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Physical and Energy Requirements of Competitive Swimming Events

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The aquatic sports competitions held during the summer Olympic Games include diving, open-water swimming, pool swimming, synchronized swimming, and water polo. Elite-level performance in each of these sports requires rigorous training and practice to develop the appropriate physiological, biomechanical, artistic, and strategic capabilities specific to each sport. Consequently, the daily training plans of these athletes are quite varied both between and within the sports. Common to all aquatic athletes, however, is that daily training and preparation consumes several hours and involves frequent periods of high-intensity exertion. Nutritional support for this high-level training is a critical element of the preparation of these athletes to ensure the energy and nutrient demands of the training and competition are met. In this article, we introduce the fundamental physical requirements of these sports and specifically explore the energetics of human locomotion in water. Subsequent articles in this issue explore the specific nutritional requirements of each aquatic sport. We hope that such exploration will provide a foundation for future investigation of the roles of optimal nutrition in optimizing performance in the aquatic sports.

Keywords: economy, power, swimming performance

International competition in aquatic sports is governed by the Fédération Internationale de Natation (FINA), which includes the sports of diving, open-water swimming, swimming, synchronized swimming, and water polo. Table 1 provides an overview of these sports, including their energetic characteristics and the nature of the physical work involved in the various events within each sport. All of these aquatic sports place exceptional physical demands on the competitors both in their competitions and in training. These demands are variable, depending on the sport, and include size, muscular strength, anaerobic power, neuromuscular skill and coordination, aesthetic and artistic quality, and aerobic endurance. The fact that these sports are performed in water where resistance to movement is much greater than on land presents additional challenges to the competitors. In successive articles in this series (Bernadot et al., 2014; Cox et al., 2014; Mujika et al., 2014; Robertson et al., 2014; Shaw

et al., 2014b), each aquatic sport is discussed in reference to how its training and competition demands affect the nutritional requirements in developing and maintaining competitive success. Here we primarily examine the physical requirements of swimming because locomotion or movement in water is common to all aquatic sports, and many of these principles help to form the basis for understanding nutritional considerations in the aquatic sports.

In international competition, swimming races are held in each of the competitive strokes including freestyle (usually front crawl), backstroke, breaststroke, and butterfly. Freestyle is the most economical of the strokes, followed by backstroke, butterfly, and breaststroke (Barbosa et al., 2006). Competitions are held either in short-course pools (25 m) or long-course pools (50 m). During the short-course season of international competition, race distances of 50, 100, and 200 m are held for each of the four stroke styles. In addition, freestyle events of 400, 800, and 1,500 m are also swum. There are also 200- and 400-m individual medleys in which the participants perform all four strokes—butterfly, backstroke, breaststroke, and freestyle, in that order—with each stroke covering one fourth of the total race distance. Relays include a 4 × 100-m freestyle relay, a 4 × 200-m freestyle relay, and a 4 × 100-m medley relay in which one member swims

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Table 1 Characteristics of the Aquatic Sports Competitions During the Summer Olympics and World Championships

Sport and Category	Events	Comments
Pool swimming (women, men; events held separately for women and men)		
Freestyle	50, 100, 200, 400, 800, and 1,500 m ^a	Events from ~20 s to 14.5 min (men) and ~25 s to 15.5 min (women)
Backstroke	50, 100, and 200 m ^b	Asymmetrical movement pattern
Butterfly	50, 100, and 200 m ^b	Symmetrical movement pattern
Breaststroke	50, 100, and 200 m ^b	Symmetrical movement pattern
Medley (butterfly, backstroke, breaststroke and freestyle)	200 and 400 m	Combination of all 4 strokes creates unique energetic requirements
Relays (most often 4 people of same sex)	4 × 50 freestyle ^c 4 × 50 medley ^c 4 × 100 freestyle 4 × 200 freestyle 4 × 100 medley 4 × 50 mixed freestyle ^c 4 × 50 mixed medley ^c	Mixed relays of 2 women and 2 men held during World Cup competitions
Open water swimming (women, men); typically swum with freestyle	5, 10, and 25 km at World Championships 10 km at Olympic Games	Race duration from ~1 hr (5 km) to ~6 hr (25 km)
Water polo (women, men); play area 20–30 m long × 10–20 m wide	Game is played as 4 8-min periods with 2-min rest after Periods 1 and 3 and 5-min rest after Period 2	Intermittent swimming, treading water and ball skills similar to team handball
Diving (women, men); 1-m and 3-m springboard, 10-m platform, synchronized diving on 3 m and 10 m	Women perform a round of 5 dives, men a round of 6 dives	Dive quality scored by a panel of judges
Synchronized swimming (women); duet and team at Olympics	Elements of dance and gymnastics performed in water without using bottom. Performances 2–4.5 min maximum length	Performances scored by panel of judges.
World Championships adds solo and free combination routines.		

^aFemales swim 800 m and males swim 1,500 m at the summer Olympic Games.

^b50 m is not held at the summer Olympic Games.

^cNot held at the summer Olympic Games.

backstroke, one swims breaststroke, one swims butterfly, and one swims freestyle, in that order. All events are held separately for men and women. The women's Olympic program does not include the 1,500-m freestyle, and the men's Olympic program deletes the 800-m freestyle. The Olympic program also deletes 50-m races in all strokes other than freestyle.

The other aquatic disciplines are water polo, diving, synchronized swimming, and open-water swimming. Water polo is a popular team sport that requires a well-developed level of swimming fitness; strength and power to compete successfully in contact situations; technical skills in catching, passing, and shooting the ball; and decision-making and team strategies and tactics (Tan et al., 2009). The energetic demands of water polo can be characterized as highly intermittent, ranging from

relatively low-intensity activity such as treading water to sudden bursts of supramaximal power during competition and practice (Pinnington et al., 1988; Smith, 1998). Diving involves jumping from a platform or springboard, sometimes while performing acrobatic movements. Divers possess strength, flexibility, and high levels of kinesthetic awareness to correctly execute their dives (Miller, 1985). Synchronized swimming is more technique oriented but requires well-developed fitness to undertake the extensive training as well as the physical demands of competitive routines (Mountjoy, 1999). Weight management is a key issue to ensure competitors meet aesthetic expectations (Mountjoy, 2014). An additional physical stress is imposed by the frequent and relatively long breath-holding times during performances. The open-water swimming event in the Olympic Games is

the 10-km swim, but other FINA-governed competitions such as World Championships have events 5, 10, and 25 km in length. With race durations of approximately 1 hr to as long as 6 hr, aerobic endurance, fuel availability, hydration, and swimming economy are primary elements to develop in training and diet.

Anthropometric Characteristics of Aquatic Athletes

The anthropometric characteristics of aquatic athletes vary substantially between and within the various disciplines and, of course, between genders. Swimmers are often tall, and there is an emphasis on leanness (to minimize drag) and muscle strength and power (to promote propulsion). Male swimmers typically have more muscle and less body fat than female swimmers. Athletes, coaches, and strength and conditioning practitioners should typically expect a twofold greater increase in lean mass in male swimmers within and between seasons than in female swimmers (Pyne et al., 2006). Other anthropometric factors such as limb length (arm span) and hand surface area are considered important. The challenge for coaches and the swimming scientist is to integrate selected kinematic, anthropometric, and hydrodynamic characteristics in individualized training programs that account for gender, distance, and stroke (Morais et al., 2012). In diving, male divers are typically taller, heavier, more mesomorphic, and less endomorphic and have less body fat than their female counterparts. In addition to these absolute differences in size, sexual dimorphism between male and female divers includes differences in relative size, skinfolds, and somatotype, with implications for coaching and selection (Carter & Ackland, 1998). In contrast to the other aquatic disciplines that favor leanness, the anthropometric and physiological characteristics of water polo players often resemble those of other team sport athletes, with higher levels of muscle mass and body fat (Tsekouras et al., 2005). Care must be taken in anthropometric and morphological testing of aquatic athletes because different methods can yield substantially different estimates of body composition and anthropometric characteristics (Andreoli et al., 2004).

Energetic Requirements in Competition

Swimming events should be energetically equivalent to middle-distance track running because of similar duration of races (e.g., the 100-m swim and 400-m run both take <60 s, and the 200-m swim and 800-m run both take <2 min). Thus, swimming athletes require elements of power, speed, and endurance to reach their performance potential. These physical elements are energetically supported with a combination of phosphate energy system, lactic acid energy system, and aerobic combustion of carbohydrate, fat, and protein. However, the fact that swimming is performed in the water poses unique challenges

to understanding the specific physiological demands placed on these athletes. A fundamental challenge is the significantly greater resistance of water than air and the difficulty in applying propulsion in a fluid medium. Because of these constraints, the swimmer's skill in reducing water resistance, and in applying propulsive forces effectively, may be more important in dictating the physiological and energetic demands of swimming than a simple kinematic analysis of race duration would reveal.

The range of exercise durations involved in aquatic sports has led coaches to design training programs that target specific adaptations to enhance both anaerobic and aerobic energy provision. Depending on the aquatic sport and specific event, this objective may be accomplished using interval training (relied on mostly in competitive swimming, open-water swimming, and water polo), prolonged continuous training at constant speed (open-water swimming), drills and game simulations (water polo), and repetitions of components of competition routines (synchronized swimming and diving). All sports also involve considerable training time in activities to develop neuromuscular skill, resistance training for muscular strength and stability, and sometimes cross-training for developing general fitness, flexibility, and weight management.

Energetics of Sprint Events

Aquatic sprint events rely heavily on energy provision mainly from muscle stores of high-energy phosphates (adenosine triphosphate, adenosine diphosphate, creatine phosphate). There is evidence that the capacity, power, and recovery of this energy system can be modified with appropriate training (Hirvonen et al., 1987; MacDougall et al., 1977) and diet (Greenhaff et al., 1993). Consequently, training using repeated supramaximal efforts is often used in an attempt to create adaptations of this energy system as a means to enhance muscle's ability to reach peak velocities as quickly as possible and maintain race speeds for the duration of the event. Dietary enhancement of this energy system is largely centered around increasing the muscle content of creatine phosphate (creatine supplements). See Derave and Tipton (2014) for a more complete discussion of these issues.

Energetics of Middle-Distance Swimming

In competitive swimming, most of the events are in the range of about 45 s to 15 min, and all of them are supported by some combination of phosphate energy, anaerobic glycolysis, and aerobic combustion of carbohydrate, fat, and protein (Capelli et al., 1998). The specific contributions of these systems depend on both the length of the race and the intensity of the pace used. Training adaptations of anaerobic glycolysis may include both increased power (maximum rate of lactic acid production) and capacity (improved muscle-buffering capacity to minimize pH disturbance in muscle (Sharp et al., 1986).

Diet may also have a favorable impact on these qualities by ensuring the athlete has adequate glycogen stores at the start of events and by raising muscle-buffering capacity with consumption of beta-alanine or other buffering substances (Derave and Tipton, 2014; Mujika et al., 2014). Together, training and diet may therefore enhance the athlete's ability to both produce and tolerate lactic acid.

Aerobic Power and Endurance

Aerobic power (rate of adenosine triphosphate resynthesis) and capacity (total amount of adenosine triphosphate resynthesis from available fuels) are developed by the combined effects of lower intensity, longer duration training, and diet. Both continuous training and interval training are common in the swimming community for this purpose and are effective in developing and maintaining high $\text{VO}_{2\text{max}}$, high lactate threshold, high oxidative capacity of muscle, and elevated fuel stores in muscle (Costill et al., 1991; Sharp, 1993). Diet can promote these adaptations in a number of ways that are reviewed in a subsequent article in this series (Derave and Tipton, 2014; Mujika et al., 2014). It is also important to recognize that aerobic endurance training may provide an additional benefit in improving the economy of swimming both at the slower endurance training speeds and possibly at race speeds. Given the large range of economy among swimmers of varied performance abilities, factors that improve their economy may markedly reduce the energy and fuel requirement of any given speed.

Propulsive Power and Biomechanics

The 50-m events are the sprint races of competitive swimming and require athletes to sustain maximal power output between 20 s and 30 s, depending on which stroke style is used. Freestyle is the fastest stroke, followed by butterfly, backstroke, and breaststroke in decreasing order of record speeds. The longest event in pool swimming is the 1,500-m freestyle, which requires approximately 15 min for the top male swimmers and 16 min for the top female swimmers and is considered the signature distance event, even though open-water swimming races include 5 km, 10 km, and 25 km.

To appreciate the physical requirements of sprint and distance events, it is important to recognize that swimming performance depends on the balance between propulsive power generated by the arm and leg actions of each of the strokes and resistance created by the drag (water resistance) encountered by the body during swimming, starting, and turning (Pendergast et al., 2005; Zamparo et al., 2011). A swimmer must generate propulsive power in excess of drag to reach and maintain race speeds. In all swimming strokes, body velocity fluctuates during the race, with breaststroke producing the largest intracycle velocity variability given the added drag of recovering both arms under the water and in drawing

the knees up to prepare for the next propulsive phase of the stroke cycle. In 1933, Karpovich towed swimmers while they were in a prone position and demonstrated that water resistance increases in direct proportion to velocity squared. Towing swimmers in a prone position underestimates the sum of all drag forces acting on the body during full-stroke swimming, so later researchers have used various means to estimate the magnitude of active drag (Di Prampero et al., 1974; Hollander et al., 1986) or used energy cost of swimming as a proxy measure in place of active drag (Holmér, 1974; Pendergast et al., 1977).

The amount of power required to overcome active drag during swimming depends on the stroke style, physical dimensions of the swimmer, technical proficiency of the swimmer, and swim speed. For this reason, coaches and swimmers have long regarded resistance training designed to increase muscle strength and power as an important component of a comprehensive training program. Published research has confirmed a close association between maximum power and sprint swimming performance (Costill et al., 1986; Hawley et al., 1992; Sharp et al., 1982) as long as power is measured using limb movement patterns that closely mimic the propulsive movements in swimming. Consequently, most competitive swimming programs use resistance training as an adjunct to in-water training.

Energetic Demands of Swimming

At any given velocity of swimming, there is substantial variability in the amount of drag between individuals and among the four swimming strokes used in competition (freestyle or front crawl, backstroke, breaststroke, and butterfly). Between individuals, the variability in drag seems to be accounted for by differences in body morphology, the speed of swimming, and the swimmer's degree of technical skill. Consequently, energy expenditure varies widely among the four competitive strokes, and there are large individual differences in energy expenditure during swimming.

Energetic Demands of the Four Stroke Styles

By measuring oxygen uptake while swimming at standardized speeds in a swimming flume, Holmér (1974; Figure 1) showed that energy expenditure during butterfly and breaststroke swimming is approximately twofold greater than in backstroke or freestyle swimming. These differences can be attributed to the increase in form drag during butterfly and breaststroke dictated by the mechanics of these strokes.

Other investigators have characterized the energetic demands of swimming using the energy expenditure (usually expressed in kilojoules/meter¹) required to displace the body over a given unit of distance and calculated from measured VO_2 , change in blood lactate concentration, and assumed alactic anaerobic contribution (Pendergast

et al., 2003; Schmidt-Nielsen, 1972). In 1998, Capelli used indirect calorimetry to evaluate energy expenditure of elite male swimmers at several submaximal speeds up to maximal swimming speeds. Energy cost was compared among the four stroke styles at swimming speeds of $1.5 \text{ m}\cdot\text{s}^{-1}$, demonstrating that front crawl had the lowest energy cost ($1.23 \text{ kJ}\cdot\text{m}^{-1}$), followed by backstroke ($1.47 \text{ kJ}\cdot\text{m}^{-1}$), butterfly ($1.55 \text{ kJ}\cdot\text{m}^{-1}$), and breaststroke (1.87

$\text{kJ}\cdot\text{m}^{-1}$). The energy cost increased exponentially with an increase in swim velocity during freestyle, backstroke, and butterfly, but this change was linear in breaststroke. With the exception of the relative ranking of breaststroke and butterfly, the economy of the four strokes agrees with Holmér's (1974) findings and was confirmed later by Barbosa et al. (2006) with 26 male and female elite swimmers (Figure 2). The lower economy of butterfly

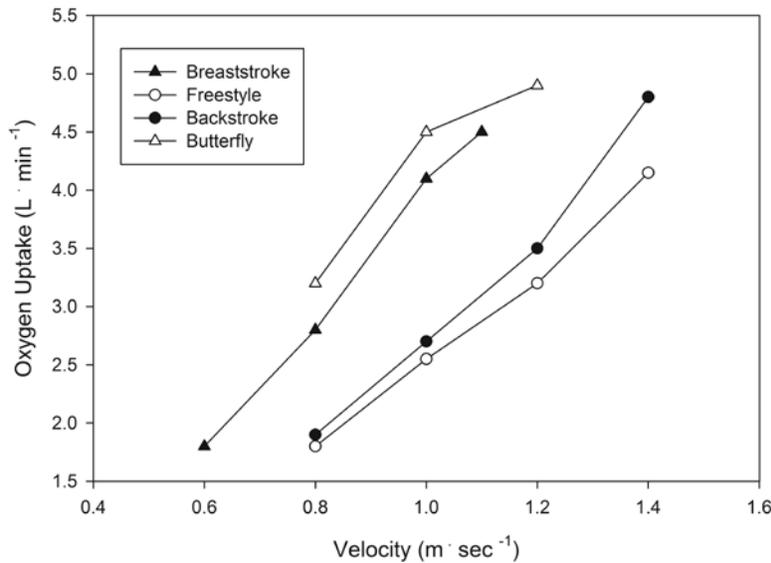


Figure 1 — Oxygen uptake as a function of swimming speed during the four competitive strokes. Adapted from “Energy Cost of Arm Stroke, Leg Kick, and the Whole Stroke in Competitive Swimming Styles,” by I. Holmér, 1974, *European Journal of Applied Physiology and Occupational Physiology*, 33, p. 94. Copyright 1974 by Lippincott, Williams and Wilkins. Adapted with permission.

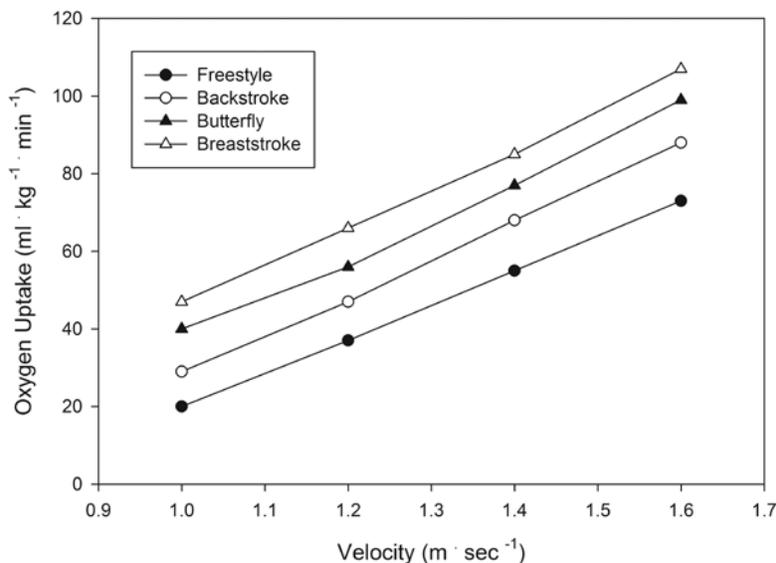


Figure 2 — Oxygen uptake at varied swimming speeds predicted from individual regressions of oxygen uptake versus swimming velocity in 26 competitive swimmers. Adapted from “Evaluation of the Energy Expenditure in Competitive Swimming Strokes,” by T.M. Barbosa, R. Fernandes, K. L. Keskinen, P. Colaco, C. Cordoso, J. Silva, and J. P. Vilas-Boas, 2006, *International Journal of Sports Medicine*, 27, p. 896. Copyright 1974 by Georg Thieme Verlag KG. Adapted with permission.

compared with breaststroke observed by Holmér may have been related to selection of less proficient swimmers who did not specialize in butterfly during training and competition compared with the elite competitors tested in the later studies by Capelli and Barbosa et al.. Direct comparisons of energy cost or economy between these studies within a given stroke style are, however, often problematic given methodological differences in ergometry (pool vs. flume), talent levels of swimmers (elite vs. nonelite competitors), and units of expression (kilojoules/meter¹ vs. liter/min⁻¹ vs. milliliter/kilogram/minute⁻¹ without reporting body mass).

Interindividual Differences in Energetic Demands of Swimming

In pioneering studies comparing energy expenditure among swimmers of varied ability or skill levels, Holmér (1979, 1972) observed that when swimming at the same speed and using the same stroke, more accomplished competitive swimmers had significantly lower energy expenditure than noncompetitive swimmers (Figure 3). For example, at a swimming velocity of 0.8 m/s⁻¹, observed VO₂ was 4.1 L/min⁻¹ for the recreational swimmer, 2.6 L/min⁻¹ for the good swimmer, and 2.0 L/min⁻¹ for the elite swimmer.

In a similar study, energy expenditure was measured at a velocity of 1.2 m/s⁻¹ for male and female world-class swimmers using freestyle (Van Handel et al., 1988). The women had a mean VO₂ of 28 ml/kg/min⁻¹, and the men had a mean VO₂ of 36 ml/kg/min⁻¹. Furthermore, the range of VO₂ between the most and least economical

swimmers was 15 ml/kg/min⁻¹, or from 25 to 40 ml/kg/min⁻¹ while swimming at the same velocity. When these swimmers' submaximal VO₂ (economy) was correlated with their best 400-m competitive performance time, a correlation of .67 was observed. Considering that these subjects were all elite athletes and likely very homogeneous with respect to performance, the relatively high correlation between economy and performance is impressive. However, VO_{2max} was also correlated significantly with their 400-m performance time, but when the analysis was conducted separately for men and women, the correlation between VO_{2max} and performance was not significant.

Several other studies of the relationship between swimming economy and performance have indicated that economy is associated with better performance ability, especially in middle-distance swimming (Chatard et al., 1990; Costill et al., 1985; Klentrou & Montpetit, 1991; Montpetit et al., 1987; Smith et al., 1988). In an elegant and informative study (Klentrou & Montpetit, 1991), 25 male Canadian swimmers age 17 yr were tested for both VO_{2max} and swimming economy while swimming in a 25-m pool. VO₂ measurements were estimated via backward extrapolation of the oxygen uptake curve during the first 20 s of recovery after each swim (2 × 250-m + 1 × 400-m maximal swim). Economy was calculated as the VO₂ required to swim at 1.3 m/s⁻¹. Of the swimmers, 12 regularly trained and competed at the 100-m freestyle distance, and the others specialized in the 400-m freestyle. The two groups had similar VO_{2max} (100 m, $M \pm SD = 4.76 \pm 0.6$ L/min⁻¹; 400 m, $M \pm SD = 4.68 \pm 0.6$ L/min⁻¹) and economy at 1.3 m/s⁻¹ (100 m, M

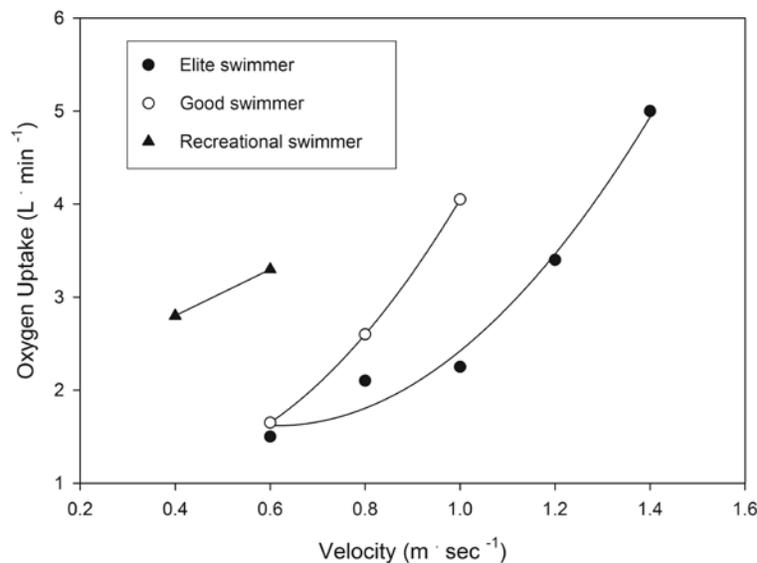


Figure 3 — Oxygen uptake versus swimming velocity compared between elite, good, and recreational swimmers. Adapted from “Physiology of Swimming Man,” by I. Holmér, 1979, *Exercise and Sport Sciences Reviews*, 7, p. 95. Copyright 1974 by Wolters Kluwer Health. Adapted with permission.

$\pm SD = 3.26 \pm 0.5 \text{ L/min}^{-1}$; 400 m, $M \pm SD = 3.38 \pm 0.5 \text{ L/min}^{-1}$). Using a forward stepwise multiple regression analysis to determine which of several physiological and anthropometric variables contributed substantially to performance, the combination of maximal stroking rate, power, arm span, and height provided the best prediction of 100-m performance time ($r = .84$). Performance in 400-m freestyle was best predicted using a combination of economy, height, and maximal stroke rate ($r = .82$). In both regression models, the maximal stroke rate was negatively related to performance, meaning that slower stroke rates were associated with better performance. By inference, therefore, better performance ability was associated with longer distance per stroke, in agreement with several other studies (Craig et al., 1985; Toussaint, 1990; Toussaint et al., 1983).

These studies provide evidence that an essential determinant of swimming performance is the skill with which the athlete can provide propulsion in the most economical manner possible. These findings also underscore the notion that energy costs of swimming are largely a function of the mechanical aspects of both propulsion and drag reduction. Holmér (1979) noted in 1979 that neither $\text{VO}_{2\text{max}}$ nor maximum lactate concentration of elite swimmers was different from a competitive cohort assessed 10 yr earlier. It appears that the improved performance was more likely accounted for by “improved technical ability, stroke mechanics, and other technical factors” (Holmér, 1979, p. 99). His conclusion echoed that of Pendergast et al. (1977), who suggested that there is a much greater potential for improvement in technical ability than for improvement in maximal energy expenditure.

Because water resistance is so great, swimmers can improve their performance by developing strong and powerful muscles, applying that power in the most effective manner with little wasted effort (propelling efficiency; Toussaint, 1990), sustaining that power for the length of race distance, and reducing body drag through effective streamlining in the stroke and coming off from wall push-offs. A swimmer with high body drag, either because of anthropometric characteristics or related to drag-producing movements or postures, will have a correspondingly greater propulsive power requirement to sustain the same speed as the swimmer with a relatively lower drag.

Conclusion

The aquatic sports discussed in this review have a broad range of physiological, biomechanical, and energy requirements for both training and competition. Nutritional support for each activity should be based on the energy requirements of training and competition and the possible role that specific nutrients and supplements might play in developing peak performance. Measurement of energy expenditure in these sports is, however, difficult given the water environment and the need to

test while participants engage in the specific activity. This challenge may be part of the reason for the relative lack of published data on energy and fuel use during aquatic sports. Energy expenditure during swimming has, however, been relatively well studied using indirect calorimetry to define the expected energy cost of swimming the four competitive strokes between elite and subelite competitive swimmers.

Methods for energy cost measurements include collection of expired air during pool swimming, flume swimming, circular pool swimming, and using a backward extrapolation method with postexercise indirect calorimetry. Although these methods have provided evidence of wide-ranging energy costs of swimming, this information is only marginally useful in the other aquatic sports because of the activity patterns involved. It is important to encourage continued investigation into the energetic and nutrient requirements for all the aquatic sports to inform the process of developing generalizable and specific recommendations for nutritional support.

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