Evidence-based recommendations for maximizing competitive swimming performance

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Abstract

The current dogma of swimming training programs promotes high-distance, high-volume workouts requiring a considerable time investment and high risk of injury to swimmers striving to achieve elite level swimming performance. In this paper, the current literature in exercise physiology, swimming performance, and nutrition is reviewed in order to provide evidence-based training guidelines to maximize performance and minimize risk of overuse injury. Suggested practices for day-of-competition exercise and nutrition are also offered. This work aims to provide training recommendations for coaches and swimmers, and to aid the work of physicians and dietitians involved in the care of swimmers. Narrative review encompassing studies done on the topic of elite swimmers and performance, metabolism, nutrition, stroke technique, tapering, and injury. Studies done in athletes of other sports regarding muscle metabolism and nutrition are also taken into consideration, as necessary, when there is a paucity of work in swimmers. This evidence-based approach to swimming training challenges current popular coaching principles, i.e. long-distance workouts, by offering a more focused and individualized training regimen that may improve performance and decrease workout-related injury risk. Specifically, inclusion of high-intensity training, stroke technique improvement, limited total distance and water time spent per week, optimized nutrition, strategic tapering, and a personalized day-of-event warm-up routine appear to be key factors for success in a swimming competition. Specific guidelines in each of these areas are reviewed or synthesized, and means of implementation are suggested. This multidisciplinary approach to swimming training that optimizes each stage of training and competition will likely improve the performance of many competitive swimmers.

Introduction

Swimming is a sport with worldwide participation, as evidenced by the 2012 Olympic Games which included seventeen pool events for both men and women. In the United States alone, there are over 2,800 clubs and 300,000 members associated with USA Swimming, 2.5 million summer league swimmers, hundreds of programs registered with the Young Men's Christian Association (YMCA), scores of swimming programs under the National Collegiate Athletic Association (NCAA), and many more affiliated with high school, National Association of Intercollegiate Athletics (NAIA) and Masters Swimming programs.(49) Compared with other sports, swimming is distinguished primarily by its simultaneous use of upper and lower extremities in a high-resistance, high-pressure aquatic environment, with respiratory timing determined by water immersion.(3) Many swimming programs, including club, collegiate, and professional organizations, use a training regimen largely involving high-volume, aerobic exercise. This training strategy is especially used by elite swimmers, who frequently participate in multiple high-volume training sessions per day.(27) Although it is deeply ingrained in swimming culture, some data questions the efficacy of extra long-distance workouts for the majority of swimmers. It is logical to assume that training programs which focus on long-distance training would be beneficial for swimmers who specialize in longer events; however, the utility of distance training in preparing for short sprint events is less clear. In addition, time restraints and exercise-related injury may prevent swimmers from being able to follow the training regimens of the most elite athletes. Thus, a training regimen which maximizes results while reducing time requirements and risk of injury could be useful for many competitive swimmers.

In this work, we briefly review muscle physiology with special attention paid to the role of muscle metabolism in sprint versus long-distance events and muscle response to training. We then discuss current findings regarding the prevalence and risk factors for overuse injury in competitive swimmers. Finally, recommendations are offered for training strategies, optimizing nutrition, design of taper periods, and day-of-competition practices. Based on available evidence and guidelines published by others, we describe a training strategy which can be adapted to fit the needs of individual competitive swimmers and which may help maximize swimming performance.

The role of muscle fiber structure and metabolism in performance

Conditioning induces changes in muscle fiber structure and metabolism

Muscles are comprised of different fiber types with unique properties that determine the nature of the work the muscle can perform. Muscles can be described in terms of the muscle fiber type, twitch speed or force, and biochemical abilities such as oxidative or glycolytic.(39) In general, it is easiest to consider Type I fibers as small, slow-twitch fibers that are able to sustain aerobic work (long duration) through their high oxidative enzyme capacity. Well-trained Type I fibers provide the distance swimmer the desired endurance at a higher intensity due to the metabolic and circulatory training advantages. The fast-twitch or Type IIX fiber type is much larger and more powerful in anaerobic work but also fatigues quickly because it relies primarily on muscle glycogen stores. Type IIX fibers allow high intensity sprint performance over shorter distances. The remaining intermediate fibers (Type IIA) have aerobic and anaerobic metabolic traits and are useful in both sprinting and endurance activities, but they make a lesser contribution than the highly specialized fiber types above. Through specialized training, the relative amount of each of these fiber types can be changed to suit the needs of an individual athlete's primary event. (39, 53) For example, a training program involving short bouts of maximal energy expenditure with extended recovery periods, known as High Intensity Training (HIT), can increase the relative amounts of Type IIA and IIX fibers and increase oxidative enzyme levels.(23) A study in untrained individuals showed that six sessions of HIT correlated with significant improvement in overall exercise performance and levels of the aerobic metabolism marker cytochrome C in the muscle.(25) Modified HIT involving slightly decreased intensity, longer exertion period, and shorter recovery period has also been shown to cause significant changes in mitochondrial oxidative enzymes and improve exercise performance.(31) These data suggest that sprint athletes may require a very different training volume and intensity compared to endurance athletes.

Contributions of anaerobic and aerobic metabolism during exercise

Anaerobic training involves exercise performed at intensities which are above VO_{2max}.(23) A series of studies in track athletes running varying distances revealed that the relative contribution of aerobic and anaerobic metabolism in muscle is dynamic, with a strong dependence on duration of exertion.(15-17) It was found that muscle energy expenditure during very short sprints is dominated by anaerobic metabolism but is not exclusively anaerobic, and vice-versa. The contributions of anaerobic and aerobic metabolism become equal at approximately 75 s of near-maximal effort in runners.(20) This correlates with the amount of time required to complete approximately 600 m of near-maximal running,(28) or approximately 150 m of freestyle swimming in world-class swimmers assuming an average velocity of 2.0 ms^{-1} over this distance.(38) Thus, over the same time period, accomplished runners and world-class swimmers appear to cover distance at a ratio of 4:1. We propose that it is reasonable to compare metabolic data between the two sports, provided that this distance conversion is performed. As an example, data from track athletes running 200 m and 400 m allow estimation of anaerobic contribution during the 50 m and 100 m freestyle events of approximately 72% and 59%, respectively, in males and 67% and 55%, respectively, in females (Figure 1).

A study of the energy contribution in swimmers during exercise found that after a 30 s maximal effort fully tethered swim, the aerobic contribution was 33 ± 8%; after four consecutive semi-tethered bouts with 30 s rest periods, anaerobic contributions were 25 ± 4, 47 ± 9, 49 ± 8, and 52 ± 9% ($P < 0.01$).(40) This data indirectly shows a correlation between swimming duration and aerobic energy contribution, as different durations of exercise were not tested. Although data regarding muscle metabolism in swimmers is limited, we conclude that swimmers who specialize in events of different duration may individualize their training to maximize performance.

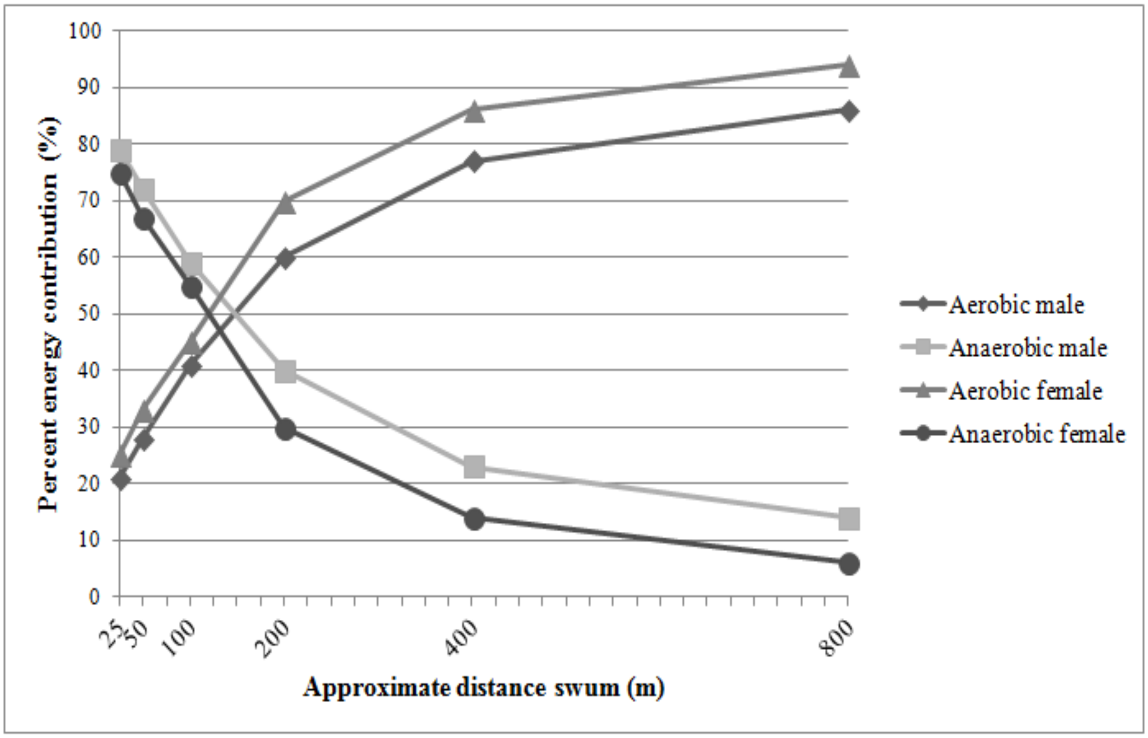

Figure 1. Estimated energy contribution of aerobic and anaerobic metabolism while swimming different distances. Aerobic metabolism predominates during races of 200 m and greater; anaerobic metabolism is the primary energy source over distances 100 m and less. Energy contribution is approximately half-and-half at approximately 150 m of swimming. Data derived from Duffield *et al*. male and female runners,(15-17) assuming a 4:1 ratio of distance running to distance swimming, as performed by elite athletes. Graphical representation is based on Laursen (2010).(28)

A training strategy for maximizing swimming performance

Maximizing aerobic capacity

Aerobic metabolism provides half of the muscle energy during 75 second duration intense events but also makes a significant contribution during shorter sprints, meaning that aerobic capacity is an important determinant of success in nearly all competitive events.(20, 28) Current data suggests that aerobic capacity is increased most efficiently by alternating low-intensity and high-intensity exercises.(28, 53) This is in accordance with several studies demonstrating similar endurance performance between athletes who train using HIT compared to those who train using low-intensity, high volume regimens.(18, 23, 29, 30) Because both forms of exercise synergistically increase the aerobic capacity of muscle, and because aerobic metabolism makes contributions even during short events, training programs should include an interplay between high-intensity, low-volume training and low-intensity, high-volume training to maximize performance in 50 to 800 meter swimming events.

Maximizing anaerobic capacity

A study of muscle biopsies of male and female track athletes showed that sprinters had a greater cross-sectional area of muscle composed of fast-twitch (Type IIX) fibers than did distance runners, while the opposite was true regarding slow-twitch (Type I) fibers.(11) Experiments in elite athletes found that the anaerobic power of sprinters was approximately twice that of long-distance runners, and that an inverse relationship existed between aerobic and anaerobic power.(12) This data suggests that the anaerobic capacity and power of muscle can be increased with targeted anaerobic exercise such as HIT and resistance training. Furthermore, these studies highlight the importance of specificity in training, *i.e.* athletes should train in a manner that reflects the nature of their competitive event(s). While genetic influences on fiber type serve as a basis for success, the influence of training contributes significantly to desired metabolic changes and enhanced performance.

Optimizing technique

Several studies have explored the utility of alternative exercises and strategies to improve swimming performance and technique.(14, 44) Many specialized exercises and drills exist that are designed to improve stroke technique, increase athlete awareness of body position and hydrodynamics, and enhance strength and/or endurance. Examples of such specialized exercises include dry-land and in-water resistance training; the use of paddles, boards, buoys, and devices which create drag; and specialized leg training. Of these exercises, only resistance exercises (lifting weights and drag devices) have been shown to improve swimming performance.(3) Swimmers and coaches may nonetheless find utility for many alternative exercises in improving overall stroke technique which, as discussed below, may also benefit the long-term health of the swimmer.

Having an efficient stroke technique is an important aspect of all swimming events, as is the execution of starts, turns, and finishes. Studies on stroke efficiency, hydrodynamics, and other aspects of swimming technique have shown that water resistance during the glide phase of starts and turns is minimized by gliding while in the prone position.(3, 32, 55) However, to date, studies have been unable to conclusively establish "best practice" guidelines for swimming starts,(50, 59) and in practice, swimmers should work individually with coaches to determine their most efficient start style. Regarding turns, few experiments have rigorously dissected the variables important to effective flip (tumble) turns. Of these, one study found that a knee flexion angle between 100˚ and 120˚ generated maximal push force with minimal time or energy loss. Another study determined that increased head-wall distance, decreased horizontal speed at force peak, and decreased 3D path length covered during the turn resulted in faster turn times.(2, 41) Studies defining the role of the finishing stroke on performance time are seemingly non-existent. However, it is reasonable for swimmers to simulate the end of a race while practicing, with the goal of maintaining velocity during the finishing stroke. Taken together, current evidence indicates that optimizing the start and turn phases of the swimming race can help improve competitive performance. Spending time perfecting the final approach and finishing stroke may also be beneficial to performance, as it may allow for swimmers to feel better prepared during competitive events.

Decreasing overuse injury risk

Exercise-related injury can be detrimental to the performance of any athlete. Overtraining or overreaching has become an important consideration in the culture of competitive swimming, where training strategies may include multiple practices per day and very high volumes of swimming.(33) The frequency of shoulder injury is high in elite swimmers, and has been shown to strongly correlate with both time in the water and distance per week (volume). Specifically, one study found that athletes swimming more than 35 km (21.8 mi) or 15 hours per week had a significantly higher risk of supraspinatus tendinopathy.(46) A review of the epidemiology of injuries in competitive swimmers found that shoulder injuries have a prevalence of 40%-91% in NCAA swimmers, and that knee and spine pain have a prevalence ranging from 34-86% and 22.2-50%, respectively.(58)

Current recommendations regarding the treatment of overuse injuries in swimmers include a combination of decreased workout load, alteration or improvement in stroke technique, and strengthening exercises, and sometimes physical therapy.(46, 58) A training regimen that involves a mixture of high-intensity, low volume exercise and low-intensity, high volume exercise would likely lower the total distance swum per week (assuming no increase in total time spent swimming) due to the introduction of necessary rest periods. Such a regimen would thus likely lower the risk of exercise-associated injury in swimmers, although the decreased training load may be seen by coaches as compromising the overall quality of training. However, as discussed above, a mixture of training intensities and durations should maximize the oxidative capacity of muscle and facilitate increased performance in intense exercise events. Incorporating this workout design may actually enhance performance while mitigating the overuse injury risk associated with current elite-level training regimens. As total time spent swimming has been shown to be a risk factor for overuse injury in elite swimmers, avoiding excessive pool time may further decrease the risk of injury.(46) In addition, dedicating time to improving stroke technique during practice may prevent and actually reverse the risk of overuse injury for a couple reasons. First, spending time on improving technique would likely decrease total swimming distance as stroke improvement requires increased rest time during which swimmers receive targeted feedback from an observant coach. Second, as stated above, improving swimming technique is recommended as a primary therapy for treating overuse injury, and its inclusion may provide benefits to swimmers with existing injury.

Some data suggest that “overuse injury” from exercise may be defined beyond orthopedics to include diminished immune function.(57) Studies in overworked athletes have found decreased sleep efficiency and duration, decreased immune function markers, and increased prevalence of upper respiratory infections.(22, 52) Guidelines on prevention of illness in athletes suggest avoiding excessive training distances, adding variety to workouts to decrease monotony and stress, including sufficient recovery periods, and being vigilant about individual performance deterioration or stress.(56) Specific recommendations include increasing load in increments of 5-10% per week, mixing "spike" intensity training with low-intensity work, and including recovery activities after highly intensive sessions.(56)

Optimizing nutrition during training

Maintaining an adequate and balanced dietary intake is crucial for optimal athletic performance, (5, 19, 47) and providing the body with the right mixture of carbohydrate, fat and protein to achieve the desired training response is the topic of multiple position statements.(1, 43) However, several studies have shown that swimmers commonly fall short of dietary guidelines. In US adolescent swimmers, inadequate intakes of calcium, vitamin D, fruit, vegetable, grains, and dairy were found, along with higher-than-recommended intake of saturated and total fat; these findings were similar to the general US adolescent population.(10) An 8-month study of nine Greek national team and Olympic swimmers found that athletes maintained a stable caloric intake regardless of training load, consumed high amounts of fat and low amounts of carbohydrate, had overly high intakes of iron and vitamin E from supplements, and inadequate iodine and magnesium despite supplements.(27)

Recommendations for most macronutrients in athletes are based on weight rather than percentage of total calories. Specifically, 6 to 10 g/kg of carbohydrates is needed for most athletes to maintain glycogen stores and recovery; protein needs range from 1.2 to 1.7 g/kg per day, which is usually achievable without supplements; dietary fat requirement is not based on weight, and is ideally between 20-35% of total energy intake.(43, 48) The frequency and content of meals are important for optimal performance and workout recovery, with a minimum of 5 meals or snacks recommended during workout days within caloric balance.(8, 9) Additionally, the importance of breakfast in athletic and cognitive performance is known, thus swimmers should attempt to eat breakfast every day.(48, 54) The ingestion of carbohydrate before strenuous workouts has also been shown to decrease stress hormone levels associated with carbohydrate depletion, and maintain immune function.(21)

Recommendations on the intake of micronutrients in athletes are not available, thus, meeting labeling guidelines is suggested for swimmers.(27) The role of dietary supplements to meet these values is somewhat controversial, but current evidence suggests that the typical use of glutamine, vitamins C and E, branched chain amino acids, and herbal supplements are not well supported with research, as these are non-beneficial to performance or can be obtained through a balanced diet. In total, athletes must work with their sports dietitian to design an individualized nutritional plan that meets their dietary needs during training and incorporates proper meal timing. Such a plan should attempt to follow published athlete dietary guidelines, be tailored to the phase of training being performed, and be assessed for athlete satisfaction. The role of proper nutrition support for elite athletes cannot be underestimated.

Effective tapering

The taper is a reduction of training load before a major sports performance, the goal of which is to maximize performance by reducing the physiologic and psychological stressors of training.(36) In principle, the taper capitalizes on physiologic adaptations which occur during training but reduces fatigue.(42) A study in rats undergoing linear periodized training found decreased stress biomarkers (corticosterone and creatine kinase) and increased glycogen stores in the liver and muscle during the taper period.(13) Soccer players undergoing a 5-day intense training camp program had decreased immune function parameters which partially recovered after two weeks of taper.(52) Several types of taper exist, including the step taper, linear taper, and exponential taper, referring to the rate of decrease in training load.(42) In addition, the duration and intensity of training during a taper can be variable. A meta-analysis attempted to determine which of these characteristics of a tapering program had the largest effects on performance in several sports.(7) Results of this study demonstrated a taper regimen including a decrease in training volume of 41-60%, no decrease in training intensity, no decrease in training frequency, a progressive decline in training volume, and total taper duration of 15-21 days resulted in statistically significant race time improvement overall.(7) Recent work has described a two-phase taper in which a progressive decrease in training load is followed by a brief, 3-day progressive increase in training load.(51) The authors of this study hypothesize that athletes may respond maximally to this increase in training without inducing fatigue. Further investigations are required to optimize two-phase taper programs, and it is not recommended for most swimmers at this time. Regardless of timing, optimal performance relies heavily on the type of training completed before and during the taper. Importantly, high-intensity training (HIT) appears to play a key role in the maintenance and enhancement of physiological adaptations during the taper period, despite decreased workout volume.(34) It should be noted that swimmers may respond differently to a taper regimen depending on their individual characteristics, specialty event, and mode of training. Each of the taper characteristics discussed can and should be customized to allow maximum results for each athlete.

In light of this data, general guidelines for an effective taper should: (1) include a progressive decrease in training load to 41-60% of maximum; (2) no change in training frequency; (3) should last approximately 2-3 weeks; and (4) include high-intensity training. This information should offer coaches a place to start when designing a taper, and should be refined to meet the needs of individual swimmers.

Day-of-competition practices

Optimal performance during swimming competition requires not only proper training, but also a competition-day strategy focusing on effective warm-up and nutrition plans. A recent review of warm-up strategies in competitive swimming showed that in-water warm-up should be approximately 1000-1500 m total, be performed at moderate intensity, and include stroke technique drills and short sets that approach or achieve race pace.(37) Additionally, a recovery period of 8-20 minutes between warm-up and competition was suggested. A dry-land warm-up routine may be helpful during competitions in which no pool space is available for warm-up, and may consist of calisthenics and total body exercises.(37) It is important to note that there is conflicting data regarding the efficacy of warm-up in swimming, and the effects of warm-up may differ depending on the type of event(s) to be performed.(37) Nonetheless, it is striking that the most effective warm-up appears to be of shorter distance than many traditional swimming warm-ups, suggesting that excessive workout load during warm-up may impair performance. This is in accordance with a study in competitive rowers who had improved power output when prescribed a 30-minute warm-up instead of a traditional 60-minute warm-up.(35) Performing short, race pace sets also appears to be important, although this may risk inducing early fatigue and should be used judiciously based on individual swimmer experiences. As there are no clear-cut recommendations for the swimming warm-up, it is logical that swimmers should work with their coaches to determine a warm-up routine that achieves the best competitive results, and develop strategies for warming up between events during long competition days.

As proper dietary intake on the day of a competitive event is a source of uncertainty for some swimmers (27, 48) it is probably easiest to remember that high intensity performance requires carbohydrate as the primary source of energy.(1, 43) Some athletes or coaches carry the poorly founded belief that carbohydrate ingestion prior to competition will result in a reactive hypoglycemic episode; adrenaline is known to be a redundant hormone that will help maintain blood glucose in anticipation of the event in the majority of athletes.(26) Current sports nutrition guidelines recommend providing the competing high intensity athlete with adequate carbohydrate in the days and hours prior to competition.(1, 43) On a day of multiple heats or events, athletes will want to top off muscle and liver glycogen stores consistent with the amount of fuel needed for the event, realizing that longer distances require more fuel.(47) Regarding muscle recovery after competitive events, adequate carbohydrate intake with a small amount of good quality protein immediately after intense exercise will expedite glycogen recovery and an anabolic hormonal milieu supporting muscle growth.(4, 6, 24) If the athlete does not have a full 24 hours for recovery from the event, consuming the recovery snack immediately after the event may facilitate muscle readiness for the next bout or event. Proper hydration is also a key element to optimal performance, specifically, achieving euhydration and normal electrolyte levels before an event is of central importance.(45) A hydration and nutrition plan should be customized for the performance and comfort of individual swimmers, and should remain a priority throughout the day of competition, as proper fueling will enhance performance and may minimize the stress of exercise on muscles.

Conclusions

Anaerobic and aerobic metabolism both contribute to the energy supply of exercising muscle: during short periods of high-intensity exercise, anaerobic metabolism predominates and vice-versa, though there no true exclusivity. Thus, it is in the interest of most swimmers to maximize aerobic capacity through an interplay of high-intensity exercise and endurance training. It is of central importance to avoid overtraining injury. The current swimming culture of multiple workout sessions per day exerts heavy stress on the musculoskeletal and metabolic systems of the body. Coaches and trainers should be aware of total training volume, and strategize to have each athlete train the "right" amount in order to achieve their peak performance goals without overreaching. In addition, time should be dedicated to the maintenance and improvement of stroke technique in swimmers of all levels, in order to decrease the risk of swimming-associated injury and increase overall swimming efficiency and performance. Proper nutrition is of utmost importance for maximizing swimming performance, and coaches should work with sports dietitians to encourage swimmers to consume a diet containing sufficient nutrients to support their training. Finally, day-of-competition strategy may be a key aspect to maximizing swimming performance, and coaches should work with swimmers individually to develop a plan which best suits their needs.

This summary of exercise science and nutrition recommendations should help coaches and swimmers design and execute an efficient training strategy that will maximize swimming performance. Future recommendations will benefit from new studies in the field of swimming exercise science. This review demonstrates the need for evidence-based guidelines for the design and execution of effective swimming training protocols.

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