Energetics of underwater swimming with SCUBA

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Abstract

Underwater swimming has unique features of breathing apparatus (SCUBA), thermal protective gear, and fins. The energy cost of underwater swimming is determined by the drag while swimming and the net mechanical efficiency. These are influenced by the cross-sectional area of the diver and gear and the frequency of the leg kick. The speeds that divers

can achieve are relatively low, thus the $\dot{V}O_2$ increases linearly with values of $\dot{V}O_2 \cdot d^{-1}$ of 30-50 $l \cdot km^{-1}$ for women and men, respectively. Diving experience had little effect on $\dot{V}O_2$ for women; however, male divers with experience had lower $\dot{V}O_2$ than beginners. The location and density of the gear can alter the diver's attitude in the water and increase the energy cost of swimming by 30% at slow speeds. The type of fin used has an effect on the depth and frequency of the kick, thus on drag and efficiency, with a range of $\dot{V}O_2$ from 25 to 50 $l \cdot km^{-1}$. A large flexible fin had the lowest energy cost and a large rigid fin the highest. Adding extra air tanks or a dry suit increased the cost of swimming by 25%. The energy cost of underwater swimming is influenced by gender, gear and its placement, fin type, and experience of the diver.

Swimming underwater presents the swimmer (diver) with several unique physiological problems (12). The first problem is that if the time of the dive exceeds breath-holding time, a source of ventilation has to be provided. The second problem is that the diver's body is exposed to a pressure that is proportional to the depth. To allow the diver to extend this depth and adjust automatically to changing depths, a self-contained underwater breathing apparatus (SCUBA) is typically used. This apparatus provides gas from a cylinder, carried on the diver's back, through a regulator to the lung at a pressure that compensates for the diver's water depth. It is important to recognize that hydrostatic pressure compresses gas volumes while not compressing fluid volumes. In general, man is positively buoyant when the lungs are full; therefore, the diver must carry weights that will allow him to "sink" underwater. The magnitude of the weight is dependent upon the positive buoyancy of the diver and his gear.

Diving is often carried out in water temperatures well below the thermal neutral water temperature of the individual, requiring the diver to wear a protective suit to provide additional insulation. As the water temperature and thermoneutral temperature of individual divers are variable, the type of protective suit needed also varies. The most widely used suit is a wet suit, which is tight fitting and usually made of neoprene. This suit provides insulation; however, it also increases the positive buoyancy of the diver and must be counterbalanced with weight.

Swimming underwater prevents the over-water recovery that is typical of surface swimming where propulsion is primarily provided by the arms. Therefore, during underwater swimming, propulsion is generally provided totally from a flutter type leg kick. Divers use fins to increase the surface area and allow effective propulsion, at least at slow speeds. Swimming fins have different physical characteristics, resulting in differences in propulsion effectiveness. Due to the extra equipment needed for underwater swimming, the water resistance (drag) may be greater than for surface swimming. In addition, the placement of the equipment could alter the swimmer's body position in relation to the horizontal (attitude) in the water and consequently, the drag. The swimmer's speed will affect the energy requirement. The swimmer's technical ability (skill) can significantly alter the energy cost of swimming (3,4,18). The energy requirement of underwater swimming would determine the potential time the diver could remain underwater since he is breathing from a fixed volume(size and pressure of the tank).

The specific purpose of this article is to present selected factors that influence the energy cost of underwater swimming with SCUBA. The gear that was used in this study is typical of a sport diver and includes a mask, regulator, single tank, whole wet suit, fins, a deflated vest type positive flotation device, and weights placed at the waist. It is not the purpose of this article to evaluate the effectiveness of the gear from different manufacturers; however, reference is given to the physical characteristics of some of the gear studied. The experiments cited were conducted in thermoneutral temperature water. Although body cooling does affect the energetics, this is not the topic of this paper. As the unique nature of the environment and swimming affects the energetics, a discussion of the methods used of measuring precedes the section on the factors that may influence the energetics.

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METHODS

Swimming is a unique form of exercise; however, the energetics can be expressed by the typical equations. Specifically:Equation

By equating units and rearranging these two equations, it can be shown that: Equation

The ratio of Db and e can be used as an expression of the technical ability or skill of the diver. This may also be expressed as the energy cost to swim a given distance ($\dot{V}O_2 \cdot d^{-1}$).

The velocity of swimming can also be expressed as:Equation

The distance traveled per kick ($d \cdot S^{-1}$) is determined, in part, by the propulsive force per kick, which is influenced by the type of fin, the diver's skill and the depth of the kick.

Using these simplified equations, one could measure the energy cost of swimming and understand its determinants by measuring Db, e, kick frequency, and kick depth. These parameters could then be used to evaluate the effects of various swimming styles, equipment or equipment placement on the energetics of swimming.

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Energy Cost

The energy cost of terrestrial exercise and surface swimming can be assessed by open circuit measurement of oxygen consumption. The“anaerobic component” can be estimated from measurements of lactic acid (3,4). It should be recognized that there are difficulties in determining the anaerobic component from either muscle or blood lactic acid (1). Even the aerobic component is difficult to measure in underwater swimming as the diver is not only underwater and breathing compressed gas, but is also moving. Previous studies have used the difference in bottle pressure at the beginning and end of a swim(12,13) as a means to estimate oxygen consumption. No measurement of ventilatory volume and carbon dioxide output can be made using this technique. We devised a bag-in-box system to determine the energy cost of swimming to be used while the diver was paced at set speeds(Fig. 1).

Divers swam at a depth of 1.25 m in a 2.5 m deep annular pool (58 m in circumference). The divers followed a pacing mark, which was moved at a fixed and predetermined speed by a monitoring platform attached to a rotor. The breathing system was attached to the monitoring platform as shown inFigure 1. The breathing system was placed in parallel with the SCUBA breathing gear via a two hose demand regulator. The inspiratory hose was connected to the supply bottle via the pressure regulator. The expiratory hose was connected to a rigid tube (2-inch PVC), which went to the monitoring platform. This tube was connected to a valve that directed its flow either back to the expiratory side of the regulator (when not collecting) or to a bag(Douglas) placed inside a box (55 gallon drum) when collecting. During collection, the gas going into the bag displaces the gas in the drum (which is at the same pressure as the diver) and is exhausted through the expiration side of the regulator. Expired gas was collected from 1 to 3 min during the steady state of each fixed speed swim. The speeds were progressively increased. After each swim, the diver was isolated from the bag-in-box and the bag was emptied (using the pressure in the drum) through a dry gas meter. Samples of gas temperature, O_2 and CO_2, were made. The ventilation, oxygen consumption, carbon dioxide output, and expiratory gas exchange ratio were calculated using standard equations.

Previously, the bag-in-box method was validated by comparing the ventilation obtained by this technique and standard open circuit techniques during cycling and swimming. The relationship between $\dot{V}_E$ versus $\dot{V}O_2$ for the bag-in-box system and the open circuit technique were not significantly different from each other (ANOVA repeated measures,$P >$ 0.05). The bag-in-box system would appear to be a valid method of determining gas exchange from submerged divers. The data reported in this paper used this method.

The bag-in-box method was used on subjects that were basic (inexperienced), sport (1 yr experience), advanced (>5 yr of diving), and professional (for at least 3 yr) divers. The $\dot{V}O_2$ increased linearly as a function of swimming velocity for all groups. The advanced divers had the lowest $\dot{V}O_2$, followed by the sport, then the basic. Interestingly, the professional divers had the highest $\dot{V}O_2$. This observation was surprising;

however, the professional divers rarely swam in their jobs and were most likely similar to the basic divers in this regard. As $\dot{V}O_2$ increased linearly with v, the data can be expressed as the $\dot{V}O_2 \cdot d^{-1}$.

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RESULTS

The energy cost of surface swimming has previously been shown to be less in women than men, even after correction for body size (18). This difference has been attributed to the differences in body density of the two genders, particularly in the lower extremities(14,17,18). Data for advanced, sport, and basic are shown in Figure 2. The female divers had significantly lower energy cost than the male divers for all skill levels. Although the male sport and basic divers had greater $\dot{V}O_2$ than the advanced divers, these differences were not seen for the female divers. These data would suggest that the body position in the water (attitude), as it affects the effective cross-sectional area, is very important and may be learned during diving training. This further suggests that the placement of buoyant and sinking forces may have a significant effect on the energy cost of swimming. From the practical point of view, when male and female divers are swimming together, the male divers will consume more oxygen, and therefore gas, resulting in shorter dive times.

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Drag and Efficiency

In previous studies, the body drag during swimming(3,22) was determined by towing subjects through the water at increasing speeds. The force measured by a strain gauge was assumed to be equal to body drag. This measurement has become known as passive drag. The drag can be expressed as: Equation

where k is a constant, C_D is the coefficient of drag, p is the density of water, and A is the effective cross-sectional area.

The C_D (dimensionless) determined in the annular pool for a group of 12 male and female subjects (of varying sizes) who were towed in the prone position was 1.12 ± 0.06. Studies using photographic technique (strobe light) in a linear pool (22) yielded C_D values for the same group of subjects of 1.08 ± 0.04. The C_D values determined in the annular pool and the linear pool were not significantly different from each other (ANOVA for repeated measures $P > 0.05$). By calculation the correction force necessary to turn in a circle with the circumference of our annular pool would be less than 1%, which would agree with the comparisons of the C_D measured by the two techniques.

The results of the experiments to determine passive drag demonstrated that being towed at the surface has the greatest drag and towed at 1.25 m the least. Being towed at 0.6 m from the surface or at the bottom of the pool were not significantly different from each other, i.e., less than at the surface and more than at 1.25 m. This demonstrates the effect of the free surface(water surface or pool bottom) in increasing body drag. This also shows that when underwater swimming, one should stay greater than 0.6 m from all surfaces. In another series of experiments, subjects were towed prone and supine. The C_D for these conditions were 1.06 and 1.04, respectively. Body orientation would not appear to affect drag in an infinitely deep pool.

These values of passive drag are of interest when examining the effects of fixed aspects of gear or the environment. However, as the subject swims, the legs “open” and “close” with the kick, resulting in changes in the effective cross-sectional area and, therefore, drag. The drag can be expressed as an “effective” average drag (active drag). As has been previously shown for surface swimming, drag while swimming (active drag) is greater than passive drag (3). There could be an even greater effect during underwater swimming. To examine the active drag D, we used a method that we previously published for swimming(3,4). This method allows the calculation of body drag, efficiency, and the total energy cost of swimming (aerobic and anaerobic) while actually swimming. In principal, the subjects swim at a constant speed (paced by the monitoring platform, Fig. 1) towed by a vertical force (-DA) which is attached to the platform and then to the subject by a series of pulleys. Part of the subject's active body drag is overcome by the -DA, and consequently, the subject has to provide less propulsive force. The subject's $\dot{V}O_2$ is proportional to the propulsive force. By plotting the $\dot{V}O_2$ vs. the -DA, a linear slope is found. The slope of this line is the inverse of net mechanical efficiency. Extrapolation of this line to resting $\dot{V}O_2$ is the body drag. Extrapolation of this relationship to the y-axis yields the total energy cost of swimming at that speed. This technique has previously been validated for surface swimming (3,4) and we assume the validation holds for underwater swimming. This technique has the advantage that energy cost, regardless of mechanism (aerobic and/or anaerobic), can be estimated from submaximal $\dot{V}O_2$ data collections. This avoids the controversies regarding the meaning of muscle and blood lactic acid.

The values for the active drag are significantly greater than for the passive drag and the shape of the curve is different. In active diving, the drag is very high at low speeds (for each group), decreases at medium speeds, and then increases at higher speeds. The reason for these differences can be seen from an examination of kicking frequency and depth. At low speed, the diver used a slow and wide kick (high drag). At medium speed, the diver increased the kicking frequency and his kick became more narrow (less drag). At high speed, the frequency was high and the depth of the kick wide (high drag). If this analysis is correct, we would expect a high efficiency(10,15) when the frequency was low (low and high speed) and a low efficiency where the frequency was high (medium speed). This is what was observed.

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Effect of Body Position

Body size and shape play an important role in determining the energy cost of surface swimming and undoubtedly underwater swimming. However, swimming technique and the distribution of body mass have been shown to be more important factors (2,11,14,15). Subjects supine at the water surface rotate about the mid-thorax ("center of air") with a torque that is determined by their mass and its distribution along the long axis of the body. In these experiments, as torque increased, the energy cost of swimming increased proportionally(11,14,15).

As discussed above, the effective cross-sectional area has an effect on drag. The effective cross-sectional area was shown to be affected by kick depth and velocity. These effects would be altered by the attitude of the diver. The application of these data to SCUBA swimming is even more interesting than surface swimming, due to the potential effects of the gear on torque. To test this hypothesis, men SCUBA divers were studied. Precalibrated lead weights of known mass were applied to each subject by means of a weight belt. The six experimental configurations were delineated in the following manner: Condition 1) 44 N at the "center of air," 2) 0 N at the"center of air" and 44 N on the waist (normal configuration), 3) 44 N on the waist and 22 N on the knee, and 4) 44 N on the waist and 22 N on the ankle. Subjects' "center of air" and torque were determined experimentally through a method of underwater weighing (seeFig. 3).

The rotational forces about the "center of air" (torque) for the weight placements used in this study are shown in Figure 3.

The subjects were firmly attached to a frame (0.7 m × 2.4 m) by quick-release belts and submerged 10 cm below the water surface while breathing through SCUBA gear. The frame and subject were supported by a fulcrum placed under the "center of air." Force was measured by a strain gauge (LVDT) at the "foot" of the frame. The "center of air" was determined for each subject by positioning the fulcrum at the point where variations in lung volume affected foot force the least. Torque (Nm) was calculated as the product of foot weight and the distance between the strain gauge attachment and "center of air." This system measured the "tendency of the feet to sink" from the horizontal position by determining the force necessary to maintain a horizontal position in the water. As weight was progressively redistributed away from the "center of air" and toward the ankle, there was a progressive increase in torque. The maximal value of torque was observed when 44 N was added to the waist with an additional 22 N on the ankles.

The energy cost to swim a given distance is plotted as a function of swimming speed in Figure 4. The $\dot{V}O_2 \cdot d^{-1}$ was greatest at the slowest speed studied and not significantly different between the two faster speeds. The effect of changing torque was to increase the $\dot{V}O_2 \cdot d^{-1}$, particularly when the torque was increased by adding weight to the knee and/or ankle.

The torque of the body, plus equipment, causes the body to rotate about the"center of air." Thus, the greater the torque, the less horizontal the subject is in the water. The deviation from the horizontal increases drag unless the subject kicks harder to keep the body horizontal, which would result in reduced efficiency and increased $\dot{V}O_2$. At the slow speed, reducing torque resulted in an attitude in the water that was closer to horizontal than conditions with increased torque (28° and 35°). At the faster speed, there were no significant differences between the weight placements. This may be due to the fact that at the faster speeds, the angles were less than at the slower speeds (29° and 22° vs 35°) and the torque-dependent effect was minimized.

The energy cost of underwater swimming was dependent upon both speed(2,5,6,7,9,13,15,16,20,21) and weight placement (11). This is important for divers swimming at slow speeds, where the rate of energy requirement is not important; however, the total cost is. The $\dot{V}O_2$ increased with speed; however, the $\dot{V}O_2 \cdot d^{-1}$ was greatest at the slowest speed (0.16 $l \cdot km^{-1}$ to 0.22 $l \cdot km^{-1}$) and similar at the two faster speeds (0.14 $l \cdot km^{-1}$ to 0.17 $l \cdot km^{-1}$ and 0.14 $l \cdot km^{-1}$ to 18 $l \cdot km^{-1}$, respectively). For longer distances, it would appear that one could conserve energy by swimming at 40.8 $m \cdot min^{-1}$, instead of 30.4 $m \cdot min^{-1}$ or 53.4 $m \cdot min^{-1}$. This effect was true at all levels of torque.

Propulsion in fin swimming is achieved by a combination of the force per kick, which is related to the depth of the kick, and the frequency of kicking. With the weights placed at the waist, the subjects had a kick frequency of 39 $k \cdot min^{-1}$, 47 $k \cdot min^{-1}$ and 59 $k \cdot min^{-1}$ and a depth of 40.6 cm, 46.4 cm and 43.2 cm at speeds of 30.6 $m \cdot min^{-1}$, 40.8 $m \cdot min^{-1}$ and 53.4 $m \cdot min^{-1}$, respectively. Swimming speed is increased, in part, by increasing kick frequency (about 0.8 kicks per m·min^{-1}). As speed was increased from 30.6 m·min^{-1} to 40.8 m·min^{-1}, kick depth increased; however, at the faster speed, the depth could not be sustained due to the higher kick frequency and, therefore, the depth decreased (35.6 cm, 45.7 cm, and 42.3 cm, respectively).

The effect of weight placement on kick frequency and kick depth was velocity-dependent. At the slowest speed where there was freedom to alter kick frequency and kick depth, reducing torque resulted in a decrease in both kick frequency (39 k·min^{-1} to 33 k·min^{-1}) and kick depth (40.6 cm to 21.1 cm). At the two faster speeds, there were no significant differences between the values. Increasing torque did not significantly affect either kick frequency or kick depth.

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Fin Selection

As described above, the subjects' kicking frequency and depth of kicking with fins determines their propulsive force, velocity, and therefore their $\dot{V}O_2$. In addition, SCUBA swimming also may require stabilization in the water, towing objects, swimming fast away from or toward something in an emergency, and/or swimming to conserve energy (12). The fin characteristics would alter the divers' performance and their resultant energy cost. Many types of fins are available and used routinely. Divers' fin preference is largely subjective. Despite manufacturer's claims, little data are available to evaluate the effectiveness of fins to meet the performance needs of the divers.

Previous studies have reported the energy cost of swimming with fins against a tether (16), free swimming at various speeds(5,6,10,13,20), or free swimming against a drag device (7,19). When combined, these data demonstrate a $\dot{V}O_2$ of about 0.8 l·min^{-1} at 15 m·min^{-1}, increasing with speed up to 2.5 l·min^{-1} at 30 m·min^{-1}. In another study, the relationship between $\dot{V}O_2$ and speed of fin swimming showed that the surface area of the fin was inversely related to the $\dot{V}O_2$ and that the maximal swimming speed was directly related to fin flexibility. High levels of $\dot{V}O_2$ are achieved in elite divers swimming against maximal tethering, up to about $4.0\ l \cdot min^{-1}$.

Studies using commercially available fins with different characteristics of size, weight, flexibility, and material composition are presented. A comparison of the effects of fin type selection on the energy cost of swimming for males appears in Figure 5. The data for the male divers failed to show a significant difference among the 10 fin types while swimming. The data for the female divers demonstrated significantly lower(20%) energy cost of swimming than men. For women, the small, very flexible fin (D) required less energy to swim ($30\ l\ O_2 \cdot km^{-1}$ vs. $32\ l\ O_2 \cdot km^{-1}$,$33\ l\ O_2 \cdot km^{-1}$,$34\ l\ O_2 \cdot km^{-1}$,$35\ l\ O_2 \cdot km^{-1}$ and $39\ l\ O_2 \cdot km^{-1}$ for D vs A-V, C, B-V, A, and B, respectively). The vented fins (A-V, B-V) were less costly than the unvented fins (A, B). The least effective fin for the females was the large, rigid fin (B).

The frequency of leg kicking during steady state swimming was not significantly different between the 10 fins for males or females. The average value for kick frequency for all males and females was $42 \pm 2\ k \cdot min^{-1}$. The relationship between the energy cost of swimming per unit distance and kick frequency was not statistically significant.

The average maximal speed that could be sustained for 58.6 m using the fins studied was greater for the men than for the women ($1.29 \pm 0.32\ m \cdot s^{-1}$ vs $1.24 \pm 0.16\ m \cdot s^{-1}$ respectively). The speeds for males with all unvented fins were not significantly different from each other. However, the vented fins (A-V, B-V, E, F) were significantly slower when compared to their unvented counterparts. For the females, the medium, rigid fin (A) was the fastest. However, a medium, moderately flexible fin (C) achieved a similar speed. The vented fins (A-V, B-V) and a large, rigid fin (B) had the slowest speeds for females.

The maximal force that could be generated by males was with the medium and large, rigid, unvented fins (A, B), with significantly lower maximal forces generated with the vented fins (A-V, B-V), the medium, moderately flexible fin(C), and the small, very flexible fin (D). For the females, the vented fins(A-V, B-V); the large, rigid fin (B); the medium, moderately flexible fin (C); and the small, very flexible fin (D) were not different from each other and produced lower maximal force than a medium, rigid fin (A). The decrease in force over the 40 s of the swim was not significantly different among the fins or between the genders and averaged 12.5% ± 3.8% of the maximal force.

Evaluation of the kick frequencies used for each fin during the tethered maximal force swim showed that for the males, the medium, moderately flexible, vented fin (A-V) and the small, very flexible fin (D) had the greatest frequencies, followed by the medium, moderately flexible, vented fin (B-V) and the medium, moderately flexible fin (C). The medium and large, rigid fins (A, B) had the lowest kick frequencies. For the females, the medium and large, rigid fins (A, B) had the lowest frequencies, while the same fins vented, the medium, moderately flexible fin (C) and the small, very flexible fin (D), were significantly higher.

Subjectively, the males and females preferred a large, rigid fin. There was no systematic preference for the vented fins. The medium, moderately, or very flexible fins had the most comfortable foot pockets.

There was a significant difference in weight between the two pairs of heavy fins and the two pairs of light fins (C and D, A and B, respectively). Swimming with one of the heavier fins (D) produced a lower $\dot{V}O_2$ than a lighter fin (B), indicating that the weight of the fin did not alter the divers' $\dot{V}O_2$ at either speed. Similarly, the presence of vents did not appear to affect $\dot{V}O_2$. At 30 $m \cdot min^{-1}$, two pairs of fins (vented (A) and unvented (B)) produced a significantly lower $\dot{V}O_2$.

Propulsion is a product of kick frequency, kick depth, and force per kick. Force per kick was not measured in this study. There were no significant differences in the kick depth for any of the fins at either speed or between speeds (43.18 ± 12.7 cm). Kick frequency was higher at 40 $m \cdot min^{-1}$ than at 30 $m \cdot min^{-1}$ for all fins (46± 7 $k \cdot min^{-1}$ vs 35 ± 5 $k \cdot min^{-1}$, respectively). The heavy, very flexible fin (D) produced a significantly lower kick frequency (31 ± 7 k·min^{-1}) than the other fins, which were not significantly different from each other (35 ± 5 k·min^{-1}).

One of the advantages of the present study was that the expired ventilation, carbon dioxide production, and $\dot{V}O_2$ could be determined. The $\dot{V}_E/\dot{V}O_2$ ratio was not significantly different among fins or speeds and averaged 19.52 ± 1.98. The expiratory gas exchange ratio ($\dot{V}CO_2/\dot{V}O_2$) was not significantly affected by fin type or speed and averaged 0.87 ± 0.24, although the range among the subjects was 0.77-0.96. The ventilatory equivalent of 19 is less than reported for exercise in air, 25. This suggests some CO_2 retention, producing an R value less than RQ. The faster speed used for steady state swims was 75% of the maximal speed, which is below the threshold where the $\dot{V}_E/\dot{V}O_2$ ratio would increase due to lactic acid in the blood (4).

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Effects of Other Gear

The experiments described above were conducted using standard sport diving gear. Divers that prolong their diving time may use dual gas tanks. As the energy cost per unit distance of swimming at slow speeds is quite high, the addition of a second tank had little effect. At faster speeds however, the effect became pronounced as the second tank and its position significantly increased drag and, therefore, $\dot{V}O_2$. Similar results were seen when the divers wore a dry suit. There was no effect on $\dot{V}O_2$ at the lowest speed; however, it did have a significant effect at the faster speed. The conclusions from the present study are in agreement with previous studies for wet (5,7,10,13,15,22) and dry suits (19). It would appear that the data from the present study are more accurate due the method of collection and direct comparison for individual subjects.

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CONCLUSIONS

The data presented in this article demonstrated that the energetic analysis used previously for swimming can also be applied to underwater swimming. The method of measurement of ventilation, oxygen consumption, and carbon dioxide production is a valid measurement. The data for ventilation during underwater swimming demonstrated a relative hypoventilation when compared with terrestrial locomotion.

The oxygen consumption for underwater SCUBA swimming was affected by the placement of the weight belt that was used to counterbalance the buoyancy created by the gear worn by the diver. To minimize the energy cost of swimming, divers should strive not only for neutral buoyancy but also equipment placement that keeps them in a horizontal position in the water. The energy cost of swimming for women was significantly less than that for men, even after correction for body size. However, this difference disappears when the men adjust their body position to be more horizontal by appropriate placement of their diving weights.

The oxygen cost of swimming at a given speed is determined by the ratio of active drag and overall net mechanical efficiency. Active drag and efficiency are influenced by speed ($Db = kv^2$) and the body position in respect to horizontal as well as the depth of the kick. Mechanical efficiency was shown to be related to the kicking frequency. Divers should determine a balance between kicking frequency and kicking depth (fin exertion) that will minimize drag and maintain efficiency. It is clear from the data presented that swimming skill can influence, to a great extent, the energy cost of swimming and that experienced divers can minimize their energy expenditure. The addition of more gear, like double tanks or dry suits, increases the energy cost slightly at lower speeds. However, at higher speeds, the effects are very large and limit performance.

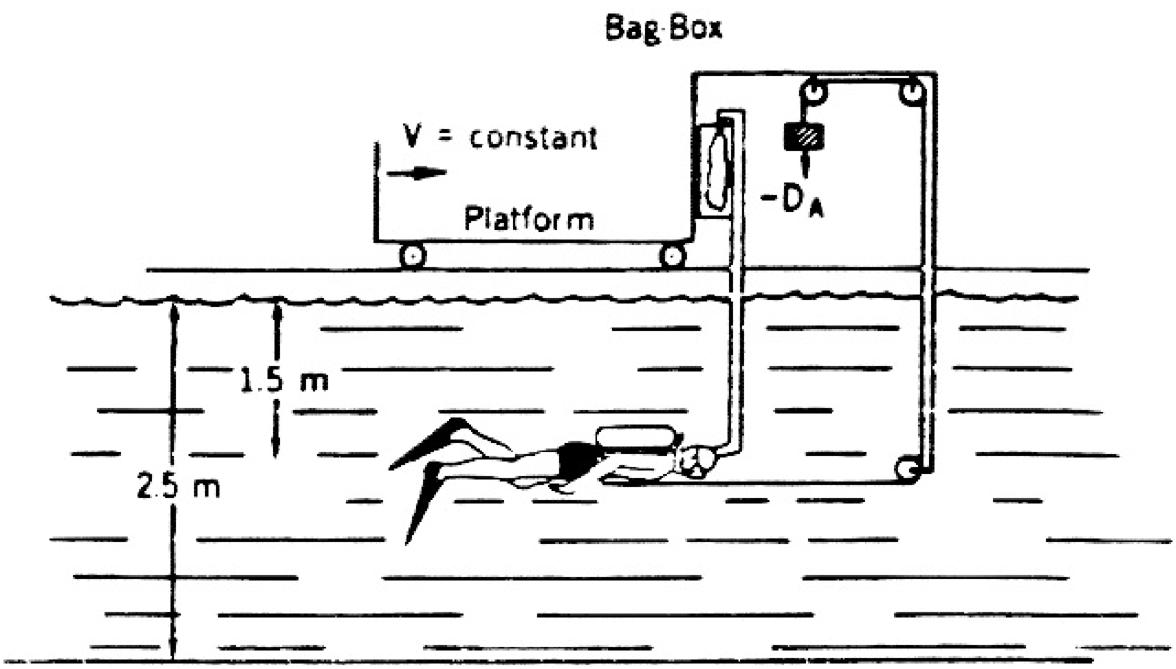
The selection of a fin type to use in diving was shown to be very subjective and based on the swimmers' “feel.” The large rigid fins required a greater force to kick and were preferred by the divers(particularly the men). In fact, the similarity of the energy cost, speed, and force that the fins could generate was more striking than their differences. The large and rigid fins had the highest energy cost; however, they produced the greatest force. This suggests that the best fin selection may be based on the task the diver has to accomplish. For swimming, it would appear that a medium sized and flexible fin would be the best. The new composite material and venting did not seem to have significant effects on the energy cost.

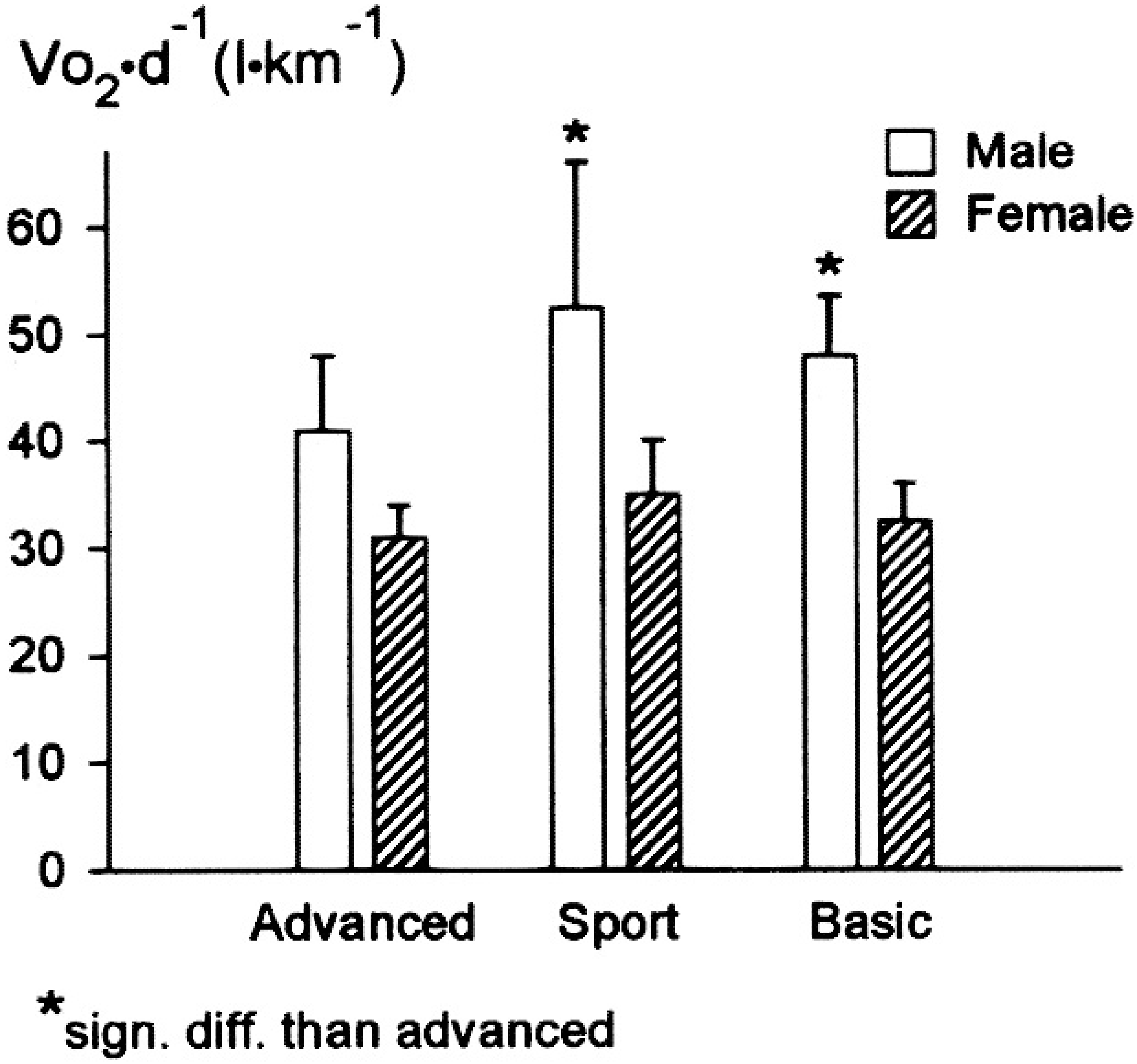
$$\text{Power } (\dot{W}) = \text{Body Drag (Db)} \cdot \text{Velocity (v)}$$

$$\text{Energy Cost } (\dot{E}) = \dot{W} \cdot \text{Efficiency (e)}^{-1}$$

$$\dot{E} = \text{Db} \cdot \text{v} \cdot \text{e}^{-1}$$

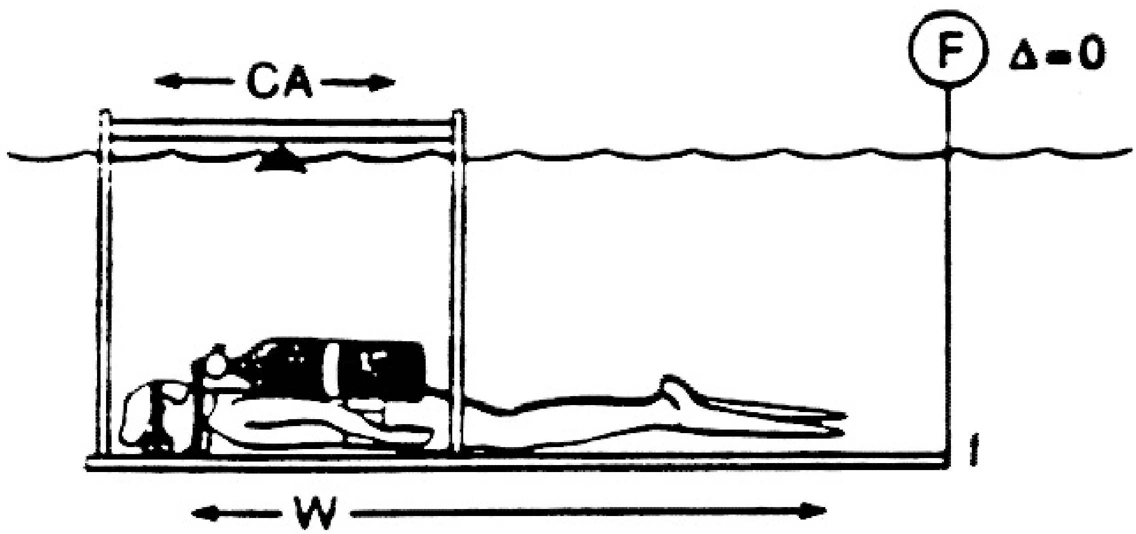
$$\text{v} = \text{Kick rate } (\dot{S}) \cdot \text{distance per kick } (\text{d} \cdot \text{S}^{-1})$$



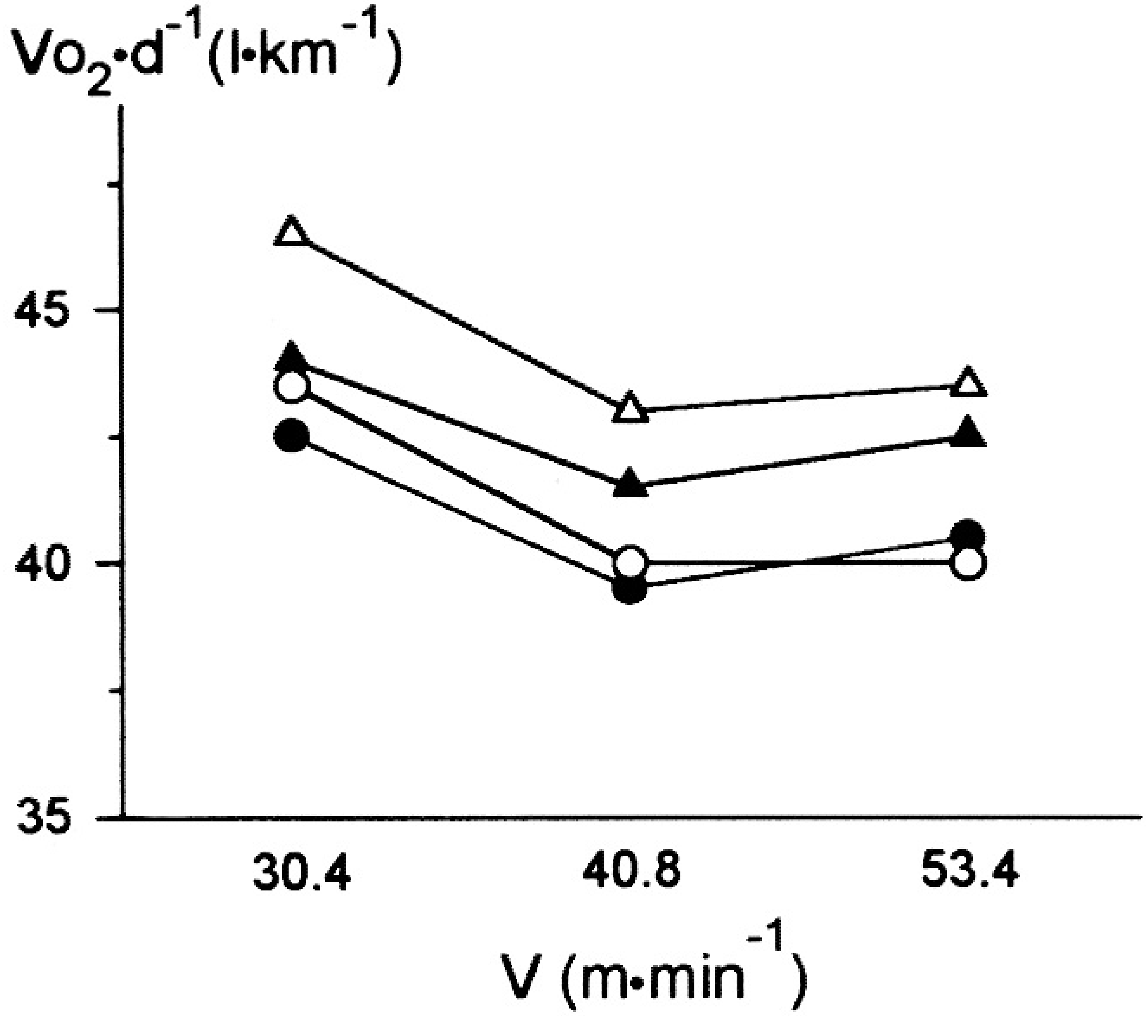


***indicates values that are significantly higher than for the advanced men. The values for the women were significantly less than for the men; however, the values for the three levels of experience in the women were not different from each other.**

$$Db = kv^2 = \frac{1}{2} C_D p A v^2$$



$$\tau = F_f \cdot d_{ca\text{-}f}$$



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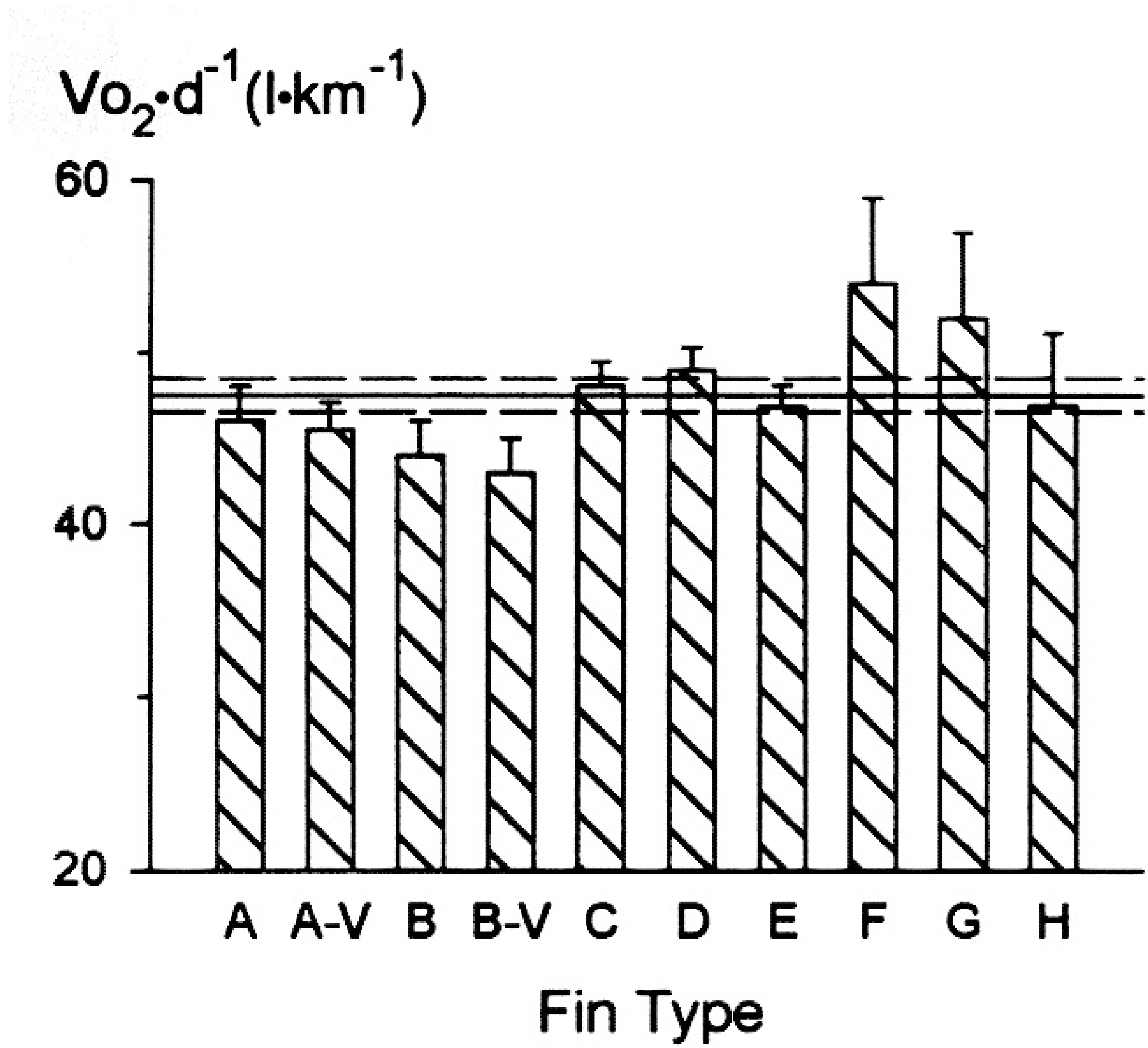

Table 1. There were no significant differences in fin type across all subjects, however the values varied from 43 to 54 l·km-1. Fins with vents (A-V and B-V) were not significantly different for the same fin without vents (A and B).

Fin	Weight (kg)	Flexibility	Surface Area (cm^2)	Vents
A	1.59	(rigid)	239	No
A-V	1.14	(mod)	240	Yes
B	1.82	(rigid)	253	No
B-V	1.36	(mod)	235	Yes
C	1.14	(mod)	222	Yes
D	0.90	(flex)	175	No
E	0.98	(rigid)	294	Yes
F	0.98	(mod)	294	Yes
G	1.20	(rigid)	264	No
H	1.23	(flex)	285	No

mod, moderate; med, medium; flex, flexible.

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Section Description

Exercise and Medical Demands of SCUBA Diving

Keywords:

OXYGEN CONSUMPTION; SCUBA SWIMMING; DIVING; DRAG; EFFICIENCY; FINS; BODY DENSITY

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