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Muscle Strength and Power as Related to Competitive Swimming

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Abstract

The following review presents current and past literature that concerns strength and power training research relevant to competitive swimming. The earliest attempts to relate strength to swimming performance were largely unsuccessful due to several factors. Many early studies failed to test for strength in movement-specific patterns. This may have artificially reduced the obtained correlations between strength and swimming performance. The measurement of arm power using movement-specific and speed-specific contractions, however, has shown a very close relationship between swimming performances and maximum power output. Among a heterogeneous sample, power output was quite predictive of swimming performance. In elite level swimmers, however, no significant relationships were obtained between power and performances at a national championship. This may have been due to the fact that above a certain level of maximum power, further improvements in power do not correspond to faster sprint speed. Implications are presented for the need to maintain power levels in these athletes. Because of these findings, training programs using movement-specific, speed-specific and perhaps duration-specific strength/power exercises are not only justified, but are encouraged.

Key Words: Muscle strength, Power, Swimming, Overtraining

Performance in competitive swimming is most simply described as a function of the balance between propulsive and resistive forces that are encountered over a given distance. Since drag has been shown to positively correlate with the square of velocity, little propulsive force will be necessary to maintain a rather slow speed while greater amounts of propulsive force are required to maintain faster speeds. It therefore seems rather obvious that muscle strength should be an important component of success in competitive swimming. It is, however, possible that strength of muscle contraction might play little role in determining the amount of propulsive force that can be generated maximally or maintained over distances of 50-1500 meters. This would imply that factors other than maximum strength such as the proper application of propulsive force, reduction of resistive forces and energy metabolism are the primary determinants of success in competitive swimming.

In the past decade or so, several reports of studies concerning the role played by muscle strength in competitive swimming have appeared (3,4,5,13,14,18,20). Although each of these studies has addressed topics relevant to training competitive swimmers, no attempt has been made to summarize these findings and to assess the implications for training that may arise from this collective body of knowledge. It is therefore the intent of this review to discuss the developments in strength research over the past few years especially as they relate to the design of training programs for competitive swimming.

To What Extent Does Strength Relate to Performance?

Whether or not, and to what extent maximum muscle strength influences one’s performance capacity is a question whose answer is imperative if we are to justify the use of sometimes extremely rigorous strength training programs used by competitive swimmers. Coaches apparently accepted this relationship as positive many years ago since strength training has become such an integral part of the preparation of competitive swimmers. Until the last few years, however, there was little objective evidence to either support or refute this notion.

In the very early stages of strength research in swimming, support was given for the principle of specificity by the findings that strength as measured with isometric dynamometers in lifting or leg press patterns and also with medicine ball throw bore little relationship to per-
formance in swimming (7). These exercises and tests were quickly discarded in favor of arm pull strength, thigh flexor and lower back kicking strengths (6). Using as the index of strength an isometric arm pull with the elbow slightly flexed, Miyashita correlated strength with performance during arms-only swimming. (13). He reports that he obtained a high positive correlation between strength and swimming speed, but did not report how closely these were related nor did he report the distance over which swimming speed was measured.

In 1979, Miyashita and Kanehisa re-examined the relationship between strength and swimming performance by measuring strength of 35 swimmers as peak isokinetic torque during arm pull and correlating it with time in a 100 meter freestyle time trial (14). The swimmers selected to participate in this study ranged in age from 11 to 21 years and consequently, also were widely distributed according to strength and 100 meter time. Among the males, a correlation between strength and performance of \( r = 0.73 \) was obtained while among the females, the correlation was \( r = 0.52 \). Both of these correlations were reported to be significant and thus implied that strength as measured in this study is somewhat important to 100 meter performance. No explanation was given regarding the lower correlation obtained with the female swimmers.

Using a more movement-specific test of arm strength than had been previously used and a wider range of performance distances, it was shown that strength (maximum power output during a single dry-land pull) bears a closer relationship to performance in sprint swimming than was shown by Miyashita and Kanehisa's data (5,20). Our studies were designed to assess the degree of influence of maximum power on performance over a wide range of competitive events and to determine if the obtained relationships are merely coincidental or truly "cause and effect." Among a group of 40 male and female competitive swimmers who had a wide range of experience in competitive swimming, maximum arm power measured on a Biokinetic Swim Bench was shown to very closely related to their performance in a 25 yard time trial. As one might expect, with increasing distance of performance, the magnitude of this relationship dropped. This was taken as evidence that as distance increases, factors other than maximum power output assume a progressively greater role in determining performance capacity.

One of the problems in all of these correlational studies is that simple correlation cannot be used to infer a cause-effect relationship between strength and performance. In other words, it is possible that both strength and performance are somewhat dependent on physical maturity and proceed with age at roughly the same rate. This would therefore imply a coincidental relationship between strength and performance. Determining the nature of this relationship is imperative to making any recommendations for training because if the relationship between performance and strength is coincidental, then there would be no apparent rationale for strength training programs that are designed to increase strength and consequently, performance. As part of our initial study in this area, we strength trained a group of ex-swimmers for four consecutive weeks using 5 sets of 10 maximal repetitions of a two-arm pull. Details of this training are contained in the referenced manuscript (20). The purpose of this training was to increase maximal arm power and to determine if increases in power would be associated with concomitant improvement in sprint performance. To eliminate the potential confounding variable of supplemental swimming training, the only swimming that was allowed during the training period was that required for conducting the 25 yard time trials each week. In the 4 week period, the subjects increased arm power by an average of 19% with an improvement in 25 yard time of 4%. It was concluded from these data that not only is strength, or more specifically maximum power output, very closely related to swimming performance, but also that the character of the relationship is such that performance is causally linked to power output. This conclusion therefore justifies the use of strength training programs designed to improve and/or maintain maximum power for the purpose of improving swimming performance.

Does Strength Discriminate Among Elite Level Performers?

If power levels relate so closely to performance then it would seem to make sense that swimmers should attempt to increase maximum power to as high a level as possible. In addition, one might also expect that elite level swimmers possess markedly higher levels of power than their sub-elite counterparts. To take this reasoning a step further, measurements of maximum arm power might also be expected to show differences between those swimmers who place high in national championships versus those who fail to qualify for finals. These are all natural extensions of the findings already discussed. The validity of such assumptions must, however, be questioned.

Feeling that even slight differences in strength among competitors would determine success in international competition, Tsuro Yanigita adopted a swimming-specific program of strength exercises he learned from Cureton in 1929 (7). He trained the Japanese Mens Olympic team according to these principles and they subsequently outperformed the world in 1932 and 1936 Olympics. Even though he had used a training program learned from the Americans, he stated that their successes were due to the fact that they worked harder at these exercises than the Americans. This may, however, have been an overly generous acknowledgement of the effectiveness of these exercises since the number of factors that actually determine ultimate success may be too numerous to count and too complex to define.
In his keynote address at the Second International Symposium on Biomechanics in Swimming, Cureton stated that up to a point strength is important, but above this limit does not discriminate between the elite swimmers (8). Little data were actually shown to support his contention and in light of later findings of the role played by power in sprint swimming, his comments deserved further study. In an extension of our previous study of the relationship between power and performance, we tested an additional 20 swimmers for sprint swimming performance and arm power (18). These subjects were at the upper end of performance capacity and many were national caliber freestyles. When their results were added to the original data base, it appeared that instead of continuation of the linear relationship obtained earlier, there occurred a “flattening” of the relationship between power and performance. This indicates that the performance benefit of increased power begins to diminish among more elite swimmers. To confirm this finding among elite-level swimmers, the American Swimming Coaches Association commissioned a study in which power levels among competitors at the 1982 US Nationals was measured and compared with performances in the competition (19).

In agreement with earlier findings that power is of greatest importance in sprinting, it was found that sprint freestyles were most powerful (men: 522 watts; women: 281 watts), middle distance freestylers somewhat less powerful (men: 482 watts; women: 264 watts) and distance freestylers were least powerful (men: 411 watts; women: 207 watts). Also, these athletes were considerably more powerful than the skilled performers studied in the earlier studies. In any event, however, there was no correlation between power and performance (whether measured as place or time) for men or women. Even when the data were grouped according to those who finished among the top 8 and those who finished below the 32nd place, there was no difference in power. It was concluded from this study that high levels of maximum power output are an important characteristic of elite level performers but that power (as measured) is incapable of discriminating among these athletes’ performance capacities.

Perhaps above a certain level of maximum strength or power, any further improvements in power do not contribute to improvements in performance. Cureton’s comments and the data obtained on the elite-level swimmers indicate this is true. If these findings on group averages are applicable to individuals, then one might question the need for strength and/or power training among national caliber swimmers. It is important to note, however, that among the competitors at nationals that were tested for power, there was a very wide range in power within the sprinters, middle distance and distance freestylers. Thus, power output may be more important for some competitors than it is for others. If an individual who succeeds at the national level has a body type and stroke characteristics that tend to cause a great deal of resistance to forward motion, he/she may require a relatively greater amount of strength or power to compensate for this increased resistance. On the other hand, a swimmer of the same performance capacity may have very efficient mechanics such that resistance is low and the requirement for power is somewhat less than his/her counterpart. If this is true, it would seem logical that the ideal swimmer would be one who has the best combination of mechanics for reducing resistance, mechanics for the proper application of propulsive power, high maximum power output and high capacity for the maintenance of near-maximal propulsive power for a given duration of competition.

Strength Changes During a Season of Training

A large amount of endurance training is generally accepted to cause a tendency for diminished levels of strength. Thus, if high levels of strength are required for success for an individual swimmer, some effort to maintain strength would seem to be justified. This may be the primary benefit of strength training during the competitive season. In 1981, the present author in collaboration with David Costill and Bob Thomas, studied the changes in maximal arm power over the course of a season of competitive swim training. The swimmers were members of the Ball State University Mens team and were tested for power output using a single double-arm pull on the Biokinetic bench. These swimmers were tested every 2 weeks throughout the season and engaged in strength/power training on weights and with the swim bench. The greatest gains in power output were made during the first 6 weeks of training, after which there was a relatively slower improvement over the next 4 weeks. Total volume of swimming training also gradually increased during this initial stage of the season. During the next 10 weeks, there was a gradual reduction in maximal power output that amounted to approximately a 10% decline. The decrease occurred over a 4 week period and remained at this level for 6 weeks. This decline occurred despite continued overload in the strength/power training. During the 3 week taper phase, there was a significant increase in power above any previous level during the season. Power reached a peak immediately prior to the championship competition for which the swimmers trained. One week following the championship meet, power had returned to a level greater than pre-season but markedly less than during the middle of the season.

The reason for the decline in power during the middle portion of the season is not clear. It is possible that such declines in strength/power could be one symptom of the overtraining syndrome. If this is an accurate assessment, then it might be expected that during a period of reduced training, power would normalize to levels somewhat higher than would be seen during the heavy training. This
may have been the reason for the sudden increase in power during the taper phase of the season. These findings of increased maximum power during taper have subsequently been confirmed in studies by Costill, et al (3) and Musch (16).

Measurements of maximum power throughout a season may hold great promise as a means of evaluating the overtraining state of swimmers and the success of attempts to “peak” athletes for major competition. At the present time, however, there are insufficient data to suggest just how much decline in power during heavy training is acceptable and/or to determine how much of an increase in power during taper is ideal. Obviously, in light of the potential usefulness of this type of a monitoring program, further research in this area is imperative.

**Power Training**

If the development and maintenance of high levels of power are as important as the previous discussion indicates, then the obvious question of which is the best method for power training should be addressed. There is no definitive answer to this question, considering the infinite variety of equipment and training methods that could be implemented. Based on data concerning strength and power training that have been published, however, recommendations for the design of power training programs can be made. By following established principles of strength/power training, a very effective program can be constructed.

Although a great deal of literature is available on the subject of strength training, very little attention has been paid to power training. One reason for this relative lack of research in power training may be that many think that by increasing strength, improvements in power output will also occur. Strength, however, is classically defined as the maximum force a muscle can exert against an unyielding resistance in a single contraction (1), while power is defined as the rate at which force is applied over distance. Thus, in spite of the fact that strength is a component of power, the two may be developed independently of each other.

For an excellent comprehensive review of research related to strength training the reader is referred to the review paper by Ahtaa (1). Based on his review of literature, it appears that the most critical factor governs increases in strength is the intensity of the load relative to maximum. For example, it has been shown that when subjects were isotonically strength trained using repeated lifts below 60% of maximum lift or above 80% of maximum lift, there is little if any gain in strength (2). It is equally apparent, however, that within the range of 60% to 80% of maximum strength, there is little evidence to suggest that variations of load have a significant bearing on the gains in strength. Thus, isotonic strength training protocols involving loads that can be lifted between 4 and 8 repetitions appear to result in optimal strength gains (17).

The effectiveness of isotonic training to improve swimming performance must be questioned on the basis of several known disadvantages of isotonic training. There is considerable evidence that the gains in strength are confined to the weakest joint angle during isotonic exercise. This is due to the fact that the maximum load that can be lifted is only maximal for the weakest angle in the range of motion and consequently, will be submaximal for all other joint angles. Secondly, there is some evidence that strength developed using isotonic contractions does not translate into improvements in swimming performance (11) due most likely to the fact that it is very difficult to imitate movement patterns of swimming with traditional isotonic equipment. A different viewpoint might be construed from the results of a recent study that measured swimming performances before and after a nine week isotonic circuit training program that relied on exercises using muscle groups involved in swimming and at fast speeds (12). The authors of this paper concluded that the circuit training program improved performance in various freestyle events in spite of the fact that the performances showed non-significant changes. Aside from the lack of objective statistical evidence of a link between the circuit training and performance changes, a major weakness of this study is that since the subjects were also engaged in 15,000 - 18,000 yards per day of swimming training, it is impossible to ascribe any performance improvements to the circuit training. Any performance improvements seen may have been due solely to the swimming training.

Isokinetic strength training apparently allows one to avoid many of the disadvantages associated with isotonic training. Because during isokinetic training, muscles can be stressed maximally over the full range of motion (21), strength gains are more consistent across different joint angles. An additional advantage of isokinetic training is that movement patterns of swimming can be more closely duplicated using Mini-gyms, swim benches and Biokinetic apparatus than with traditional weight lifting. Thus, greater translation to improvements in performance can be expected.

It has been frequently noted that gains in strength are speed specific with isokinetic training (9, 15). Generally, with slow speed training, the gains in strength are confined to slow movement velocities while high speed training results in gains in strength evident at both slow and fast speeds of movement (9). Since competitive swimming involves relatively fast movement speeds, isokinetic strength training at fast speeds can be recommended. The same recommendation cannot, however, be made for isotonic training since performing weight lifting at fast speeds can easily cause injury. Even if one were to decrease the load during isotonic training to allow for fast speed lifts, the load placed on the muscle would necessarily be
reduced to a level below that required to induce significant strength changes. Rather, the specific physiological characteristic that would be developed would be muscular endurance, a capacity that very likely is best developed using endurance swimming training.

With regard to training to increase power, there are few actual studies that have compared specific methodologies. There can be no doubt that any one of a number of programs could be utilized to increase power. The more efficient programs (resulting in great gains in relatively little time), however, would most likely employ movement specific exercises done at speeds that fairly closely approximate the speeds used during swimming. It is no coincidence that in our initial studies of power output on the Biokinetic bench, that the highest levels of power output were obtained at arm speeds very similar to those encountered during sprint swimming and that the more accomplished sprinters achieved peak power at somewhat higher speeds of movement than the less skilled sprinters (20). Most of the swimmers we tested reached peak power at speed settings on the bench between 3 and 6. Thus, in using this equipment, it would appear that training in this speed range is quite beneficial and in keeping with the principle of speed specificity.

Because specificity of speed and movement patterns is such a basic tenet of optimal strength and power training, one has to wonder if using actual swimming might not be the best method of training to improve power. After all, there is no better way to exactly duplicate the skill than with swimming. Many novel methods of using swimming training for improving strength and power have been tried such as using devices to increase drag, tethered swimming and short fast sprints. Power developed during partially tethered swimming has been shown to bear a closer relationship to sprint swimming performance than does the dryland measurement of power on the Biokinetic bench (3,4). This may therefore support the use of such highly specific power training as perhaps the best method for improving the ability to express power during performance even though mechanics are somewhat altered during partially tethered swimming (10). Although partially tethered swimming appears to be an excellent mode of power testing, its effectiveness as a means of power training has not yet been directly tested. The effort required to evaluate this question would be well spent in light of the potential application of this method in swimming programs.

Summary

It appears from the findings of recent research that strength, per se, may be relatively unimportant to the performance of competitive swimmers. The ability to express high power in swimming-specific movements, however, bears a very close relationship to swimming performance. Coaches are therefore justified in using training methodologies designed to increase maximum power output. It appears, based on the evidence to date, that training that uses either speed-specific isokinetics (or Biokinetic, if the distinction must be made) or some types of swimming power training offer the most advantages for development of peak power that can be applied to the task of propulsion. The value of isotonic training in improving performance is far less clear and perhaps needs further study.

An issue that has not been addressed with much research concerns optimal intensity, frequency and duration of power training. Evidence has, however, appeared [20] that as little as 3 sets of 10 maximal isokinetic repetitions at high speed done 3 times per week can be quite effective in improving power and performance. Whether the same benefit can be obtained in elite level swimmers is doubtful if they already possess high maximal power output. Maintenance of power during heavy swimming training may thus form the basis of strength/power training in these athletes.

Another area sorely lacking in research is the concept of duration-specific power training. Some coaches have attempted to use strength/power training sets that are based on the approximate duration of the competitive event(s) for which the swimmer is training. Power output that can be generated in 45 sec of repeated contractions will undoubtedly be far below maximum power in one pull, yet may relate better to performance of 100 yards than the single effort. Use of such duration-specific power training may therefore improve performance by improving the swimmer's ability to sustain a higher percentage of maximal power output during a competitive event. For example, a swimmer with relatively low maximal power output of 300 watts in one pull may be able to sustain 250 watts per pull during a 100 yard freestyle while another swimmer with high maximal power of 400 watts might be able to sustain only 200 watts per pull during 100 yards. All other factors equal, the swimmer with the lower maximum power in one pull would have the performance advantage due to the high percentage of maximum power that can be maintained over the duration of the competitive event. The swimmer who possesses both a high maximal power output and the capacity to sustain a high percentage of this maximal power over the distance has the greatest advantage. Thus, combining maximum power training and duration-specific power training may provide a nearly ideal performance related power training program. This will have to be confirmed with additional research and application to competitive swimmers before we can be sure of the merit of this type of methodology.
References

Swimming Skill: A Review of Basic Theory

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Introduction

Over the past two decades, research in swimming biomechanics has produced a major reassessment of the basic theories surrounding swimming skill. This paper reviews research findings concerning the general theory of swimming propulsion. Further, the specific techniques employed by skilled swimmers in all four strokes are summarized. Finally, propulsive efficiency is discussed from a theoretical viewpoint in order to clarify the foundations of aquatic skill.

The discussion of swimming skill is presented from three levels of inquiry:

1. From the kinematic level, the fundamental patterns of motion utilized by skilled competitors is defined. Further, the basic principles of fluid mechanics are combined with data on stroke kinematics to provide a theoretical explanation of the propulsive mechanisms used in swimming. The Bernoulli principle of propulsion (that diagonal sculling motions provide the basis of efficient hand motions in swimming; Counselman, 1969) is presented along with the early literature in this area. We will see that the Bernoulli principle theory of propulsion has the universal support of the scientific community. In contrast, the previously accepted push back-action reaction theory (that straight back pushing motions are used by good swimmers, Hedges, 1933; Silvia, 1970; Collis and Kirchhoff, 1974) is rejected on the basis of cinematographic evidence.

2. The original Bernoulli's principle theory on swimming propulsion has been extended through evidence collected at the kinetic level of analysis. At this level, estimates of the propulsive forces and joint torques employed by skilled swimmers are reviewed, and a refined description of the end product of aquatic skill is defined. Studies of outstanding swimmers help define the optimal interaction between the human organism and the aquatic environment. Our discussion includes the consideration that an impulse of hand force delivered within a critical range of motion is a fundamental characteristic of aquatic skill. In contrast, the view that efficient propulsion follows from a uniform production of force is rejected.

3. From a theoretical level, a discussion of the interdependence of biomechanical and physiological theories helps to solidify understanding of the techniques observed in skilled swimmers. Basic theory allows us to understand why skilled swimmers choose to use the techniques discussed at the kinetic level of analysis.

Analysis from the Kinematic Level

The Bernoulli Principle Theory

Counselman (1969, 1971), and Brown and Counselman, (1970), presented the first arguments which acknowledged the importance of lift force in swimming. It was stated that propeller-like sculling hand motions were used by skilled swimmers instead of the previously supposed push back-paddling hand motions. The contrasting features of the Bernoulli principle of Propulsion and the action reaction viewpoint are illustrated in Figure 1.

In the action reaction theory a straight back pulling pattern is purported to provide optimal swimming efficiency. The hand is assumed to be held at right angles to its line of motion and drag forces are seen as the source of swimming propulsion. A canoe paddle is used as an example of a drag force producing implement. In contrast, the Bernoulli principle theory of propulsion states that curvilinear pulling patterns are made with respect to the water, acute hand angles are made between the hand plane and its pulling pattern, and lift forces play an important role in the production of propulsive force. A propellar blade is used as an example of a lift force producing implement.

Counselman utilized light trace photography of swimming pulling patterns to support his theoretical viewpoint. Curvilinear patterns, similar to that of Figure 2 were presented to illustrate that many swimming hand motions exit the water in front of their point of entry. Note that a static camera position is used in the collection of the illustrated pulling pattern data. By holding the camera still, the motion of the swimmer's hand with respect to the water (and thus the propulsive action of the hand on the water) is isolated by the recorded pulling pattern data.
The Bernoulli principle theory proposed that lift forces are produced by the swimmer's hands, feet and forearms. The mechanism responsible for the production of lift force is illustrated in Figure 3. Note that the lift force vector is directed at right angles to the line of motion of the propelling surface in each example. Thus, with an airfoil, lift forces are generally directed upwards; with a propeller, lift is aimed primarily forwards; and with curvilinear hand pulling patterns, the direction of lift forces change constantly, but is at right angles to the pulling pattern at any instant in time. Drag forces are also produced by wings, propellers and hands. The line of action of drag forces is opposite to the instantaneous line of motion of the propelling surface (Schlehauf, 1974).

Hand Propulsion

Subsequent to Counsilman's 1969 article, numerous papers were published in support of the Bernoulli principle theory. Hay, 1973; Rackham, 1975; Barths, 1981, 1979; Persyn, 1978; Ungerechts, 1979; and Reichle, 1979 presented empirical information clarifying the analogy between skilled pulling motions and propeller like sculling motions. Quantitative cinematographic evidence was presented by Schlehauf, 1974 and Barths and Adrian, 1975. Barths and Adrian found that a parallel relationship existed between sculling hand motions and body acceleration in butterfly swimmers. Schlehauf found that a highly skilled freestyler utilized his most rapid hand actions in the side to side up and down dimensions of motion. Further, it was shown that the combination of lift and drag forces acting on the hand may be expected to vary with hand pitch as shown in Figure 4.

If the hand moves through the water with a very small angle of pitch (about 15 degrees - Figure 4a), a small drag force component and moderate lift force component are created. If the hand employs a 35-45 degree angle of pitch, both the lift and drag force components produced are large (Figure 4b). Finally, if the hand uses a large angle of pitch (nearly 90 degrees - Figure 4c) a large drag force is created and almost no lift force is produced.

A typical swimming motion and hand pitch angle is shown in Figure 5. Notice that the 35 - 45 degree angle between the swimmer's hands and its line of motion creates...
lift and drag force components which are approximately equal in size. Note that the hand propulsion force vectors shown in Figure 5 are identical to those of Figure 4b, with the exception that the hand line of motion of the freestyler is oriented along a diagonal line. As a result, the drag force acts opposite to the hand line of motion (upward and to the right on the page), and the lift force acts at right angles to the hand line of action (upward and to the left on the page). Because of the diagonal line of pull chosen by the swimmer, the hand resultant propulsive force (the net effect of both the lift and drag force components taken together) is aimed nearly straight forwards.

In effect, a swimmer can insure that hand propulsive forces are aimed forwards (and not wasted to the side or in up/down directions) by selecting an optimal hand pitch angle. For a pulling motion which progresses through the water along a 45 degree angle with respect to the forward direction (Figure 5) a 35-45 degree angle of pitch produces optimal results. For a pulling motion which is more sideways (as in the inward scull motion in breaststroke) a larger lift drag ratio is required to "aim" the hand forces forward. Thus, in breaststroke, smaller hand pitch angles (15 - 35 degrees) may be expected to yield propulsive forces which are aimed nearly straight forward.

**Figure 5.** Forward propulsion through lift drag interaction.

**Foot Propulsion**

The Bernoulli principle theory may be applied to kicking propulsive actions as well as those of the hand. Studies of flutter kick movements have shown to produce the saw-tooth pattern illustrated in Figure 6 (Hoecke and Gruendler (1975), Counsilman (1977) and Reichle (1982)).

An analogy may be drawn between kicking patterns and propeller blade motions. On a down thrust the foot may be expected to produce the propulsive force components shown. Propeller blades are designed to change their orientation with respect to the propeller axis in accordance with varying speeds of progression of the boat. This change in propeller orientation allows for the maintenance of acute angles of pitch at any boat speed. In the case of a human foot, the "variable pitch feature" is limited by the degree of plantar flexion ankle flexibility. With greater ankle flexibility, more acute pitch angles are possible and less force is lost in the up-down dimension (Figure 6b). In effect, the flexible ankle allows for an acute angle of pitch and a high lift drag ratio (see Figure 4a). With a relatively large lift force component, the net propulsion produced by the kick is aimed more forwards.

**Analysis from the Kinetic Level**

In the previous section, the characteristics of skilled movement patterns and a theoretical explanation of the propulsive forces generated in swimming were discussed. In the following paragraphs experimental evidence is presented which substantiates the Bernoulli principle theory of propulsion.

At the onset, it must be noted that while the majority of the scientific community accepted Counsilman's theory, there were those who preferred to maintain the push back-action reaction viewpoint. For example, Holt (1976), published an empirical argument which denounced the possibility that lift force could be created by the human hand.

In support of the Bernoulli principle theory, research from the fluid mechanics laboratory (Schleilhauff, 1977) presented experimental evidence in support of the importance of lift force in propulsion. Models of human hands were placed in the open water channel and propulsive characteristics were defined across a wide range of hand orientations with respect to the water flow. The force producing qualities of the hand were shown to be virtually identical to those of a low aspect ratio (short stubby) airfoil. Subsequent research, Wood (1979), Remmonds and Bartlett (1981), and Nomura (personal cor-
respondence) produced results similar to Schleihauf (1977, 1979).

The experimental evidence on hand propulsive force potentials provided for both the confirmation of the Bernoulli principle as well as a mechanism for the substantial extension of the original theory. Through the combination of fluid laboratory data and a film analysis procedure, an objective evaluation of the biomechanical aspects of swimming skill may be defined.

The Hydrodynamic Analysis Procedure

The motion of a hand through water is governed by the same physical principles which have been established in airfoil/propeller blade research. The degree of skill of a competitive swimmer depends upon his or her mastery (at a subconscious level) of skills which conform to these physical principles. Conversely, the accurate analysis of a skilled swimmer’s hand motion may only be accomplished in conjunction with a complete understanding of hydrodynamic theory.

The quantification of the force producing characteristics of the hand may be expressed in terms of coefficient of lift (C₁) and coefficient of drag (Cₐ) versus angle of pitch curves. Figures 7 and 8 show representative Cl and Cd values determined in Schleihauf (1979), for a hand held flat, with fingers together and thumb fully abducted. The data in the curves confirm the supposition that hydrodynamic theory applies equally well to wing, propeller and hand motions. Figure 7 indicates that the lift force produced by a hand held at a small angle of pitch is also small. As the hand pitch increases, lift force builds to a maximal value around 40-45 degrees. Thereafter lift force diminishes with increasing angles of pitch. Figure 8 indicates that drag force increases continuously with increasing angle of pitch. Given the information contained in these curves, estimates of the forces produced by any type of hand motion in water can be computed.

Note that each Cl and Cd value depends upon two variables: 1) The hand angle of pitch (AP); measured as the angle between the hand plane and its line of motion. And, 2) the hand sweepback angle (SB); which defines the leading edge of the hand as shown in Figure 9a. Figure 9b shows the difference between a hand orientation of AP = 35, SB = 0 and AP = 35, SB = 90 (degrees).

Given the quantitative information on hand C₁ and Cd values, it is possible to estimate hand propulsive force based upon cinematographic information. Four lighted landmarks on the hand may be digitized from two film views to supply the necessary information on hand orientation and hand speed to allow solution of Equations (1) and (2):

\[
L = \frac{1}{2} \text{Ro} V^2 C_1 S \\
D = \frac{1}{2} \text{Ro} V^2 C_d S
\]

Where:

- \(L\) = magnitude of hand lift force
- \(D\) = magnitude of drag force
- \(\text{Ro}\) = density of water
- \(V\) = hand speed
- \(C_1\) = coefficient of lift
- \(C_d\) = coefficient of drag
- \(S\) = hand plane area

Further, the direction of the hand propulsive force vector may also be determined from three dimensional coordinate data on the hand. A complete description of the

Validation Experiments

In order to determine an estimate of the degree of accuracy to be expected with the hydrodynamic analysis procedure, three experimental conditions were studied (Schleithauf, 1977, 1979). In the experiments a swimmer was asked to balance a known load while performing a vertical sculling, tethered breaststroke pull, or tethered freestyle pulling task (Figure 10). Three dimensional film data was collected on a stroke cycle in which the resisting load was being evenly balanced.

The film data was then reduced and estimates of hand and forearm force production were made at each instant in the arm pull. The computed force output — which is based upon the fluid laboratory data and film analysis procedure — was then compared to the known load the swimmer was balancing. The results showed that in three separate stroking motions, the estimated propulsive force data was within 5% of the expected values.

![Figure 10. Validation experiments. A) Vertical sculling. B) Tethered breaststroke. C) Tethered freestyle.](image)

Advantages of the Hydrodynamic Analysis Method

A primary advantage of the hydrodynamic analysis procedure is that it may be applied to any hand and arm motion in water. Through simple film records we are able to quantify not only the kinematics but also the kinematics of human motion. Such a complete analysis potential from film alone is not easily accomplished in other areas of biomechanics. Typically, force plate or force/pressure transducer data must be combined with filmed records to yield similar results. It is also interesting to note that while direct measurement techniques are generally more accurate than film techniques, this is not the case in swimming. Pressure transducers have been used to measure the hydrodynamic pressures which are produced at the palm of the hand during free swimming. In early studies, (Van Menen & Rijken, 1973) the transducers were so large and bulky that the lift drag force producing characteristics of the hand were undoubtedly altered. In subsequent studies, (Dupuis, et al., 1979), the transducers were much smaller, but the pressure recordings included both the hydrostatic pressures—due to the depth of the hand underwater—as well as the hydrodynamic pressures which resulted from propulsive hand motions. In recent work (Svec, 1982), a pressure transducer paddle has been developed which corrects for the hydrostatic pressure component, and measures propulsive pressures only.

Even with the Svec pressure transducer, it must be noted that the direct measurement of palm pressures yields a rough estimate of hand propulsive force at best. Figure 11 shows the pressure distributions which exist on wings at two different angles of pitch. Note that the pressure component which exists at the mid-point of the under-

![Figure 11. Wing pressure distributions.](image)

side of the wing is a poor estimator of the overall force acting on the wing. Further, even if the pressure measured at a point on the hand palm were representative of hand force, the information would be meaningless without knowledge of the force direction. Figure 12 shows two swimming motions which produce identical force magnitudes. The pressure recordings would theoretically show equal measures of palmar pressure for Figure 12a and 12b, even though the stroke of Figure 12a provides six times more effective propulsion. As a result, pressure transducer studies of free swimming would need to be supplemented by film analysis in order to yield data meaningful to the coach or athlete.
dimensional hand force vector includes components into or out of the paper.)

The above figure shows that zig-zag curvilinear pulling patterns are used in each of the four competitive strokes. In each stroke, diagonal pulling motions make use of the principle of lift-drag interaction to create efficient propulsion.

Freestyle, backstroke, and butterfly involve pulling patterns which form an angle of approximately 50 to 70 with the forward dimension. These diagonal lines of pull are helpful in creating propulsive forces which are aimed primarily forwards. In the case of breaststroke, a pattern orientation of about 75 to 95 with the body's line of progression is created on the inward scull action of the stroke. As a result, in breaststroke, the propulsive force is angled to the side and upward as well as forward.

It should be noted also that, within a given competitive stroke, a range of optimal stroking styles may be expected across a sampling of skilled swimmers. Depending upon the individual's strengths, flexibilities and training backgrounds, "ideal" patterns vary with individual swimmers. (See Schleihau, 1977 for a more extensive review of swimming styles in all four strokes.)

Propulsive Force Distributions

An analysis of the propulsive forces created within a stroke cycle indicates that an impulsive force distribution is characteristic of skilled stroke technique. A typical effective propulsive force curve for each of the competitive strokes is shown in Figure 14 a-d. The critical range of the pulling pattern which is associated with the propulsive peaks is cross hatched in both the hand resultant (R) force curve data and the pulling pattern for each stroke.

The data presented in Figure 14 is taken from Schleihau (1981). Counsilman and Wasilak (1980) on the basis of hand speed data, have also theorized that optimal propulsion follows from impulsive force distributions. They state: "The power pulses from the arm stroke are applied in surges and the maximum force generated by the hand peaks near the end of the arm stroke." Similarly Svec (1982), has presented pressure transducer data which suggest that impulses of hand force are applied in swimming.

Joint Torque Computation

The joint torques (net muscular actions) which occur at the swimmer's wrist, elbow, and shoulder may be determined through established biomechanical procedures (Andrews, 1974), once the arm propulsive forces and kinematics are known. The details of the swimming computational procedure may be found in Schleihau, et al., (1982).

The joint torque curves for a skilled freestyler are shown in Figure 15. The largest torques of good swimmers appear to occur at the shoulder joint, where the net muscular actions are about twice as forceful as these at the elbow.
tions of skilled swimmers were shown to be more intensive than those of the elbow. With poor swimmers, the opposite situation was found; elbow muscular actions were more intensive than those at the shoulder.

The above discussion describes the ingredients of aquatic skill from a biomechanical viewpoint. Next, the propulsive efficiency of skilled aquatic motions is discussed.

Optimization of Propulsive Efficiency - Theoretical Viewpoints

Observations of the movement patterns and propulsive force output of skilled swimmers provides an external view of the ingredients of aquatic skill. In order to achieve an understanding of the internal processes which produce propulsive force, our next step is to consider the muscular contraction circumstances of skilled swimming movements.

The Efficiency of Sculling Movements

Schenau (1981) has made the important observation that swimming performance is limited by three factors:

1) The net propulsive force produced (as discussed above).
2) The active drag or the resistance created by the swimmer as he progresses through the water.
3) The propulsive efficiency created by the combination of the swimmer’s muscular effort and the mechanics of his motion.

The third point above is frequently overlooked in the literature. While a swimmer’s performance may seem to be a simple interaction of his propulsion and active drag, it is also important to note that a given net propulsive force output may be produced with a variety of physiological efficiencies.

For example, consider the motions shown in Figure 16a and b. In each of the illustrated motions, the hand speed in the water (and therefore, the approximate force potential) is identical. However, the movement speeds relative to the swimmer’s body are not the same. In the push back motion, 4.71 meters per second (mps) relative to the body is required to produce 3.05 mps relative to the water. In the sculling motion, only 4.15 mps relative to the body is required to produce a 3.05 mps water speed. This information implies that sculling motions translate hand movement speeds to the water more efficiently than push back motions.

Figure 16c shows Perrine and Edgerton’s (1978) in vivo force velocity relationship for human muscle (adapted from Hill’s equation). The maximal force possible at a given speed of contraction is represented by the illustrated curve. Note that the maximal potential force of a slower contraction speed is higher than that of a fast contraction speed. Thus, the slower movement speed (4.15 mps) associated with the sculling motion above would involve a higher potential force production than the push back
degrees in sculling motions, but can not occur in push back motions.

It should also be noted that in freestyle, curvilinear sculling motions tend to be combined with shoulder roll actions. The combination of body roll along with the upward sweep finish of a freestyle stroke, allows the strength of the large muscle groups of the trunk to be transferred to the hand through the serape effect (Logan and McKinney, 1970).

Figure 18 shows that sculling finishing motions combine the strengths of the trunk muscles along with the shoulder and elbow joint muscle groups. In contrast, a straight back pulling motion — with no forceful upward swept movement component — would not take advantage of shoulder roll or the potentially powerful shoulder joint rotations.

**Theoretical Support for Impulsive Force Distribution**

The above discussions provide theoretical arguments which confirm the importance of zig-zag curvilinear sculling motions in swimming. In this section, the theoretical
issues which support the use of impulsive force distributions are discussed.

First, we should note that the importance of impulsive force distributions in swimming has only recently been realized. Prior to the Bernoulli principle theory, efficient propulsion was presumed to follow from a uniform square wave distribution of propulsive force.

The mechanical rationale for the efficiency of the square wave propulsive force distribution is given by the smooth running eight cylinder automobile engine. In a car, the uniform torque sent to the drive wheels was expected to minimize the inertial lags (acceleration/deceleration) of the system. The explosions which occur in an automobile engine may be carefully timed to produce a seemingly continuous flow of torque to the drive shaft. In the case of swimming, however, the mechanical analogy breaks down. The movements of a two arm stroke swimmer (or a two legged runner) can hardly be likened mechanically to the rolling of a wheel. While it is clear that the propulsion from a given arm stroke should flow continuously to the next, it is not clear that within a given stroke, a uniform force output is desirable. For example, studies of fish swimming (Wiehs, 1974) show that an overall optimal combination of mechanical and physiological efficiency results from burst swimming — where large impulses of power are followed by glide phases in the swimming movement. Similarly, in running, the horizontal ground reaction force component in no way approximates a uniform production of force. Finally, in human swimming, a pulse of propulsive force output, followed by a gliding phase is clearly evident in many stroking styles.

The zig-zag line of pull which is employed in sculling motions in itself necessitates the use of impulsive force distributions. Figure 19 shows that with each change in pulling direction, the hand speed must slow down, and force must necessarily diminish (Area A). In the middle of a diagonal motion the hand achieves peak speed, and peak force (Area B). Finally, at the end of the stroke, a smooth transition to zero force occurs as the hand moves out of the water to begin the recovery. These biomechanical circumstances are responsible for the natural occurrence of a force pulse near the middle of a diagonal motion.

A pulse of force seems to be economical from the neurophysiological level as well. Perrine and Edgerton, 1978, found that on an isokinetic knee extension exercise, their subjects were able to reach higher instantaneous force levels if a ramp like build up of force was planned by the subject. Even though the contraction took less than 2 seconds, the impulsive "effort" distribution gave higher peak values than uniform "100%" efforts. Perrine and Edgerton attributed the success of the impulsive method to "neutral fatigue" which may be present in very short duration maximal intensity muscular effort.

Finally, our serape effect argument would seem to support the observation that some swimming motions create much larger pulses of force than others. For example, the finishing portion of a freestyle arm pull produces a force pulse which is much larger than the mid-stroke segment. It seems that the swimmer's can best "seize the moment of least resistance" (Bernstein, 1967) at the end of the stroke where the benefits of sculling actions, strong muscle groups, and the serape effect all combine.

Conclusions

In the foregoing discussions, the basic theory surrounding aquatic skill has been discussed from kinematic, kinetic and theoretical levels. The following list summarizes our main points:

1) Sculling hand actions are used by skilled swimmers in all four competitive strokes.
2) Diagonal pulling patterns allow straightforward propulsion through the combination of lift and drag force.
3) A pulse of propulsive force is created within an isolated pulling area in each stroke.
4) Within any sample of swimmers, there is a range of efficient propulsive styles, each suited to the individual attributes of a given swimmer.
5) The muscle force vs. contraction speed relationship seems to favor sideways and diagonal motions for optimal translation of a swimmer's hand speed to the water.
6) Curvilinear pulling patterns allow efficient energy expenditure through the use of large muscle group activity (the Serape effect) in the generation of a pulse of force.

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Abstract

In keeping with the original intent of the JSR, to act as a “researcher-to-coach” publication and to “educate coaches while informing them” the following bibliography has been compiled to serve the swimming community. These references have been assembled from a number of sources and although not a difficult task it was considerably labor intensive. Not all swimming related material is found within this listing. An attempt was made to include only those references judged by the authors to be information or research oriented and valuable to the swimming coach. It is hoped that this bibliography will be useful by providing a quick and easy guide to information. If the response to this endeavor is positive it is our intent to continue these efforts in subsequent issues of JSR by assembling bibliographies for preceding and future years.

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The Relationship Between Anatomical Characteristics and Swimming Performance in State Age-Group Championship Competitors

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Abstract

The success of any talent identification and development programme is dependent upon a clear understanding of the performance requirements. Profiling the anatomical and physiological characteristics of elite young swimmers could provide coaches with criteria upon which to identify talent. An examination of 82 age-group competitive swimmers was undertaken to investigate the relative importance of anatomical and physiological parameters to high level performance in 100m freestyle and 100m butterfly events.

Significant correlates with the freestyle performance ratio were the lung function variables of Forced Vital Capacity (FVC), Forced expiratory volume (FEV1), and peak air flow; the triceps skinfold and thigh flexion strength. In addition, the femoral bicondylar width and stem length variables, when divided by standing height, were found to be significant discriminators in 100m freestyle performance. In the analysis of butterfly performance the significant correlates were arm flexion/extension mobility as well as the measures of percentage body fat. Femoral bicondylar width and stem length ratios were also significant in butterfly analysis, as were the ratios of lower limb length and thigh length divided by standing height.

Introduction

In swimming, as in many other sports, world records have been regularly broken in recent years and these improvements can be noted by comparing medal winning performances from the past with current world standards. With more children participating in a wider range of sports, potential champions can be identified and encouraged to fulfill their potential.

Many coaches feel that more intensive race preparation has been responsible for much of the improvement in swimming performances. Increases in the number of weekly training sessions, the distance covered per session, the intensity of the workouts and the use of interval training methods have resulted in a better prepared athlete. In addition, better designed swimming pools have provided an environment more conducive to high level performances.

Judging by developments in Eastern European countries, a systematic programme of talent identification and development can also have a considerable impact on future performances. Comparing an individual's anatomical and physiological characteristics with the established norms of others who have been successful in a particular sport can provide coaches with criteria upon which to formulate their coaching decisions. Then, a combination of technique modification and highly specific remedial training programmes to develop the required physical capacities can be undertaken. The success of talent identification and development programmes, however, is dependent upon the performance requirements being clearly and accurately understood. By profiling the anatomical and physiological characteristics of elite young swimmers and grading the relative importance of each in relation to performance, coaches could be provided with criteria upon which to base the process of talent identification and
development in that sport.

Eighty-two competitors aged 9-13 years, who were finalists or reserve finalists in the Western Australian State Swimming Championships were involved in the project. An examination of these children was carried out in order to investigate the relative importance of those anatomical and physiological characteristics which were thought to contribute to high level performance in the 100m freestyle and 100m butterfly events. The measurements taken can be found in Tables I-VI.

Treatment of the Data

Dependent and independent variables were both treated prior to statistical analysis. The swimming times were not entered directly as dependent variables. The ratio of each time in comparison to the Western Australian State record for the appropriate stroke, distance and age group was used.

This approach to treating the swimming times eliminated the age factor and allowed the sample to be placed in order of ability, according to the performance ratios. An example of the procedure used to calculate performance ratios is outlined below:

Swimmer No. 1 (male)
Age — 10 years
100 meter freestyle time— 72.5 seconds
The State Record for this event— 68.5 seconds
Performance ratio = The swimmer's time
The State record time
= 72.5
68.5
= 1.058

Swimmer No. 2 (male)
Age — 12 years
100 metre freestyle time— 65.7 seconds
State Record for this event— 61.39 seconds
Performance ratio = 65.70
61.39
= 1.070

Swimmer No. 1 was therefore rated as a higher level performer than swimmer No. 2, since the performance ratio was closer to 1.0.

A different approach was employed to analyse the contribution that anthropometric characteristics make to performance. The majority of anthropometric variables were divided by standing height and a ratio was generated. This allowed the study to focus directly on the influence of body dimensions on swimming performances. An example of the procedure used is outlined below:

Swimmer No. 1
Arm length— 27.4 cms
Standing Height— 149.7
Arm ratio = Arm Length
Standing height
= 27.4
149.7
= 0.183

Swimmer No. 2
Arm length— 29.2 cms
Standing height— 150.4 cms
Arm ratio = 29.2
150.4
= 0.194

Swimmer No. 2 therefore possessed a proportionally longer arm length when compared to swimmer No. 1. This approach allowed the 82 swimmers to be ordered according to the size of their anthropometric ratios. In addition, selected anatomical and physiological variables were treated by partial correlation statistics to eliminate the effect of age. This procedure was necessary because age correlated highly with many independent variables.

Pearson Product Moment and Partial correlation statistical analysis procedures were employed to analyse the relationship between the independent variables and performance ratios in freestyle and butterfly. The independent variables which demonstrated a significant correlation with performance were entered into a stepwise multiple regression analysis in order to generate prediction equations.

Results and Discussion

For the interest of those readers who are familiar with statistical analysis of data, the following section will include references to statistical results and tables. Please note that the inclusion of statistics is for completeness only, and should not deter the unfamiliar reader from reading the discussion and conclusion that are based on these results.

1. Relationship between Selected Anatomical and Physiological Variables and Performance

Prior to presenting and discussing results, attention should be drawn to the correlation coefficients in Tables I and II. It is important to remember when analysing the results, that swimming times were entered into the
analysis as performance ratios. As each subject’s swimming times were divided by State records for each event, lower performance ratios were indicative of faster performances. Caution should therefore be taken when interpreting relationships between independent variables and performance ratios. For example, a negative correlation of -.4373 for Forced Vital Capacity (FVC) (Table I)

<table>
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<th>Variables</th>
<th>Correlations</th>
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<td></td>
<td>Freestyle</td>
<td>Butterfly</td>
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<td>-.3547*</td>
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<td>PWC170</td>
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* Significant at the 0.05 level of confidence.

Correlation coefficients of 0.189 and 0.211 were required for significance in freestyle and butterfly respectively.

demonstrated that a larger FVC was associated with a lower performance ratios which reflected faster swimming times. On the other hand, a positive correlation of .2854 for percent of body fat (Table II) meant that larger fat deposits were associated with higher performance ratios, which reflected slower times.

Correlation coefficients for anatomical and physiological variables with the effect of age partialed out of the analysis are presented in tables III and IV for freestyle and butterfly respectively.

Freestyle Performance

In the freestyle analysis (Table III) FVC, Forced Expiratory Volume For one second (FEV1.0) and peak air flow were significant, as were the variables of triceps skinfold and thigh flexion strength. (Tables 2 and 3).

Several studies have reported that lung volumes were higher in swimmers than in the normal population (1, 3, 18, 24). In regard to athletic performance, however, it has been reported that there is little correlation with lung volumes, particularly when body size was taken into consideration (19). The results of this study concluded that the variables of FVC, FEV1.0 and peak flow were significant contributors to freestyle performance, even when the effect of age was partialed from the analysis.

Blanksby et al. (7) hypothesised that a large FVC could assist a swimmer’s flotation because air has a very low specific gravity (S.G. = 0.0012) and a swimmer’s buoyancy could be assisted. Bar-Or (3) also found that finalists scored higher in FVC than did semi-finalists who competed in the same competition.

<table>
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<tr>
<td>Arm Extension Strength</td>
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</tr>
<tr>
<td>Arm Flexion/Extension Flexibility</td>
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</tr>
<tr>
<td>FVC</td>
<td>-.2975*</td>
</tr>
<tr>
<td>FEV1.0</td>
<td>-.2869*</td>
</tr>
<tr>
<td>Peak Flow</td>
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</tr>
<tr>
<td>PWC170</td>
<td>-.0726</td>
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<tr>
<td>Triceps Skinfold</td>
<td>-.2036*</td>
</tr>
<tr>
<td>Standing Height</td>
<td>-.1388</td>
</tr>
<tr>
<td>Body Mass</td>
<td>-.1166</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 level of confidence.

A correlation coefficient of 0.189 was required for significance.
The development of strength is important in elite swimming performance and a swimmer who improves strength levels can work at a reduced percentage of his maximal workload, therefore delaying the onset of fatigue. This would be advantageous in each stroke, particularly in sprint events. Although the arms produce most of the propulsive force in swimming, the legs do make a significant contribution (2). The ability to forcefully flex the thigh at the hip joint would therefore be advantageous in developing an efficient kicking action. In longer events generally agreed that leg action is more of a stabiliser than a propelling force, but in sprint events the legs provide a greater contribution to the propulsive forces generated. Jensen and Mcllwain (17) supported this view by reporting the importance of the hip flexor muscles in producing an efficient kicking action.

Arm extension strength, which was reported as characteristic of leading University swimmers (8), was not a significant characteristic in the younger subjects of this study. Table III also show that leg extension and hand grip strength were not significant discriminators.

Helmut (16) stated that determination of computed variables such as somatotype, were often less valuable in identifying performance requirements for a particular sport, in comparison to individual measures. He contended that individually obtained information was pooled and consequently lost in computing these measurements. For this reason all the independent variables in this study were analysed for individual contributions to performance, in addition to analysing the significance of the computed variables they generate. The importance of this approach was exemplified when it was noted that body density and percent body fat were non-significant. This result indicated that thicker triceps skinfolds were detrimental to performance.

The time limitations inherent in this study made procurement of VO₂ max. values unrealistic with such a large sample. In spite of time limitations, it was felt that sub-maximal assessments were of value for young children. The Physical Work Capacity at a heart rate of 170 (generally noted as the PWC₁₇₀ test) was chosen to demonstrate aerobic power despite it being non-specific for swimming.

Montoye and Gayle (20) eliminated the influence of age and body size on oxygen uptake and reduced the correlation with performance from \( r = .76 \) to \( r = .59 \). This correlation still accounted for greater variance in performance than the physical exercise capacity variable in this study. The true contribution of this characteristic may have been masked by the sample's homogeneity. Because children are normally very active during their pre-adolescent and adolescent years, the differences between trained and untrained children on measures of physical exercise capacity are often minimal when compared to adults whose activity levels are more varied. Although the importance of this characteristic has been reported in relation to swimming performance (7, 19), physical exercise capacity was not a significant discriminator in the freestyle analysis.

Standing height and body mass were also not significant when the effect of age was partialled from the initial correlation coefficients. Several studies have shown that swimmers were taller in comparison to their non-athletic peers (3, 16, 18). Sprague (21) found that greater height was a significant factor in freestyle and not significant in breaststroke, backstroke or butterfly performance.

Bloomfield (8) and Cureton (13) reported that elite swimmers possessed greater values for shoulder flexibility in comparison to lower level performers. A wide range of movement around the shoulder joint has been reported to permit arm clearance in freestyle, without the need for compensatory body movements which increase frontal resistance (12, 14). Increased shoulder flexibility was not a significant factor in the freestyle analysis in this study.

b. Butterfly Performance

Table IV shows that arm flexion/extension flexibility; subscapular, suprailliac and triceps skinfolds; body density; percent body fat and endomorphy were significant in the butterfly analysis.

A high degree of shoulder flexibility in butterfly would presumably allow the arms to be positioned in a better

<table>
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<tr>
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<tr>
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<tr>
<td>PWC₁₇₀</td>
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</tr>
<tr>
<td>Triceps Skinfold</td>
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</tr>
<tr>
<td>Subscapular Skinfold</td>
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</tr>
<tr>
<td>Suprailliac Skinfold</td>
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</tr>
<tr>
<td>Body Density</td>
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</tr>
<tr>
<td>Percent Body Fat</td>
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<tr>
<td>Standing Height</td>
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</tr>
<tr>
<td>Body Mass</td>
<td>.0736</td>
</tr>
<tr>
<td>Endomorphy</td>
<td>.3380*</td>
</tr>
</tbody>
</table>

* Significant at the 0.05 level of confidence.
A correlation coefficient of 0.211 was required for significance.
"catch" position to created more efficient propulsive forces. In addition, ample range of movement around the shoulder girdle would keep frontal resistance to a minimum in butterfly performance (11, 12). The amount of resistance encountered by the body is dependent upon the amount of water that has to be pushed out of the way as the swimmer moves forward and the speed at which a swimmer moves. The resistance is therefore proportional to the cross-sectional area of the swimmer and increases by a multiple factor as swimming speed increases. To reduce frontal resistance in butterfly the competitor aims to remain streamlined by assuming a narrow, horizontal position in the water. The negative correlation for shoulder flexibility indicated that higher values for this characteristic would assist in achieving this task.

Although the individual measures of subscapular, suprailiac and triceps skinfolds were significant, the discussion of body composition will focus on the computed variable of percent of body fat. This characteristic correlated positively with performance, implying that high fat values were associated with slower performance times. Although body fat may assist floatation while swimming, the detrimental effect would appear to outweigh the advantage, particularly in events of short duration (17, 21). The results of this study also found that high percent body fat hinders performance possibly because adipose tissue plays a minimal role in energy production and a greater workload would be created by possessing additional frontal resistance for swimmers and impair efficient functioning of the cardiovascular system (10).

The mean percent body fat value for males and females in this sample (15.1%) was similar to that presented by Bagnall and Kellett (4) (16.8%) from a study of 21 male and female swimmers, aged 13-19 years. The time difference between the two studies could explain the minor variations in body fat values because swimmers today are training with an increased intensity and total workloads are higher. This could explain the trend towards lower fat values in younger subjects.

The endomorphic (fat) component of the somatotype rating in swimmers appears to have been decreasing over the last 20 years as the majority of American College swimmers are now ecto-mesomorphs (22). Mesomorphy (muscle) is still the dominant component, however the most consistent aspect of the swimming somatotype is a low rating of 2 for endomorphy (15). The low endomorphic and high mesomorphic ratings reflect the high proportion of lean body tissue possessed by the elite performer. Bloomfield (8) reported that national level competitors possessed a higher specific gravity in comparison to lower level performers. The results of this study support the finding that low body fat and high proportions of lean body tissue are advantageous in butterfly performance.

Although greater arm extension strength was reported to be characteristic of butterfly competitors in comparison to other stroke specialists (9), this variable discriminator was not significant, and nor were other strength measures in these young swimmers.

2. Relationship between Selected Anthropometric Ratios and Performance

Table V shows the relationship between freestyle and butterfly performance ratios and raw data from selected anthropometric variables. The correlation coefficients which resulted when these variables were divided by standing height and correlated with performance are presented in Table VI.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Correlations</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
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<td></td>
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<td>Butterfly</td>
<td></td>
</tr>
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<td>Upper Limb Length</td>
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<td></td>
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<td>Thigh Length</td>
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<td></td>
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<td>Foreleg Length</td>
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<td>Bicromial Width</td>
<td>-2.486*</td>
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<tr>
<td>Hip Width</td>
<td>-2.350*</td>
<td>-1.909</td>
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</tr>
<tr>
<td>Chest Depth</td>
<td>-2.695*</td>
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<tr>
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<td>Calf Girth</td>
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<tr>
<td>Stem Length</td>
<td>-2.983*</td>
<td>-3.253*</td>
<td></td>
</tr>
</tbody>
</table>

* Significant at the 0.05 level of confidence.

Correlation coefficients of 0.189 and 0.211 were required for significance in freestyle and butterfly respectively.

a. Freestyle Performance

Femoral bicondylar width and stem length were significant discriminators in performance of the 100 metre freestyle analysis.

In an investigation of the relationship between various anthropometric measures and performance, Helmuth (16) reported that shoulder width and chest girth correlated significantly with 100 metre freestyle times. Sprague (21) also concluded that bicep girth correlated significantly with freestyle performance. Each of these variables however, were not significant in this study, nor were the other girth and width measures, other than femoral bicondylar width. Although Bloomfield (8) contended that,
with senior level swimmers, a high brachial and crural index could be advantageous in providing a larger paddle arm and a greater kicking speed, the indices and anatomical length measures were not significant in this study.

The positive correlations for femoral bicondylar width and stem length demonstrated that smaller scores for these characteristics could be advantageous in freestyle performance. There was no other study found to support or refute these findings.

b. **Butterfly Performance**

Femoral bicondylar width and stem length were significant in the butterfly analysis, as were the measures of lower limb and thigh lengths. Although Spurgeon and Sargent (22) reported that a long stem length was characteristic of senior butterfly competitors, a short stem length and long legs appear to be advantageous for successful butterfly performance in younger swimmers in this study. The significant negative correlations for lower limb and thigh lengths (Table VI) reflected the importance of these variables, but other anatomical length measures were not significant.

Bloomfield and Blanksby (9) also noted that leading butterfly competitors possessed a large chest depth.

Results in the present study however, demonstrated that this independent variable does not contribute significantly to performance.

c. **Multiple Regression Analysis**

Significant variables from Tables III, IV and VI were entered into a stepwise regression analysis to generate prediction equations for freestyle and butterfly performance.

The results of the freestyle regression demonstrated that 20.29% of the variance in performance could be accounted for by thigh flexion strength, FEV̇₁, triceps skinfold, and femoral bicondylar width. In butterfly, the variance accounted for in the above variables amounted to 19.8%.

Although several studies have shown that a number of anatomical and physiological variables were characteristic of swimmers who competed in different strokes and events (4, 9, 22), this study demonstrated that the independent variables included as possible predictors of performance, contributed only a small portion of the total variance in freestyle and butterfly performance. This highlights the need to investigate whether there are better tests which provide a greater relationship with swimming performance; whether the group is too homogeneous and swimmers ranging from elite to poor should comprise the sample; whether training backgrounds and efficiency in water can be better studied; or whether the complex make up of the human competitor enables many different combinations of physical and psychological characteristics to achieve success in swimming.

### Coaching Implications

The results of this study suggest that for elite young freestyle swimmers:

1. It is advantageous to possess larger pulmonary function measures such as FVC, FEV₁, and peak air flow.
2. Greater thigh flexion strength contributes significantly to performance.
3. Aerobic power as measured by a PWC₁₇₀ test is not a significant discriminating factor between swimmers in short distance events.
4. Being taller than other children competing in the same age group was not an advantage in Freestyle and Butterfly.
5. High levels of shoulder flexibility are not essential for successful performance.
6. Short stem lengths in these young swimmers was related to high level performances, despite the fact that past research has indicated that mature swimmers possessed greater stem lengths.

It was also concluded that for elite young butterfly swimmers:

1. High levels of shoulder flexibility contributed significantly to performance.

### TABLE VI

<table>
<thead>
<tr>
<th>Variables</th>
<th>Freestyle</th>
<th>Butterfly</th>
</tr>
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<tbody>
<tr>
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</tr>
<tr>
<td>Stem Length</td>
<td>.1930*</td>
<td>.2137*</td>
</tr>
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</table>

1. All variables in Table VI were divided by standing height to form ratios.

* Significant at the 0.05 level of confidence.

Correlation coefficients of 0.189 and 0.211 were required for significance in freestyle and butterfly respectively.
2. Greater body density and lower percent body fat measures were advantageous to high level performance.

3. A lower endomorphy (fat) rating was important for successful performance.

4. A short stem length and longer lower limbs assisted performance in these age group swimmers despite the fact that other investigators have found long stem lengths and short extremities to be characteristic of mature high level performers.

5. A larger chest depth, which was identified by other investigators as a characteristic of mature butterfly competitors, was not a significant contributor of high level performance in these age group swimmers.

References


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3. TEXT—The text should contain separate sections for the:
   a. Introduction. This section should state the purpose, the rationale, and the essential related literature.
   b. Methodology. This section should include a clear description of the experimental subjects and their controls. The description of the methodology should provide enough detail for others to duplicate the study. References should be provided for established methods and statistical procedures. Non-established methods and statistical procedures should be supported with rationale.
   c. Findings. The findings presented in the text, tables, and figures should follow a logical and parallel sequence. The statistical significance of appropriate results should be acknowledged.
   d. Discussion. This section should emphasize the study's important and original aspects while avoiding a repeat of data presented in the findings section.
   e. Conclusions. The author should provide conclusions supported by their data. This section of the manuscript is of particular importance to the purpose of the journal. It should be of at least 500 words in length and provide: in simple, laymen, terms; an interpretation of findings and implications to the on-deck coaching and training of swimmers.

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