

The influence of drag on human locomotion in water.

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Pendergast D, Mollendorf J, Zamparo P, Termini A, Bushnell D, Paschke D. The influence of drag on human locomotion in water. *Undersea Hyperb Med* 2005; 32(1):45-57. Propulsion in water requires a propulsive force to overcome drag. Male subjects were measured for cycle frequency, energy cost and drag (D) as a function of velocity (V), up to maximal V, for fin and front crawl swimming, kayaking and rowing. The locomotion with the largest propulsive arms and longest hulls traveled the greatest distance per cycle (d/c) and reached higher maximal V. D while locomoting increased as a function of V, with lower levels for kayaking and rowing at lower Vs. For Vs below 1 m/s, pressure D dominated, while friction D dominated up to 3 m/s, after which wave D dominated total D. Sport training reduced the D, increased d/c, and thus lowered C and increased maximal V. Maximal powers and responses to training were similar in all types of locomotion. To minimize C or maximize V, D has to be minimized by tailoring D type (friction, pressure or wave) to the form of locomotion and velocity.

INTRODUCTION

Although more energetically costly than locomotion on land, man has used locomotion on or in water for thousands of years. Locomotion in water, like swimming, diving, kayaking and rowing are commonly used in occupations or for recreation and competitive sports. On land, the work of locomotion is easily expressed; however, the work that has to be done in water includes that needed to overcome water resistance (drag) called propulsive work and the work that is wasted in accelerating water away from the body (kinetic work), in addition to internal work (38).

The fluid dynamics of laminar flow and turbulent flow are well defined, however, in the transitional flow region, the physics of flow are difficult to understand. It has been shown for surface swimmers that laminar flow ends at the largest circumference of the head and turbulent flow occurs below the knees, and the remainder of the body is in transitional flow (21). About 80% of the hull of a kayak

or shell is also in transitional flow (1). The total drag of the swimmer/boat is comprised of drag from friction between the hull and water, the pressure or form drag created when water is separated to allow the hull to pass through, and wave drag which is a result of accelerating the water away from the body. Whereas the wetted surface area is critical for boats, as it determines frictional drag, in swimmers the frictional component of drag is low and the pressure drag is high. Thus the frontal cross-sectional area is critical (21) and is influenced by the weight in water and the weight distribution of the swimmer, called torque (3, 35, 36).

At a constant speed, the propulsive force developed in aquatic locomotion has to be equal to the drag of the body or boat and body. In actual swimming or paddling the arm/leg movements that develop the propulsion also create drag. Therefore, drag during locomotion (active drag) is significantly higher than the drag measured by towing an object through the water (passive drag). Although passive drag is easily

measured, active drag has only been inferred from metabolic measures. Active drag was estimated by di Prampero et al (10) from the measurement of submaximal oxygen consumption and has been used in many forms of aquatic locomotion (25, 26, 38).

The propulsive force used to overcome the drag is equally as hard to assess as the drag itself. Estimates of the maximal propulsive force of swimming can be made from the waves of transmission down the body (17, 21, 38) and for rowing on theoretical grounds (4). The propulsive force generated by the subject is responsible for the distance the body/boat travels per arm/kick cycle, as originally reported by Craig et al (8). The determination of this distance/cycle (d/c) can be used to estimate the balance between propulsive force and the drag of the hull.

The energy cost of locomotion is reasonably easy to determine over the range of speeds that can be maintained aerobically in aquatic sports; however, determining the anaerobic contribution is significantly more difficult. Indirect methods have been used to determine the rate and capacity of the anaerobic contribution and validated against other methods for running, cycling and swimming (12; 31). We are not aware of data for the anaerobic contribution to the energy cost of other forms of aquatic locomotion.

Based on the physics of locomotion in water and the physiology of man, all forms of aquatic locomotion are expected to follow similar basic rules. An examination of the drag and energy cost of propulsion in water, and the factors that influence it, may lead to a better understanding of the basic physics of locomotion in water and improve man's performance. Thus this comparative study was carried out to examine data for various forms of locomotion in water to find commonalities and differences in the bioenergetics of locomotion.

METHODS

The types of locomotion in water studied here were swimming at the surface with legs only, with fins, with arms and legs (front crawl), kayaking and rowing, as well as underwater fin swimming. The data are a result of a combination of laboratory testing techniques in an annular swimming pool (60 m in circumference and 2.5 m wide and deep), a 50 m competitive swimming pool and in open water in a canal 75-100 m wide and 10 m deep. The subjects for these studies were University age men who were competing at the highest national level in Collegiate or Club sports. The characteristics of the subjects and the aquatic locomotion modes used are described in Table 1.

Table 1. Physical and physiological characteristics (mean \pm s.d.) of the subjects used in these studies and the types of locomotion are shown.

Activity	n	Age yrs	Height m	Weight kg	VO2max Pre-tr l/min	VO2max Post-tr l/min	Propeller length cm	Hull weight kg	Hull length m
Leg Swim	7	20 \pm 2	1.79 \pm 0.7	71.6 \pm 7.2	3.15 \pm 0.38		99	3.4	1.79
Fin surf.	7	20 \pm 2	1.79 \pm 0.7	71.6 \pm 7.2	3.15 \pm 0.38		159	3.4	1.79
Fin unwt	8	24 \pm 2	1.82 \pm 0.6	90.9 \pm 9.3	3.85 \pm 0.68		159	3.4	1.82
Front Crawl	22	19 \pm 1	1.81 \pm 0.1	75.0 \pm 3.2	3.86 \pm 0.12	4.86 \pm 0.63	173	3.4	1.81
Kayaking	17	25 \pm 5	1.78 \pm 0.8	77.0 \pm 9.5	3.39 \pm 0.51	4.58 \pm 0.67	208	12.5	5
Rowing	8	21 \pm 3	1.79 \pm 0.3	68.8 \pm 5.2	3.81 \pm 0.33	4.73 \pm 0.30	772	93	17.6

Propeller length = length of arm, leg, paddle or oar

Hull weight = weight in water of the body, kayak or rowing shell

Hull length = the length between head and foot of a swimmer and bow to stern of kayak or rowing shell

Stroke and Kick Mechanics: The relationship between the average velocity the body achieved as a function of the number of propulsive cycles (strokes and/or kicks) (8) was determined in open water for all forms of locomotion. In each case a measured course was determined and the time to cover it and the number of propulsive cycles were determined using a stroke watch. Due to the ratio of exercise-to-recovery used in testing, metabolism was not considered a factor in this relationship. After data collection the distance that the hull progressed per propulsive cycle (d/c) was calculated by dividing velocity (m/min) by the cycle frequency (c/min).

Energy Cost of Locomotion: The velocity of progress in all tests was set by an impeller type flow meter mounted at the depth of water of the subject, and the subject was paced by a monitoring platform or power boat. For speeds that could be supported completely by oxidative metabolism, VO_2 was determined by standard open circuit methods. Expired gas was collected in meteorological balloons on a monitoring platform in the annular pool testing and for rowing from a power boat or balloons stored inside the hull of the kayak; volume was determined using a dry gas meter. The expired fractions were determined either by O_2 and CO_2 analyzers or a mass spectrometer.

For the anaerobic contribution to locomotion, blood was drawn at 5, 7 and 9 min post exercise by venipuncture and lactic acid was determined enzymatically using standard kits. The peak value was used in all calculations of the anaerobic contribution. To estimate the anaerobic contribution, the athletes progressed at set speeds until exhaustion, and the time and lactic acid concentration were determined. The maximal time was then calculated and the athletes completed one-half of the maximal time for each speed. It was assumed that at a given speed, the rate of lactic acid was constant, and thus, the rate of lactic acid accumulation for a

given speed was calculated from the two determinations. The rate of lactic acid was converted to an oxygen equivalent using previously validated values ($3\text{mlO}_2/\text{kg}$, 11, 12). The total energy cost at higher speeds was determined by adding the rate of the anaerobic contribution at each speed to $\text{VO}_{2\text{max}}$.

Determination of Drag: Both passive drag and active drag were determined. For towing experiments, the swimmers or athletes in their hulls were towed passively at the water surface at velocities that started at 0.2 m/sec and were increased in 0.2 m/sec increments up to the maximal competitive speeds for the shortest distances. Force (drag) was determined using a transducer and was recorded using a computer. During passive towing experiments the swimmers were videotaped through an underwater window using a digital video camera to determine the frontal surface area variation with swimming speed. This was not done in kayaking or rowing as the hulls are displacement and do not change their frontal area with speed as is the case in swimmers. After each swim, the frontal surface area of the swimmer was calculated from the angle of the body (from the horizontal) and measurements of the diver's shoulder, hip, knees and ankle widths and depths.

Active drag was determined by the method of di Prampero et al (12), which can be applied to all forms of locomotion in water and is a valid measure of drag. In practice, the athletes were paced at fixed speeds while being partially towed by external forces that reduced the propulsive force (and thus the energy requirement) required by the athlete. The VO_2 was plotted as a function of the external force and extrapolated to the force which would reduce propulsive force and thus VO_2 to basal levels, which was the drag while actually swimming or paddling (active drag).

For propulsion in water, the most relevant kinds of drag are the profile (form) drag (i.e. the sum of the skin-friction drag and the pressure drag) and the wave and spray drag. A surface can be approximated by an arrangement of circular cylinders in axial flow and since the boundary layers are typically thin, the flows can be modeled as flows over flat plates (7). The Reynolds number based on swimmer length, L , is defined as $Re_L = V L/\nu$, where V is the swimming speed and ν is the fluid kinematic viscosity. For the Reynolds numbers observed in competitive swimming, the flow experiences transition-to-turbulence and separates from the surface, and the pressure drag is caused by viscosity.

For flow over a flat plate at zero angle-of-attack, transition-to-turbulence begins at about $Re_L = 5 \times 10^5$ and ends at about $Re_L = 10^7$ in a quiescent ambient (13). For a 170cm tall swimmer, the Reynolds numbers based on swimmer length (height) corresponding to $V = 0.3$ m/s and 2.2 m/s are 5.10×10^5 and 3.74×10^6 respectively. Consequently, the flow over the length of the swimmer's body is neither completely laminar nor completely turbulent; it is transitional and ill-defined. As a result, the forward portion of the swimmer, modeled as a flat plate, will be in laminar flow and most of the aft portion of the swimmer will be in transitional flow.

The skin-friction drag of the swimmer, D_{SF} , was calculated for a flat plate in the transition-to-turbulence region (13) as:

$$D_{SF} = q A_S [0.074 / Re_L^{1/5} - 1740 / Re_L] \quad (1)$$

where q is the dynamic pressure, $\frac{1}{2} \rho V^2$, ρ is the fluid density and A_S is the surface area. The corresponding pressure drag (D_p) was calculated using the results in Fox and McDonald (13). The skin-friction drag was calculated using one-half (1/2) of the wetted area, as it is assumed that the swimmer or hull

would be partially out of the water. The D_p was formulated to be proportional to the second power of the velocity and directly proportional to the frontal surface area which is a measured function of $\Theta(V)$. The D_w was formulated to be proportional to the fourth power of the velocity, with the proportionality constant determined by regression of the data. Drag decomposition consisted of summing the drag components and then determining the proportionality constants as well as the transition Reynolds number using a standard multiple, non-linear regression package.

Effects of Training: Another method of analyzing aquatic locomotion is to examine how these factors change with specific sport training in that form of locomotion. To this end data are presented from training studies on swimmers, kayakers and oarsmen. For the swimmers and kayakers, four years of training were evaluated, whereas for the oarsmen, only one year was studied. The training consisted of progressive exercise starting with maximal aerobic power, i.e. training for 4 bouts of exercise (8-12 min) at 125% of VO_2 max with 10 min recovery between bouts (exercise below 60% VO_2 max). The training has been found to give maximal improvement in VO_2 max, as well as lactic acid removal (30). This phase of the training lasted eight weeks and was followed by a gradual conversion from 4 bouts at 125% VO_2 max to 25 bouts at 150% VO_2 max (race pace) over the next 20 weeks. Biomechanical and physiological variables were determined prior to and after training.

RESULTS

Biomechanical: The data for the average velocity achieved as a function of cycle frequency for all forms of locomotion in water are shown in Figure 1.

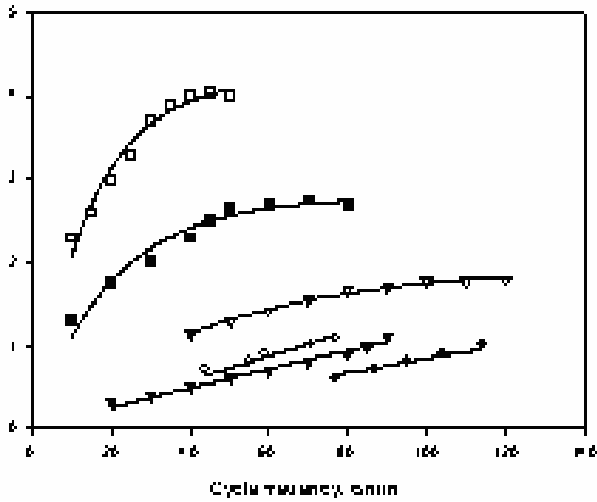


Fig. 1. The velocity of progression, m/sec, are plotted as a function of cycle frequency, c/min, for swimming with legs (●), fins at the surface (○), front crawl (Δ), fins underwater (▼), kayaking (■) and rowing (□).

Fig 2. Total energy cost (aerobic plus anaerobic), KJ/min are plotted as a function of velocity of progression, m/sec, for swimming with leg (●), fins (○) and front crawl (Δ) at the surface, fins underwater (▼) and kayaking (■) and rowing (□).

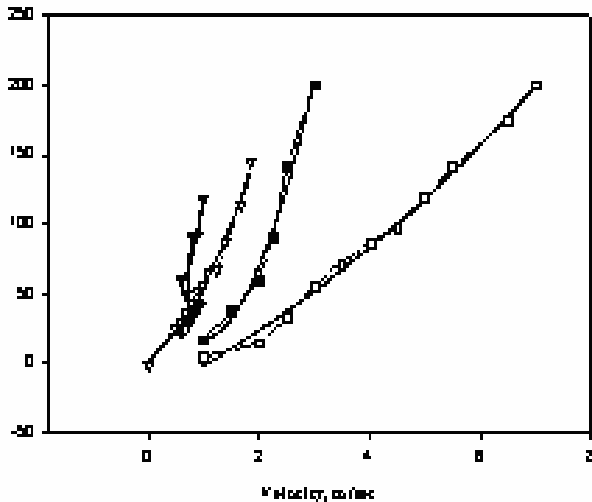
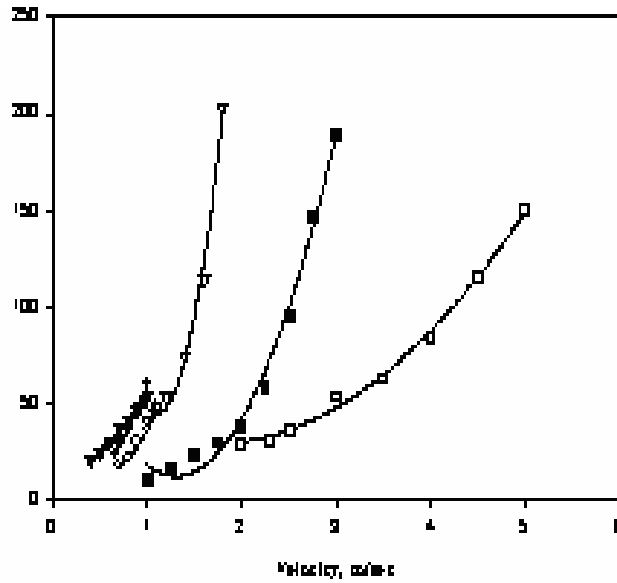


Fig 3. Active Body drags in N are plotted as a function of velocity, m/sec, for swimming with legs (●), fins (○) and front crawl (Δ) at the surface, fins underwater (▼) and kayaking (■) and rowing (□).

It can be seen that the relationships for v/cf and d/c follow similar patterns for all forms of locomotion. The maximal distance per cycle was greatest for rowing (13.8 m/c), then kayaking (7.8 m/c), then swimming (1.73 m/c), then fins at the surface (0.95 m/c), fins underwater (0.7 m/c), and lowest for leg kicking (0.52). The d/c was not significantly affected by velocity for velocities below 1.1 m/sec for all forms of locomotion, however for speeds above 1.1 m/sec, the d/c decreased as a function of velocity up to the maximal velocity: by 48% for swimming, 74% for kayaking and 65% for rowing.

It can also be observed that the maximal speeds for the forms of locomotion using arms or legs, are inversely related to the maximal stroke rate. The maximal stroke rate is inversely related to the length of the propulsive arm used (Table 1 for oar, paddle, arms, legs), while the maximal speed is directly related.

Comparing the effect of swimming on the surface with fins to underwater swimming revealed that the cycle frequency was greater (25-35%), while the d/c was less (18-30%) underwater.

Energy cost of locomotion: The total energy cost of locomotion is plotted as a function of velocity for all forms of locomotion, over the range of velocities where data are available, in Figure 2. These data demonstrate that the energy cost increased as a function of velocity, with a similar pattern among the various forms of locomotion. It is interesting to note that for legs or arm propulsion the maximal rate of energy supply is not significantly different among the forms of locomotion, however the maximal velocities were greatest for rowing, then kayaking, then swimming and finally, for all leg propulsions. The maximal velocity of the various forms of locomotion are related to their respective maximal d/c as: $V_{max} = 0.89 d/c + 0.31$ ($r = 0.98$), while maximal velocity is inversely

related to maximal stroke rate: $v_{max} = -0.06 c/min + 7.58$ ($r = 0.89$).

The energy cost as a function of distance, C , swimming with fins underwater had the highest minimal C (below 1.0 m/s) and it did not change much with velocity $C = 0.89V^{0.05}$. The C increased as a function of velocity for surface swimming ($0.53V^{2.02}$), while kayaking ($C = 0.09V^{2.25}$) and rowing ($C = 0.11V^{0.93}$) were significantly less, respectively. The lower C would be expected to be associated with a greater d/c , which was the case in this study.

Drag: Active drag is shown in Figure 3, for the forms of locomotion studied, plotted as a function of V . Passive drag, with the subject towed without movement, was significantly lower for the body at the surface and for the kayak than active drag at all velocities. For swimming, the relationship was $Da = 2.12 Dp + 2.59$ ($r = 0.99$) and for kayaking, $Da = 1.36 Dp + 21.79$, and when combined $Da = 1.53 Dp + 21$.

Active drags increased as a function of velocity with the rate of increase being greatest for fins underwater, fins or legs or front crawl at the surface, kayaking and finally rowing. The relatively high drag for underwater swimming explains the high energy cost, but the similar drags between leg, fin and front crawl at the surface means that the primary difference in their energy cost of swimming must be their respective efficiencies. The low drag at low V s of kayaking and rowing, account for their low energy cost of progression.

Total drag was decomposed into its elements and the analysis is shown in Table 2.

At the maximal speeds tested in this study passive drag at the surface ($V = 2.2$ m/sec) was 80.4 N with 23 %, 51 % and 26% of the drag coming from D_{sf} , D_p and D_w respectively. Active drag swimming with only legs ($V = 1.0$ m/sec) was 42.46 N with 24%, 74% and 2% due to D_{sf} , D_p and D_w respectively. Adding

fins to leg swimming at the surface increased total D to 53.94 N ($V = 1.0$ m/sec) with Dsf 38%, Dp 58% and Dw 4 % of the total drag. The total D swimming under water with fins was 115 N ($V = 1.0$ m/sec) with 76% Dsf, 23.6% Dp and .4 % Dw. For front crawl swimming at 2.0 m/sec, the total D was 159 N with Dsf 25%, Dp 55% and Dw 20%. Passive D of kayaking was 139 N ($V = 3$ m/sec) with Dsf 7%, Dp 1 % and Dw 92%. The active drag of kayaking increased to 22.6 N ($V = 3.0$ m/sec) with Dsf = 16%, Dp = 4% and Dw = 80%. The passive drag of rowing was 186 N ($v = 7$ m/sec) with 24% from Dsf, 52% Dp and 24% Dw. During swimming at the surface, Dp dominates D (51-74%) with Dsf contributing a significant amount; however, Dw contributes little due to the low relative speeds. During underwater swimming, unexpectedly, Dsf becomes the dominate form of drag (76%) with Dp accounting for the remainder. The D of kayaking, passive and active, is dominated by Dw (80% and 92%, respectively), with Dsf contributing 16% to active D and Dp negligible. Although with a similarly shaped hull, the passive D of the rowing shell is significantly less that the kayak (18%), and the V greater (3.0 vs. 7.0 m/sec), due to it's longer length (1), the Dsk and Dw are similar (24%)

with Dp contributing 52%. These data provide important insights into the physics of drag and can be used to minimize drag in different forms of locomotion by reducing the main drag component for each form of locomotion and specific speeds.

Effect of Training: The energy cost for swimming, kayaking and rowing as a function of velocity at all speeds was significantly lower after training than before training by 15-25% for swimming, 25-33% for kayaking and 6-10% for rowing.

The cycle frequencies at all speeds were lower after training than before, resulting in a greater distance per cycle. There were no significant differences in the slopes of these relationships of C to d/c for swimming, kayaking or rowing when comparing pre to post training, thus, within a form of locomotion, the C is primarily determined by the d/c and the athlete's active drag.

Active drag for swimming and kayaking are shown in Figure 4 as a function of velocity prior to and after 4 years of training for swimming and kayaking. Active drag decreased 18% to 50% in kayaking while only 17% to 36% in swimming. The reduced drag accounts, in part, for the reduced energy cost of progression.

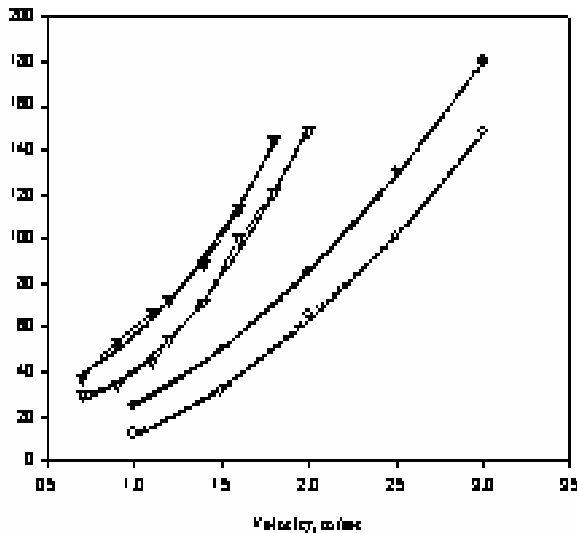


Fig. 4. Active drags, N, are plotted as a function of velocity m/sec, for kayaking (●) and swimming (▼) prior to (closed) and after training (open).

Table 2. Drag for the various forms of propulsion decomposed into pressure drag (Dp), skin friction (Dsf) and wave drag (Dw) as described in the methods. The equations are the best fit as determined by iteration using the sum of least squares technique.

Form	Dp	Dsk	Dw
L-S	$(1.68) V^2 A_f [\theta (V)]$	$(11.7) [(5.36) \times 10^{-7}] V + (0.074)V^{1.8}$	$(0.0961)V^4$
F-S	$(1.69) V^2 A_f [\theta (V)]$	$(28.3) [(1.24) \times 10^{-6}] V + (0.074)V^{1.8}$	$(0.147)V^4$
F-UW	$(1.50) V^2 A_f [\theta (V)]$	$(21.0) [(2.76) \times 10^{-4}] V + (0.074)V^{1.8}$	$(9.63 \times 10^{-7})V^4$
S-P	$(0.89) V^2 A_f [\theta (V)]$	$(6.16) f (V)$	$(0.099)V^4$
FC	$(2.01) V^2 A_f [\theta (V)]$	$(15.9) [(2.76) \times 10^{-4}] V + (0.074)V^{1.8}$	$(0.209)V^4$
K-P	$(0.002) V^2$	$(2.02) [(2.76) \times 10^{-4}] V + (0.074)V^{1.8}$	$(0.161)V^4$
K-A	$(0.115) V^2$	$(1.29) V$	$(0.240)V^4$
R-P	$(0.207) V^2$	$(1.94) [(2.72) \times 10^{-4}] V + (0.074)V^{1.8}$	$(0.207)V^4$

Where: Dp = pressure drag, Dsk = skin friction, Dw = wave
 L = leg, F = fins, FC = front crawl, K = kayak, R = rowing
 P = passive, A = active
 S = surface, UW = underwater
 Af [$\theta (V)$] = the variation of frontal area with angle, a function of V

DISCUSSION

The present study demonstrated that all forms of locomotion in water compared in this study followed similar rules of physics, in spite of the fact that the propulsive arms were either primarily legs (swimming with legs or fins) or arms (front crawl), or arms with propulsive extensions (kayaking and rowing), and were performed at or under the water surface. These data also show that the physics of the system is velocity dependent.

Biomechanics: As demonstrated the velocity of progression in all forms of locomotion were dependent upon a unique combination of the distance the hull traveled per cycle (d/c, m/c) and the frequency of the cycles (cf). The overall propulsion required at a given speed is a combination of useful work (drag, D) and wasted work. The latter is a combination of internal work (Wint) and energy wasted in kinetic energy imparted to the water (Wkin) (20, 38). The wasted energy (Wint and Wkin) is determined by the balance between the drag on the propeller and the drag on the hull of the object being propelled (body, kayak, shell). The greater the ratio of useful to wasted energy the higher the

propelling efficiency. Furthermore, the d/c is related to the propelling efficiency of each form of locomotion and was increased with training.

If the force generated by the contracting muscles is greater than the resistance of the propeller and less than the drag of the hull, the propulsive arm will slip through the water and provide less propulsive force, and greater wasted kinetic energy. Thus, the propulsive force that can be applied to the propulsive arm cannot exceed its resistance in the water, or drag of the propulsive arm. In the case of both legs and arms the maximal force generated, measured against a strain gauge with the subjects tethered, was 110 N for the legs with fins, 195 N during front crawl, 220 N in Kayaking and 318 N in rowing. These values represent less than 20% of the maximal force that these muscle groups can generate in air (14), where the ground (unlike water) cannot be accelerated.

The greater the drag on the hull, compared to the propulsive arm (hand, fin, paddle or oar), the more energy that is wasted to Wkin due to water slipping over the sides of the propeller for leg swimming (17, 21,

27), or in arm propulsion, due to the slippage of the propulsive arm through the water causing water to be accelerated in the direction opposite of progression (18). This causes a decrease in d/c , and requires an increase in cycle frequency (18) that leads to increased W_{int} (38). The net result of these balances of forces is a decrease in propelling efficiency (34) and distance per stroke. Training in both swimming and kayaking resulted in an increased d/c ; implying a decrease in hull drag, and thus a decrease in wasted energy. Less energy is wasted in trained athletes due to lower cycle frequencies, reducing W_{int} (20, 38), and increased thrust (21, 27) thereby reducing W_{kin} leading to increased propulsive efficiency. Estimating propelling efficiency from our data showed swimming and kayaking training would result in an increase in propelling efficiency from 48% to 49% and 53% to 55% respectively. These improvements alone would result in a decrease in C of 0.64 KJ/m to 0.62KJ/m changes and 0.55 KJ/m to 0.53 KJ/m, in swimming and kayaking, respectively. The relatively small increases in propelling efficiency are inconsistent with the larger increases in d/c and decrease in C between forms of locomotion and training, and suggest that another factor is influencing these two parameters. The other determinant of these two factors is the active drag of the system.

There is a statistically significant relationship between the energy cost of progression and active drag that has the expression: Energy cost/min (KJ/min) = $0.877 \text{ Drag} + 19.53$ ($r = 0.87$) over the range of velocities for the various forms of locomotion studied. Based on this relationship, the energy cost of progression is largely related to the active drag, and reduced by 20% due to the reduction of the drag of the hull, as a result of the training in swimming and kayaking. These data suggest that the large increase in the distance the body travels

per cycle, for a small increase in η_p , is due to the decrease of the drag of the hull, allowing the hull to move over the fixed position of the propelling arm, and minimizing the kinetic work (less slip of the propulsive arm) and internal work (lower cycle frequency). The data from this study are consistent with a previous study in swimming, where it was shown that the use of hand paddles, to increase surface area and drag of the propulsive arm, improved η_p (32). The forms of locomotion with the greatest surface areas of the propulsive arm have the greatest d/c , implying greater η_p .

As can be seen from the equations for the relationships between drag and velocity shown in Table 2, total drag increased very rapidly as a function of velocity for each form of locomotion. As the maximal velocity of a hull is set by its length (1), it is not surprising that the rowing shell and kayak have higher maximal speeds than the swimmer. For the kayak and shell, as displacement hulls, their volume “floats” the hull at the surface and they are fairly well balanced fore to aft, thus their pressure drag is low. However, for the swimmer, particularly at lower speeds, the overall length or wetted surface is not the entire determinant of the drag. At speeds less than 1 m/sec, swimmers have an attitude in the water that is different from horizontal, thus their frontal surface area is a major determinant of their drag. Swimmers are not displacement hulls, and although they float, they naturally float vertically, as they rotate around their center of mass with the legs having greater density than the upper body (including the lung) (22, 26, 37, 3). During forward progression in the water, the angle of the swimmer to the horizontal, and thus the frontal surface area, is a balance of the torque, or rotational forces, and the hydrodynamic lift against the body. Since the swimmer’s torque is constant (2, 23, 26, 35) as the velocity of progression increases, and the hydrodynamic lift increases, the body becomes more

horizontal. Thus, at higher speeds, the frontal surface area, and this component of the drag, is less. This can be seen in the D vs. velocity curves (and equations) for swimmers, compared to those of the kayak and shell, as there is a term for the body angle (θ) (Table 2). The increase in drag as a function of velocity below 1 m/sec increases at a higher rate than above 1.0 m/s, such that the active or passive drag is identical between 0.9 and 1.0 m/sec respectively. The latter speed is where the body angle is horizontal and frontal surface area minimal.

At speeds above 1.0 m/sec, where the hull is horizontal in the water, the body torque is not a factor. However, the depth that the hull sinks in the water is important as it determines the wetted surface area. For swimmers, the total underwater weight of a male swimmer is 33.4 ± 2.0 N, the torque is 13.7 ± 5.9 N, and the remainder of the sinking force (22.6 ± 2.0 N) is the weight acting directly to submerge the hull and increase the wetted surface area. The larger this sinking weight, the greater the energy cost of swimming. This has also been shown for drag in rowing, which increased about 10% for a 20% increase in weight (29), and kayaking where the C increased 20% for a 20% increase in weight (25). The frontal surface area and wetted surface area would affect the various components of drag (D_{sf} , D_p , D_w) differently at different speeds and require different methods of drag reduction.

An examination of Table 2 reveals that for the various forms of locomotion, D_{sf} , D_p and D_w make a different contribution to the total drag. Swimming at the surface with legs and fins, where speeds are low (less than 1 m/sec) and the swimmers torque plays a role, it is not surprising that D_p accounts for the largest part of the total drag (58 to 74%) with D_{sf} the remainder (24-38%) due to the frontal surface area effects. Swimming underwater at similar low speeds results in an increase in the D_{sf} contribution as the total

body surface area contributes to this component of the drag. Swimming front crawl at the surface results in a large component of D_p for hull displacement (55%), and similar amounts of D_{sf} and D_w (25-20%, respectively). For speeds greater than swimming, in a hull slightly longer, the kayak's drag is dominated by wave drag (80%). However, at even higher speeds in a hull with a longer wetted surface area the total drag is dominated by D_p (52%), with D_{sf} and D_w making equal contributions (24%). Although not shown, the laminar flow separation point, to transitional flow, for all swimmers was 10 cm from the top of the head, while for the kayak and shell it may be 0.5 to 1 m (Mollendorf, personal communication). It is difficult to determine the factors that effect drag in transitional flow from the physics, however to decrease D_{sf} , other than decreasing the surface area of contact between water and hull, attaching laminar flow using turbulence generators or trip wires may have promise. For the kayak, minimizing wave drag by altering hull design seems the most promising approach, while a combination of the techniques for swimmers and the kayak may work for rowing shells.

Physiological: The data for the energy cost of propulsion as a function of velocity at low speeds from the present study are in agreement with that previously reported for fin kicking (26), swimming (2, 23, 30, 31), kayaking (16, 25, 37) and rowing (10, 15, 29). Previous studies have validated the use of lactate data to determine the anaerobic contribution to the energy cost of locomotion (2, 10, 11, 33) kayaking (37). The total energy determined from the estimate of drag and swimming efficiency (11) and that estimated from VO_2 max and lactic acid measures were not significantly different from each other. As discussed by Capelli et al (2) for swimming and Zamparo et al (37) for kayaking, a time constant was assumed for the attainment of VO_2 max and the high

energy phosphate contribution to the total energy was a small fraction of the total and thus could be ignored.

The maximal oxygen consumptions, determined specifically in each activity across forms of locomotion, were lower for leg swimming and surface fin swimming, and not significantly different among the other forms of locomotion (Table 1). The absolute values ranged from 3.39 to 3.86 l/min which translates to 42 to 55mlO₂/min/kg. These values of VO₂ max are lower than those reported for athletes of similar caliber from land sports (14). However, after training the values increased to 60 to 69mlO₂/min/kg, which are consistent with the VO₂max for collegiate age athletes for most sports, and not different from the athletes participating in sports studied. Previous studies have shown that trained athletes have the same VO₂-on responses and VO₂max values, irrespective of the limbs used in the sport (5, 6, 23, 24). The athletes studied at the pre-training state were training with long distances at speeds less than 80% of VO₂ max. However, after training above 125% of VO₂max that was done in this study, the values reported by others were similar for similar sports. This implies that long slow training may limit the development of maximal aerobic power in trained athletes, which can be corrected with higher intensity training.

The anaerobic contribution to the various forms of locomotion can be determined by comparing the energy cost data in Figure 3 to the VO₂ max data in Table 1. The maximal lactate concentrations for leg kicking and fin swimming were lower (6.5 ± 2.3 mmol/l) than the values for the competitive sports (11 to 14 mmol/l), which were comparable to values from other studies of similar forms of locomotion (14, 15, 19).

Interestingly, the maximal lactate concentration increased after the first year of the four year training program, but it did not increase in the remaining years. The increase in maximal speed was greater than could be accounted for by changes in VO₂max. Therefore, it has to be concluded that the lactate uptake increased significantly, which is in agreement with previous aquatic studies (19) and other sports.

In summary, the physics of progression in water can be applied to the various forms of locomotion studied. It appears that the application of Lighthill's slender fish model (17) to propulsion with the legs is appropriate (21, 38) and fits the data well. The challenge remains to analyze propulsion generated with the arms. It appears that previous studies on rowing using theoretical analysis based on strain gauge and potentiometer measurements on the oar (4) or the sculler's center of mass movement in relationship to the boat and the force applied (28) do not adequately explain the biomechanics of rowing. The theoretical analysis of swimming, using an animal rowing model (9) and a "paddle wheel" model by Martin et al (18), although promising, does not adequately fit the data; and in addition, does not incorporate the potential propulsion from the legs.

The active body drag of water locomotion can be estimated by the method of di Prampero et al (11) and the methods presented here can be used to decompose friction, pressure and wave drag. From the physiological standpoint the responses to exercise in water are similar to those reported for land locomotion. Athletes performing in water respond to training and can achieve levels of aerobic and anaerobic power similar to athletes that perform on land.

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