus and parallel to the long axis of the body.

3. *Hip skinfold.* The skinfold is lifted on the right midaxillary line just above the crest of the ilium. The fold is lifted to follow the natural diagonal line at this point (dorsally upward).

4. *Back skinfold.* The skinfold is located 1 cm below the inferior tip of the left scapula, and the fold is lifted parallel to the long axis of the body.

The four readings are summed and the total skinfold reading may either be used directly as a measure of fatness or converted into percent fat through reference to Table 6. Percentile ranks for the four fat measurements have been determined for male college swimmers 18-23 years of age and female age group swimmers 12-17 years of age (Table 7).

TABLE 6. PREDICTION OF PERCENT FAT FROM SKINFOLD MEASURES FOR MALE SWIMMERS

Skinfolds	% Fat	Body density
135	26.4	1.0304
128	25.4	1.0329
121	24.3	1.0357
114	23.2	1.0386
107	22.1	1.0414
100	21.0	1.0442
93	20.0	1.0468
86	18.9	1.0502
79	17.9	1.0524
72	16.8	1.0553
65	15.7	1.0582
59	14.8	1.0634
52	13.7	1.0635
45	12.7	1.0662
38	11.6	1.0692
31	10.5	1.0722
24	9.5	1.0750
17	8.4	1.0780

Note: Percent fat was calculated from a modification of Yuhasz's formula (see reference, p. 6). Body density was calculated from the Keys and Brozek formula (p. 6).

TABLE 7. PERCENTILES FOR THE SUM OF FOUR FAT MEASUREMENTS FOR MALE AND FEMALE SWIMMERS

Percentile	Male	Female
99	20	27
90	24	32
80	26	38
70	28	42
60	30	44
50	32	48
40	35	52
30	41	56
20	47	61
10	56	74
1	76	80
	(N = 33)	(N = 69)

Note: Since the lower the fat measurement the greater the percentage of body weight that is bone and muscle (greater body density), the lower fat measurement is assigned the higher percentile.

APPENDIX C

Tests of Maximum Oxygen Uptake

The tethered swimming test [1] involves swimming in place while attached to a pulley weight system. Three-min. swim periods are followed by a 3-min. rest period. The swimmer holds up a 10-lb. weight for the first swim period, and 2.5 lb. are added each subsequent work period until the swimmer cannot support the weight for 3 min. Gas collections are made during the last minute of each level and every minute as the swimmer approaches maximum.

During free swimming, maximum oxygen uptake may be obtained either during 5- to 10-min. swims at the maximum velocity that can be maintained or during 50-yd. sprints with 10-sec. rest intervals. Gas collections should not be started until the swimmer reaches maximum, usually after 5 min. in the aerobic swim or after 10 to 15 repeats in interval work. To offset the effect of the turns, collections in pools should be started 5 yd. from a turn and stopped at the touch.

[1] Magel, J. R., and Faulkner, J. A. Maximum oxygen uptakes of college swimmers. *J. appl. Physiol.* In press, 1967.

APPENDIX D

Calculation of Force Exerted per Arm Pull in Front Crawl Stroke

$f = kv^2$ — f = force exerted in kilograms
$v = 2$ m/sec. — k = constant 3.17 (Table 3)
$f = 3.17 \times 2^2$ — v = velocity in meters/sec.
$f = 12.7$
$f = 70\%$ arm pull $+ 30\%$ leg kick

$$f\text{ (arms)} = \frac{70}{100} \times 12.7 = 8.9\text{ kg}$$

Double arm pull = 136 kg
Single arm pull = 68 kg

Percent maximum pulled each stroke $= \frac{8.9}{68} \times 100 = 13\%$

APPENDIX E

Rough Calculation of the Work Done and Net Caloric Cost of a Swimming Practice

I. *Practice.* 600-yd. warm-up in 14 min.
3 sets 10 × 100 yd. at 60-sec. pace.

II. *Work Done.* $w = kv^2s$ (Table 3)

1. 600 yd. in 14 min. = 12 × 50 yd. at 35-sec. pace.
   50 yd. at 35-sec. pace = 245 kgm.
   600 yd. = 12 × 245 = 2,940 kgm.
2. 3 sets 10 × 100 yd. at 60-sec. pace = 60 × 50 yd. at 30-sec. pace.
   50 yd. at 30-sec. pace = 334 kgm.
   3 sets 10 × 100 yd. = 60 × 334 = 20,040 kgm.

   Total = 2,940 + 20,040 = 22,980 kgm.

III. *Efficiency.* (Table 5)

4% at 35-sec. pace
4.9% at 30-sec. pace

IV. *Oxygen cost of*

$$\text{Distance} = \frac{.04686 \times \text{kgm}}{\text{Efficiency}} = \frac{.04686 \times 2940}{4.0} = 34.4 \text{ liters/min.}$$

$$\text{Repeats} = \frac{04686 \times \text{kgm}}{\text{Efficiency}} = \frac{.04686 \times 20{,}040}{4.9} = 191.6 \text{ liters/min.}$$

Total oxygen cost = 34.4 + 191.6 = 226.0 liters/min.

V. *Caloric cost*

Net caloric cost = oxygen cost × 5 = 1,130 kcal.

APPENDIX F

Sample Calculation of the Efficiency of a Swimmer

Maximum oxygen intake 4.8 liters/min.

Maximum oxygen debt 12 liters

Event 400 m

Time 4 min. 50 sec. (290 sec.)

1. Oxygen cost per minute
   Aerobic cost = 290 ÷ 60 × 4.8 = 23 liters
   Anaerobic cost = 12 liters
   Total oxygen cost of event = 35 liters
   Oxygen cost per min. = 35 × 60 ÷ 290 = 5.5 liters/min.

Velocity = 400 ÷ 290 = 1.58 m/sec.

Force = 3.17 × $(1.58)^2$ = 6.6 kg

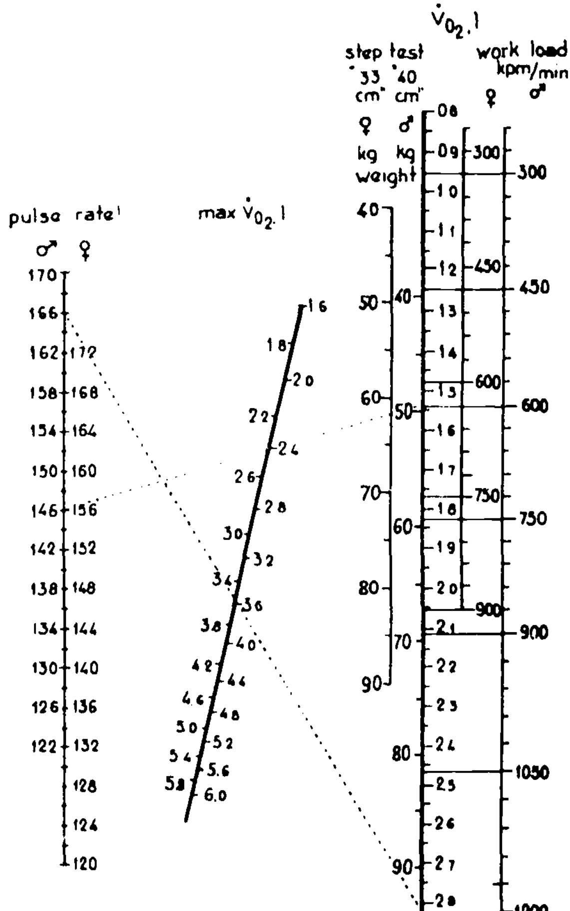
Distance = 1.58 × 60 = 86 m/min.

1 mkg of work = .0004686 liters/min. oxygen

2. Efficiency $= \dfrac{kv^2s \times .0004686}{O_2 \text{ cost liters/min.}}$

$$= \frac{3.17 \times (158)^2 \times 95 \times .0004686}{7.5}$$

$$= 4.70\%$$



The adjusted nomogram for calculation of aerobic work capacity from submaximal pulse rate and O_2 uptake values (cycling, running or walking and step test). In tests without direct O_2 uptake measurement it can be estimated by reading horizontally from the "body weight" scale (step test) or "work load" scale (cycle test) to the "O_2 uptake" scale. The point on the "O_2 uptake" scale ($\dot{V}O_2$, l) shall be connected with the corresponding point on the "pulse rate" scale and the predicted maximal O_2 uptake read on the middle scale. A female subject (61 kg) reaches a heart rate of 156 at step test; predicted max. $\dot{V}O_2$ = 2.4 l. A male subject reaches a heart rate of 166 at cycling test on a work load of 1,200 kpm/min; predicted max. $\dot{V}O_2$ = 3.6 l (exemplified by dotted lines).

FIGURE 9. Nomogram for the estimation of maximum oxygen uptake from heart rate and work load. (From Astrand, I. Aerobic work capacity in men and women with special reference to age. *Acta physiol. Scand.* 49: suppl. 169, 1960. With permission of the publisher.)

APPENDIX G

Pulse Rate After Swimming

An estimate of the pulse rate during repeats on time trials may be obtained by counting the pulsations in the carotid artery immediately afterward. As the swimmer touches at the finish he turns his back to the end of the pool and stands on bottom. The coach kneels on the deck and reaches over the swimmer's right shoulder to palpate the artery.

To obtain the pulse rate the fingers are placed over the right carotid artery in the angle of the jaw. The number of pulsations are counted for a 15-sec. period and then multiplied by four to obtain the pulse rate in beats per minute.

APPENDIX H

The Astrand-Ryhming Nomogram for Calculation of Aerobic Capacity[1]

A submaximum step test is used to obtain a steady-state heart rate. The bench height is 40 cm for young males and 33 cm for females. The swimmers step at 22.5 steps/min. The best procedure is to step up-up-down-down in time to a metronome set at 90 beats/min. The heart rate should be taken during the exercise after a steady state has been reached. The heart rate will usually plateau after 2 min. Thirty-sec. readings a minute apart should be made until two readings are within 5 beats/min. of each other. Readings during stepping are most easily obtained by a sphygmomanometer. If this procedure cannot be used, the subject should stop every 2 min. while a 10-sec. pulse count is made at either the radial or carotid artery (see Appendix G). The test should not take more than 5 or 6 min. The appropriate heart rate and body weight are then lined up on the nomogram (see Figure 9) and the maximum oxygen uptake is obtained from the center scale.

[1] Astrand, I. Aerobic work capacity in men and women, with special reference to age. *Acta physiol. Scand.*, Vol. 49, Suppl. 169, Stockholm, 1960.

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