Evaluation of fins used in underwater swimming

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Pendergast DR, Mollendorf J, Logue C, Samimy S, Evaluation of fins used in underwater swimming. Undersea Hyperb Med 2003; 30(1): 55-71 - Underwater swimmers use fins which augment thrust to overcome drag and propel the diver. The VdotO2 of swimming as a function of speed, velocity as a function of kick frequency, maximal speed (v), maximal oxygen consumption (VdotO$_2$) and the maximal thrust were determined for eight fins in 10 male divers swimming at 1.25 m depth in a 60 m annular pool. A theoretical analysis of fin cycles was also performed. VdotO$_2$ increased as a second order polynomial as a function of velocity; VdotO$_2$ = 0.045 + 1.65B V + 1.66 (2) V^2 (r^2= 0.997), VdotO$_2$ = 0.25 + 1.03 V + 1.83 V^2 (r^2= 0.997) and VdotO$_2$ = -0.15 + 2.26 V + 1.49 V^2 (r^2= 0.997), for least, average and most economical fins respectively. Kick frequency increased linearly with velocity and had a unique movement path (signature), giving theoretical values that agreed with the measured thrust, drag and efficiency. In conclusion, virtually all thrust comes from the downward power stroke, with rigid fins kicked deep (high drag), while flexible fins are kicked less deep but with higher frequency (low efficiency). Kick depth and frequency explain the performance of the eight tested fins, and should be optimized to enhance diver performance.

active drag, oxygen consumption, efficiency, underwater swimming, thrust, SCUBA

INTRODUCTION

Underwater activities are quite common and include sport, commercial and military divers. Although the tasks of these groups vary widely, one common factor in underwater swimming is the use of fins for propulsion. Fins come in a wide variety of shapes, materials and designs, which are reported to affect their performance. The performance of divers using fins is impacted by the energy cost of swimming, as it determines their breathing-air use, and thus their dive time, oxygen exposure and thermal status, as well as potential fatigue.

The energy cost of swimming is determined by the average velocity of forward progression and the ratio of the power required (including drag and internal and kinetic power) to the mechanical efficiency while actually swimming (active)(1). The diver must generate a force equal and opposite in direction to the drag. Some studies have determined drag by towing underwater swimmers passively (2, 3, 4). Further studies were needed because passive drag grossly underestimates active drag (5), the fins used in these studies were not adequately described, and VdotO2 was not determined uniformly.

Two techniques have been published to determine active drag and efficiency (6,7,8), but only one includes the effects of a leg kick (6), and this methodology has not been applied to underwater swimming. The type of fin selected by the diver, along with his/her technical ability, are major determinants of drag, internal and kinetic work, and efficiency.

The energy cost of underwater swimming at or near the surface has previously been reported (9, 3, 10, 11) and the values ranged from 1.3 to 2.5 l/min while swimming at speeds of 0.5 to 1.2 knots, maximal $\mathrm{VdotO_2}$ of 3.1 to 4.2 l/min and rapid fatigue at higher speeds. In another study $\mathrm{VdotO_2}$ was not affect by depth (1.8 to 54m)(12). It has also been shown that the energy cost of swimming was negatively correlated with fin surface area, but not flexibility, while maximal speed was negatively correlated with flexibility (13, 14). More recently it was reported that fin selection affects $\mathrm{VdotO_2}$ by as much as 25%, with large, heavy, rigid fins requiring the highest $\mathrm{VdotO_2}$ and smaller less rigid fins less (5). A previous study has suggested that the venturis and vents in fins did not affect their economy (13).

A firm conclusion about the best types of fins cannot be made from previous studies, and many new fins designs have been marketed based on various physical characteristics without supportive data. To date, no clear understanding of the effects of the characteristics of fins on the energy cost of underwater swimming is available.

Previous theoretical work has applied flow over a thin and flexible waving plate of finite chord leading to a progressive wave of given wavelength to imposed transverse oscillatory movements of swimming in slender animals like fish and eels (15, 16, 17, 18). This analysis yields theoretical estimates of thrust, the power required for maintaining motion and the energy imparted to the fluid, and allows calculation of propulsive efficiency. More recently, the waving plate theories have been applied successfully to fins (19) and to surface swimmers using legs, and when they use fins as well, to calculate economy, total mechanical work, propelling efficiency and mechanical efficiency (1). It is our hypothesis that fins of different designs used during underwater swimming could be evaluated using the wave plate theories to determine the effectiveness of specific fins in producing thrust, and thus propelling efficiency, and the required energy cost of swimming.

The purposes of this study were to propose quantitative methods and to evaluate commercially available fins, with different physical characteristics, that are widely used in diving. Fins of various sizes, materials, flexibilities, and designs were tested for the energy cost of swimming, maximal and sustained speeds, and thrust. A theoretical analysis, using the Lighthill model (16), combined with measurements of drag and drag efficiency for selected conditions was done in an attempt to provide further input to the understanding of fin performance.

METHODS

Subjects

The subjects for this project were recruited from the local community. Ten male divers were studied. The divers were all SCUBA certified instructors or professional divers and had been diving for between 3-15 years and self-reported 100 hrs/yr of diving. The average ages of the subjects were 32 ± 3.8 years, heights 182 ± 6 cm, weights 90.86 ± 9.28 kg, and body fat 12 ± 4 % (determined by underwater weighing).

Protocol

The University's Institutional Review Board approved the protocol, and the divers gave informed consent, completed a history and were given a physical examination. The divers participated in a series of five experimental protocols lasting two hours each that were conducted on the same day and time of the week over an 8-week period. During this period, the divers maintained their normal diving, working and training schedules. The divers were compensated for their participation. With the exception of the fins being tested, the divers wore their personal gear in all experiments. Although manufactures varied the wetsuits used were ¼ inch thick foam neoprene and the diver's weight belt was adjusted to neutral buoyancy using a spring scale. The divers used a mask, and a single surface supplied air tank mounted on a backpack. Eight fins, randomized in order for each subject, were tested over five 2-hour sessions. The air temperature was maintained at 22ºC and the water temperature was maintained at 25ºC (previously determined to be thermally neutral during exercise with a ¼ inch thick wet suit).

Energy Cost Measurements

The energy cost of swimming over a range of speeds that can be achieved using oxidative metabolism was measured (VdotO_2). The divers swam at a depth of 1.25 m in an annular pool 2.5 m deep by 2.5 m wide and 60 m in circumference. The divers were paced by, and measurements were taken from, a monitoring platform (1.25 by 2.5 m), the velocity of which was set by a calibrated flow meter (PT-301, Mead Inst. Corp., Riverdale, NY) that was calibrated by comparison to land speed in still water. The test started at 0.4 m/sec for 5 min and then the velocity was increased 0.1 m/sec every 3 min until voluntary exhaustion (14 to 23 min). After completion of the first maximal swim, the diver was given a 20 min rest and then two addition swims were completed in one session (about 2 hours). Three fins were studied per session, with one fin repeated for reliability of VdotO_2, including maximal (r^2=0.94).

VdotO_2 was measured using a pressurized bag-in-box system developed in-house and tested against standard open circuit methods (r^2 = 0.94 between pressurized and standard open circuit methods). The system was comprised of a two-hose regulator, surface supplied through an aluminum tank, with the exhaust side of the mouthpiece piped (2.5" PVC) to the monitoring platform. This was directed by PVC tubing and valves (2.5") either back to the exhaust side of the regulator or to a meteorological balloon inside a pressurize 55 gallon drum. The entire system was maintained at the diver's pressure by the diver's regulator. During gas collection the diver's exhaust filled the balloon, which displaced gas from the drum back to the regulator. Between collections the diver's exhaust was returned directly to the regulator from the box and the balloon was exhausted through a calibrated dry gas meter (Harvard, USA) to determine expired volume (VE, BTPS). The O_2 and CO_2 fractions in the expired gas were determined using a calibrated mass spectrometer (MGA 1100, Perkin Elmer, CA, USA) and VdotO2 (STPD) was calculated.

Drag and Efficiency

Active body drag (Db) and efficiency were measured using four pairs of fins, by a method developed in this laboratory (6) that is based on measurements of VdotO_2 during sub-maximal swims at a fixed velocity. The divers swam at 0.7 m/sec while a series of progressively decreasing known free-hanging masses (0.5 to 6.5 kg) were attached to the swimmer's waist by means of a rope and pulleys and a weight belt. The diver swam continuously, while the masses were decreased every 3 min, until the diver was free swimming, unassisted by the weights. The rope attached to the diver passed through a system of pulleys fixed to the monitoring platform in front of the swimmer, thus the force acted horizontally along the direction of the diver's movement. The force generated by the added masses (deleted drag, D^-) partially pulled the diver and reduced the propulsive thrust required by the diver proportionally to the force added (D^-). Since thrust is associated with the VdotO$_2$ of the diver, the diver's VdotO$_2$ is determined by his active drag minus the D^-. After plotting the VdotO$_2$ as a function of D^-, the VdotO$_2$ of free swimming by extrapolation to $D^- = 0$, while the active drag of the diver is determined when D^- equals Db and VdotO$_2$ above rest is 0. Efficiency can then be calculated as the product of Db and velocity, divided by the VdotO$_2$ of free swimming.

Kick Frequency and Velocity Measurements

The purpose of this test was to establish the maximal velocity that can be achieved as a function of kick frequencies, from minimal to maximal. In practice, the divers free swam at 1.25 m depth, using SCUBA, for 20 m in the annular pool. The divers swam several bouts for between 40 and 20 sec. and rested for 2-3 min each, thus metabolic factors were not limiting velocity. The divers started at the slowest kick frequency they could sustain and increase the frequency progressively until they reached their maximum. The diver's instantaneous velocity for each swim was integrated to calculate the average velocity, which was plotted as a function of kick frequency (20). The slope of the velocity-kick frequency regression was the distance that the diver's body traveled per kick, and represents the thrust per kick cycle (both legs).

Maximal Thrust Measures

To determine the maximal thrust of the diver, the divers swam "all out" against a strain gauge (Omega Engineering/Newport Meter ICCA-250, USA) mounted on the stationary monitoring platform. The diver wore SCUBA gear and swam at 1.25 m depth for 20 sec, and then rested for 5 min prior to swimming with the next fin. The thrust values were integrated over that time to give an average maximal static thrust.

Fin Characteristics

Each of the 8 fins tested in this study possessed its own unique characteristics. The fins were purchased from a commercial dive shop. The fins were sized to fit the individual subject and the average physical characteristics of the fins are presented in Table 1. All of the fins had winglets (flanges) but were of variable shape, width and length. All but two of the fins (partially split) had solid blades, three fins had vents and three had ridges. The split fin's split was duct taped closed for one trial. The effective fin length is defined as the length of the fin beginning immediately aft of the fins' foot pocket (leading edge, LE) and ending at the end of the fin blade (training edge, TE). The LE and TE widths were taken to be at the LE and TE of the fin blade, respectively. The surface area was calculated as the area of a trapezoid; the bases equal to the LE & TE widths and with a height equal to the effective fin length. The fin mass was determined by weighing each fin on an electronic scale (Toledo Scale model 8142).

Table 1: Fins tested along with their average descriptive characteristics

Fin	Mat.	Flan.	Vents	Ribs	L	Wth_{LE}	Wih_{TE}	SA	Mass	EI
					m	m	m	m^2	N	$N{*}m^2$
Mares Attack	FG	W:1/2 L	No	No	0.62	0.14	0.22	0.11	1.17	5.45
Apollo Bio-Fin Pro	R	El;FL	No	No	0.33	0.18	0.22	0.07	1.32	1.32
Apollo-taped	R	El;FL	No	No	0.33	0.18	0.22	0.07	1.32	1.32
US Divers Blades	R/P	N;FL	No	Yes	0.40	0.20	0.21	0.08	1.06	2.45
SCUBA Pro Jet	R	W:T;FL	Yes	Yes	0.30	0.16	0.23	0.06	1.13	1.92
Mares Avanti Quattro	P/R	W;T;FL	No	No	0.38	0.17	0.21	0.07	0.94	1.95
Oceanic Ocean Pro	P	W;T;FL	Yes	No	0.36	0.15	0.23	0.07	0.94	1.95
US Divers Compro	P	W;T;FL	Yes	Yes	0.34	0.16	0.25	0.07	1.03	2.72

Where: Blades are: FG = fiberglass; R = rubber; P = plastic

Flanges are: W = wide, H = half; F = full; L = length; T = tapered

Fins are: LE = leading edge; TE = trailing edge; Wih = width; SA = surface area
EI = stiffness

To classify each fin's stiffness, they were hung on an adjustable-length rigid artificial foot in air at a temperature of 22ºC (similar to water temperature of 25ºC) as cantilever beams with weights added at the TE. An adjustable-length rigid artificial foot was constructed to fill and secure the foot pocket of each fin. The fin deflection was measured in both the power and recovery stroke orientations and averaged. These hanging weight experiments and simple elastic beam theory allowed us to compute the fin stiffness as an EI-value (Table 1). At each weight, the deflection was recorded at ¼ TE, ½ TE, ¾ TE, and at the TE. The deflections were inputted into a beam theory:

$$deflection(y) = \frac{wieght}{EI}\left(\frac{x^3}{6} - \frac{Lx^2}{2}\right) \qquad \text{..(1)}$$

where "*weight*" is the load at the TE. The EI-value is calculated from equation (1) using the measured deflections. Also, *x* is the distance from the LE and *L* is the effective fin length.

Fin Signature Analysis

As the divers swam each lap, they passed by three 4′ by 4′ underwater viewing windows that were grided (2" squares). A SONY Handycam Vision Camcorder (model#129909) was used to record each pass for video analysis. The video scale was calibrated using a calibration frame suspended in front of the video camera in-line with the swimmers path. The scaling factors obtained were used to scale the diver's coordinates to actual dimensions during computer analysis. The videos were analyzed at 1/15s intervals for trunk, hip, knee, and ankle angles related to the horizontal, coordinates of the LE and TE, as well as the angles of the LE and TE and digitized into a computer. As the thrust from a fin is generated by a complete kick cycle (thrust, transition, recovery, transition), one kick cycle was analyzed for each trial. Once the coordinates for the fin were obtained the position of the LE and TE and fin angles were determined; and a fin signature was plotted (Figure 1). The coordinate origin of the signature is defined as: Z (vertical position) = 0 at ½ LE kick depth, and x (horizontal position) = 0 at position of the lowest LE segment (19, 21). The fin signatures are graphs that display the spatial position and orientation of the leading edge (ankle, LE) and trailing edge (fin tip, TE) segments of the fin over one kick cycle. Each fin had a unique fin signature based on the divers kicking style (LE) and the physical characteristics of the fin (TE).

Figure 1 - A

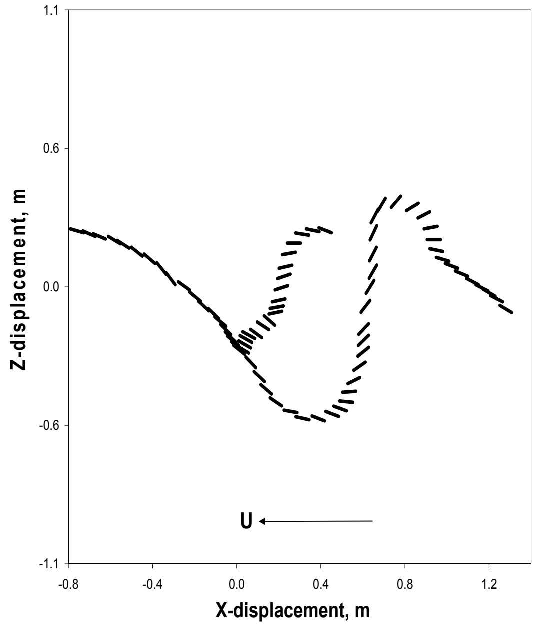

Figure 1. In the adjacent plate (A) in this figure the LE and TE, along with their respective angles are plotted as a function of time for the Attack fin for one fin cycle is plotted. These data were used to calculate the data in Table 5, using the Lighthill Model (16,17). In the lower plot (B) the thrust developed as a function of time is plotted for the same fin, with periods of transition, recovery and power indicated

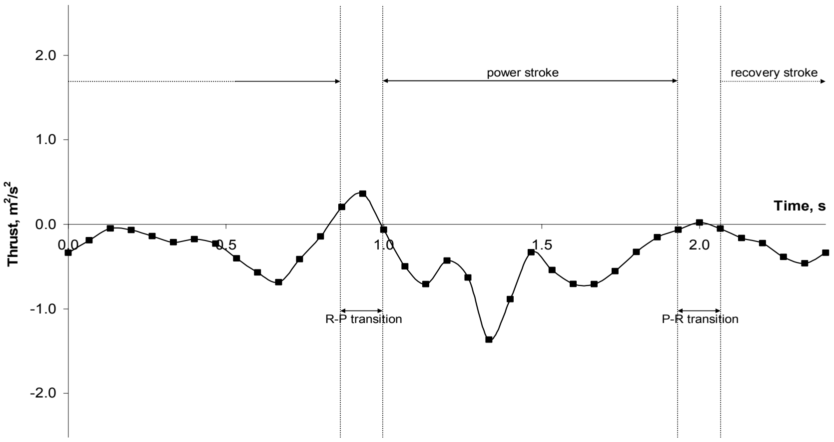

Figure 1 - B

These data were used to compute instantaneous and average thrust and power values based on the Lighthill formulation (16); as well as the kick cycle's Froude efficiency. These values were computed for one fin, and the average work and thrust values were multiplied by two assuming the signatures of both legs were the same (19,21).

Statistical Analysis

Descriptive data (mean ± S.D.) were calculated and plotted (Sigma Plot 8.0) for all measured parameters. Statistical significances to compare fins were examined using Analysis of Variance for Repeated Measures (ANOVARM Sigma Stat 4.0). The regression models that gave the best statistical fit (linear, multiple, and exponential) were used to fit the data for the various parameters, and the type is indicated in the text. A significance level of ≤ 0.05 was accepted for all statistical comparisons.

RESULTS

Energy Cost of Swimming

The average data (±S.D.) for the VdotO$_2$ as a function of velocity are shown in Table 3 for each of the 8 fins studied. Based on significant differences in VdotO2 among the fins (Table 2), the data was divided into three groups of fins, and they are presented in Figure 2. The fin groupings were Attack, Apollo and Jet (lowest); Quattro, Ocean and Blades (intermediate) and Compro (highest). The second order polynomial fit of VdotO$_2$ and velocity for the group of fins with the significantly highest, average and lowest values were: VdotO2 = 0.045 + 1.65B V + 1.66 (2) V^2 (r^2= 0.997), VdotO$_2$ = 0.25 + 1.03 V + 1.83 V^2 (r^2= 0.997) and VdotO$_2$ = -0.15 + 2.26 V + 1.49 V^2 (r^2= 0.997), respectively. Interestingly, both rigid (Attack, Jet) and flexible (Apollo) fins were in the most economical group.

Combining and examining the data presented in Tables 1 and 2 reveals that the type of material, winglets (flanges), splits (longitudinal) vents or ribs, alone, did not significantly influence the VdotO$_2$ of swimming. The length (0.40 to 0.34 m), width of the leading (0.16 to 0.17 m) or trailing (0.22 to 0.25 m) edges, surface area (0.07-0.08 m^2), weight (2.3 to 2.72 kg) or flexibility (EI 2.3 to 2.72) did not affect the energy cost of swimming among the three groups of fins presented in Figure 2.

The maximal aerobic power and the plateau velocity for VdotO_2 (maximal aerobic speed) for swimming with each fin are shown in Table 3. Average VdotO_2 max for all fins was 2.408 ± 0.71 l/min, with the highest values being 2.493 l/min. Jet fins (-9%) had a VdotO_2max significantly lower than the other fins, which were similar to each other. The maximal aerobic speeds for all fins averaged 0.77 ± 0.04 m/sec. The maximal aerobic velocity was significantly higher for the Attack (6%) and Apollo taped fins (6%) and slower for the Compro (10%).

Table 2. Oxygen consumption of free swimming (l/min) as a function of velocity (m/sec) using different fins

Fin		Velocity, m/sec					
		0.4	0.5	0.6	0.7	0.8	0.9
Attack	Mean	0.951	1.192	1.466	1.878	2.244	2.615**
	s.d	0.172	0.182	0.226	0.322	0.329	0.440
Apollo	Mean	0.975	1.210	1.495	1.878	2.413	2.728**
	s.d.	0.162	0.226	0.264	0.341	0.339	0.365
Apollo Taped	Mean	0.958	1.197	1.450	1.783	2.250	2.596**
	s.d.	0.140	0.144	0.181	0.251	0.381	0.320
Blades	Mean	0.964	1.272	1.678	2.128	2.584	3.023*
	s.d.	0.144	0.176	0.396	0.604	0.773	0.933
Jet	Mean	0.987	1.222	1.531	1.928	2.285	2.536**
	s.d.	0.182	0.157	0.247	0.311	0.333	0.359
Quatro	Mean	1.040	1.223	1.653	2.152	2.531	2.893*
	s.d.	0.191	0.960	0.181	0.382	0.358	0.451
Ocean	Mean	1.018	1.305	1.638	2.124	2.610	2.949*
	s.d.	0.158	0.171	0.223	0.344	0.402	0.494
Compro	Mean	1.096	1.397	1.866	2.389	2.928	3.354
	s.d.	0.149	0.206	0.469	0.655	0.798	0.989

* Indicates significnatly greater than the average of all fins.
** Indicates significantly less than the average of all fins.

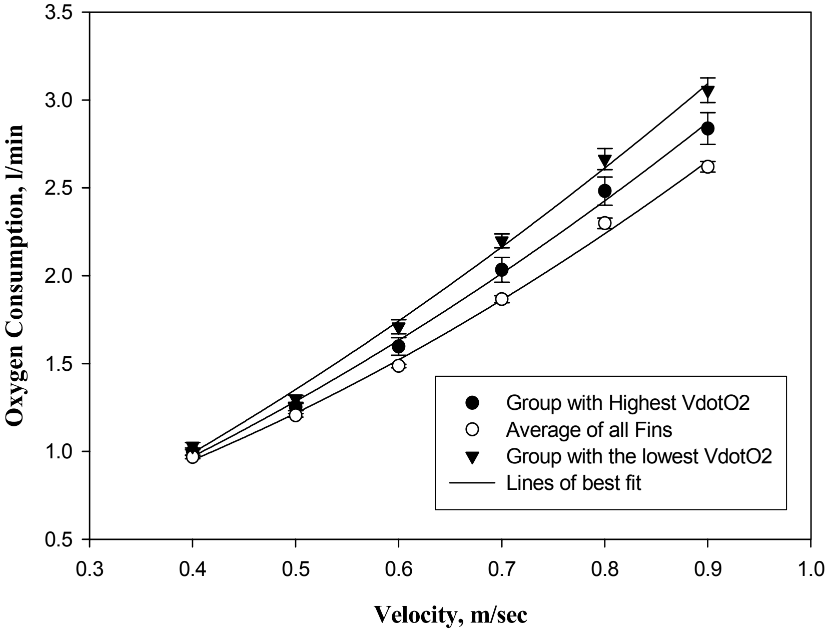

Figure 2. The steady state oxygen consumption (mean ± s.d.), for three groups of fins that were significantly different from each other (Table 2), while free swimming are plotted as a function of velocity. The group of fins with the highest VdotO$_2$ (least economical) is represented by ▲, intermediate by the ○ and the lowest (most economical) by ●.

Table 3. Maximal aerobic power, velocity that can be achieved with oxidative metabolism and maximal tethered force for the eight fins tested for men and women

	Attack	Apollo	Apollo T	Blades	Jet	Quatro	Ocean	Compro
Aerobic Power (l/min)								
	2.436	2.367	2.435	2.396	2.272*	2.377	2.493	2.485
	0.416	0.219	0.332	0.387	0.399	0.210	0.384	0.564
Aerobic Velocity (m/sec)								
	0.82*	0.79	0.83*	0.76	0.77	0.75	0.77	0.69**
	0.11	0.90	0.08	0.10	0.07	0.07	0.07	0.11
Maximal Tethered Force (Neutrons)								
	178	137	141	151	147	130	150	134
	30	20	15	24	45	23	35	24

* significantly higher than the average value

** significantly lower than the average value

Drag and Efficiency

Interestingly, the Attack and Apollo fins had similar VdotO_2 values (1.96 and 2.04 l/min, respectively), however, the Attack fin (more rigid) had a drag of 69.73 N while the Apollo fins' was significantly less (49.72 N), due to greater kick depth with the Attack. Due to the narrow kick depth, the frequencies of kicking with the Apollo and Apollo taped were significantly higher (Table 4), therefore the efficiency was lower (5.01%) compared to the Attack fin (6.97%). The two fins with a higher VdotO_2 (2.20-2.23 l/min) had high drag (56.88 – 61.79 N) and low efficiencies (5.3%). This comparison indicates that both drag (kick depth) and efficiency (kick frequency) have to be optimized to minimize the energy cost of swimming and accounts for the similar performance of the Attack and Apollo fins.

Table 4. Data analysis of the kick frequency and velocity relationship for all fins.

Fin	Max d/K	Kf at Max d/K	V max	Kfmax	d/K at v max
Attack	1.19*	41**	1.16*	78	0.93*
	0.40	13	0.16	21	0.25
Apollo taped	0.94	49	1.01	90*	0.71**
	0.22	15	0.10	18	0.17
Apollo	0.84**	58*	1.00	88*	0.68**
	0.21	15	0.11	17	0.11
Blade	1.07	51	0.99	72**	0.90*
	0.33	13	0.11	22	0.27
Quattro	1.11	55	1.00	73**	0.87
	0.26	24	0.11	20	0.17
Compro	0.90	58*	0.93	78	0.78
	0.21	17	0.09	25	0.21
Jet	0.99	51	1.00	81	0.81
	0.27	9	0.07	25	0.23
Ocean	0.95	53	0.95	76	0.76
	0.30	19	0.13	15	0.18

*	significantly higher than the average value
**	significantly lower than the average value

Kick Frequency-Velocity

The relationships between v and Kf were analyzed for the maximal distance per kick (v/Kf, max d/K), the maximal Kf at which the max d/K was achieved, the maximal velocity that could be achieved (vmax) and the Kf and d/K at v max according to Craig (20) (Table 4). The average values of max d/K and Kf at the max d/K were 1.00 ± 0.12 m/K and 52 ± 5, respectively. The max d/K increased as a function of stiffness (EI, Table1) (d/K=0.07 EI + 0.83(r=0.78). Similarly the d/K at max V increased linearly with stiffness (EI) (d/K=0.05 EI + 0.68 (r=0.79).

The d/K for the Attack fin was significantly higher (19%), while the d/K for the Apollo was significantly lower (16%). The Kf at the max d/K were highest for the Apollo and lowest for the Attack fin. The v max averaged 1.01 ± 0.07, with a max Kf of 80 ± 7 k/min. The maximal swimming velocity was highest for the Attack (15%). Although the maximal Kf was higher for the Apollo (13%), the d/K was significantly lower (14%). The Kf for the Attack was not different, but the divers could sustain a higher d/K at max (15%), thus the v max was greater.

The major difference in the Kf-v relationship among the fins was that the more flexible fins had to be swum at a higher frequencies as the d/K was significantly less, and as maximal frequency is fixed, the maximal velocity is limited by the d/K, which is related to thrust, and is lower for the more flexible fins.

Maximal Thrust

The maximal tethered (static) force (thrust) swimming with all fins is shown in Table 3. The average thrust was 157.71 ± 16.28 N. The divers generated significantly greater thrust (22 %) with the Attack fin than with the remainder of the fins.

Combining and examining the data from Tables 1, 4 and 5 reveals that the stiffest fin (Attack, EI = 5.45) had the highest maximal thrust (Attack, 192 N) and resulted in the diver covering the greatest distance per kick (1.19 m/k) compared to the fins with medium (EI = 2.13) and low stiffness (EI = 1.32), which had 156.73 N and 142.61 N maximal thrust and 0.99m and 0.84m d/k, respectively.

Body Position in the Water

The angle of inclination from the horizontal decreased from 17º to 1º from horizontal as a function of velocity from 0.4 to 1.0 m/sec (angle = - 26 v + 25º). The data for joint angles are consistent with the increasing kick frequency and with increasing velocity, as the hip angle decreases (Hip angle = -16º v + 42º, r^2= -0.68) and the ankle angle increases (Ankle angle = 16º v + 147º, r^2 = 0.67) with v as the power increases, while the knee angle was held fixed at 154º ± 4º. The knee and ankle angles were not different among the fins tested, however the hip angles were significantly less for the Apollo, Apollo taped and Ocean fins (23º ± 1º) when compared with the Attack, Blades, Quattro, and Compro fins (29º ± 3º). There was a significant linear relationship between stiffness (EI) and the hip angle which was = 2.6 EI + 19 (r=0.76). The fins with the greater hip angle were the fins kicked deeper and with a lower frequency (higher thrust per kick), while the fins with lower hip angle were kicked at higher frequencies with a more shallow kick (lower thrust per kick).

Theoretical Analysis

Figure 1 contains one fin signature for a representative fin and the respective instantaneous thrust as a function of time (Mares Attack fin). Table 5 summarizes the Froude efficiencies and average thrusts computed from Lighthill's formulations (17, 19) for each of the eight fins from their signatures, along with the time and thrust during the transition, recovery and power phases calculated from the signatures and thrust/time plots shown in Figure 1,(see page ?).

Table 5. **Average values for average thrust, thrust in transition, recovery and power, and the % of the total time spent in each phase of the kick cycle at a representative speed (0.6 m/sec)**

Fin	Thrust (N)				% of total cycle time			η_f
	Ave	Trans	Rec	Pow	Trans	Rec	Pow	%
Attack	8.7**	1.8	7.4**	15.2*	15	46	39	60
Apollo	11.2	0.3	12.7	17.7	15	56	29**	72*
Apollo Taped	12.5	22.6*	15.5	44.0	15	52	33	44**
Jet	13.9**	0.9	9.1**	31.5*	15	52	33	60
Blades	10.2	1.0	13.5	10.6**	15	46	39	57
Quattro	14.0*	2.6	9.5**	30.0*	15	54	31	64
Ocean	10.4	1.2	10.8	13.5**	15	33**	52	66
Compro	11.5	1.7	17.5*	11.2**	15	46	39	55

Ave = average; Trans = transistion; Rec = recovery; η_f = Froude Efficiency
* signficantly higher than the average value
** signfiicantly lower than the average value

The Apollo fin possesses the lowest Froude efficiency, probably due to the split in the fin's blade. The split allows water to "pass through" it instead of having the water pass over the surface to produce the desired pressure gradient between the attacking and leeward surfaces. The Apollo (Taped) and Quattro fins each have Froude efficiencies well above 60%. The common characteristic between these two configurations is that both have flanges along the lateral edges of the blade to direct flow to the fin tip which acts as dykes to channel the flow along the fin's surface and ultimately being ejected from the TE.

The characteristic that is common amongst all the fin signatures is the thrust values during the transition portions of each kick cycle (Figure 1 and Table 5). As the TE transitions from the recovery stroke to the power stroke (or vice versa) the fin loses the pressure gradient between the attacking and leeward surfaces of the fin. The loss of the pressure gradient reduces the potential for forward propulsive thrust during the transition periods. Overall, 0.52s of each kick cycle does not benefit the diver's forward momentum. The average elapsed time for the fin signatures was 2.1s. Assuming 0.52s of each kick cycle is "wasted", 25% of a kick cycle is used only to transition the fin's TE to the power or recovery stroke. To improve the performance of the fin, the time required to complete the transition should be minimized.

Table 5 shows the percentage of time for each phase of the kick cycle as well as the average thrust, during each of these phases. The transition period is assumed to consume 15% of every kick cycle and did not add significant thrust to the kick cycle. The Ocean fin had the only signature where the power stroke constituted 52% of the kick cycle. The power stroke in the seven remaining signatures constituted 31 to 39% of the kick cycle. However, the Apollo, Jet, and Quattro fins (the three signatures with the greatest overall average thrust, Table 5), had average thrust values during the power stroke in excess of $+1.0 m^2/s^2$. The Apollo fin had the greatest average thrust during the power stroke, however it also had the greatest negative thrust during the transitions.

In regard to how fin configurations influence energy cost, performing an iterative multiple linear regression with the inferred thrust, from the fin signatures (Figure 1) as the dependant variable, it was found that the calculated thrust, from the Lighthill's theory (16, 17), could be predicted using the Strouhal number and the LE kick depth. The Strouhal number is defined as:

$$Str = \frac{\omega l_e}{U_{sig}} \text{..} (2)$$

That is, the product of measured kick frequency (radians/second) times effective fin length (m) divided by the measured swimming speed (m/s). The predicting equation ($R^2 = 0.72$) is:

$$Thrust = -34.702 + 51.469 k_d\big|_{LE} + 4.375 Str \text{....................................} (3)$$

The Strouhal number is the most significant (P=0.024) of the two independent variables; $k_d|_{LE}$ has a P=0.177. Equation (2) can be used in conjunction with the equation that relates $k_d|_{LE}$ and k_f, which is:

$$k_d\big|_{LE} = -0.0204\omega^2 + 0.145\omega + 0.0176 \text{......................................} (4)$$

Then, substituting equations (2) and (3) into (4):

$$Thrust = -1.05\omega^2 + \omega\left(7.463 + 4.365\frac{l_e}{U_{sig}}\right) - 33.796 \text{....................................} (5)$$

Examining the data in Figure 2, the power for each phase values were significantly lower for the medium (32%) and higher (64%) VdotO2 groups than for the low group. The lower power of the two groups of fins would require a proportionally higher kick frequency, and thus higher $VdotO_2$, particularly since it would lead to a lower efficiency. This was evident as the total thrusts among the 3 groups were identical at this speed (Table 5). The Froude efficiencies among the 3 groups of fins with different $VdotO_2$s were significantly lower for the fin with the highest $VdotO_2$ (55%), however the moderate and low $VdotO_2$ fins had similar values (63 and 59%), indicating in the later case that positive thrust must have offset part of the negative thrust. The fins with a higher power and lower oxygen consumption were in the power phase less time (34%) than the fins with less power (39 to 41%), with the remaining time being spent in non-power generating phases (transition and recovery, 67% and 59-61% respectively).

DISCUSSION

As pointed out by Zampero (1), fins act as passive locomotory tools for swimming by improving economy and speed of progression. Fin selection is most often made on the basis of the diver's perception of the effectiveness of the fin. In our studies, the divers invariably ranked the stiff fins as the best and the flexible fins as the worse, which did not correlate with the objective evaluation of these fins.

The physics of underwater swimming with fins is complicated, as demonstrated by the data from the present study showing fins with very different designs can have similar energy costs of swimming (Attack vs Apollo). Some fin comparisons are reported for swimming at slow speeds with measurements of air consumption, however due to the low ventilation, the diver can consciously or unconsciously alter their ventilation independently of their $VdotO_2$. This invalidates these types of studies. This point was emphasized in this study as the reliability of ventilation and velocity was very low ($r = 0.54$), while the reliability of $VdotO_2$ and velocity was very high ($r = 0.94$). Fins designed on the basis of physical principles for airfoils or propellers do no necessarily lower the energy cost of swimming (Apollo vs Appolo taped). This demonstrates that, based on our current understanding of the physics of underwater swimming with fins, theoretical models have to be evaluated empirically as was done in this study.

The energy cost of swimming (economy) is determined, in part, by the body drag. Body drag has been measured passively (2, 3, 4). However, these data are of limited use as active drag is significantly higher and may not be proportional to passive drag. In addition, kinetic work and internal work have to be added to the total power requirement of fin swimming to calculate the total power, and when expressed as a function of the energy requirement, the efficiency (1).

The drag that the diver must overcome has to be satisfied by a propulsive force or thrust. The thrust and efficiency of underwater fin swimming were evaluated using the Lighthill model (16,17) and revealed that the thrust per kick comes primarily from the power stroke, which was greater in more economical fins. The transition and recovery phases provide little thrust, and in fact, added to the overall drag, and had to be compensated for by an increase in kick frequency to meet the overall thrust requirement (Table 5). An increase in kick frequency increases internal work and thus the energy requirement (1) as moving a small mass of water rapidly is less efficient than moving a large mass of water slowly (22). The total thrust (thrust/ kick times kick frequency) was similar among the fins for a given speed, but for the fins with a higher thrust per kick, $VdotO_2$ was proportionally lower (Tables 2 and 5). It has been reported that curved fins had greater thrust than straight fins (12). In our work, fins where the successive TE segments that progressed at 90º to the horizontal produced the most thrust during the power phase, which was predicted by the Lighthill model (16,17). As most of the power was produced in the power phase, and little in the recovery phase, it may be advantageous to have higher thrust in the power phase but relieve the force required for recovery. This is due to the flow of water over the upside of the fin and the lower muscular force of the hamstring muscles (hip abduction) (23).

Since seven of the eight fins have recovery strokes occupying approximately one-half the kick cycle, it would be advantageous to maximize the average thrust during the recovery stroke. This approach could be achieved by a fin configuration that would require the fin's TE to progress through the water the same way and the fin to behave the same executing the power or recovery stroke (16, 17). However, the anatomical joints and muscular power (25) a human diver uses during fin swimming (hip, knee, and ankle) and body attitude in the water does not allow a symmetrical range of motion when flexing and extending. This fact leaves fin improvement to increasing thrust in the power phase and minimizing drag in the recovery and transition phases.

Channeling of water down the fin by troughs or rubber channels (Quattro fin) does not appear to improve thrust or economy. The use of vents, either forward or reward facing or venturis does not improve economy as was seen in this study and previous studies (5,13), apparently as water does not pass through the vents, thus they do not relieve the negative thrust in the recovery phase. Also, the vents would presumably "leak" water, and hence reduce the pressure difference that results in thrust, during the power phase of the kick cycle. The longitudinal splits in the Apollo fin does not appear to improve its thrust (Table 5) nor did they lower VdotO_2 (Table 2), thus it is reasonable to speculate that the water either leaked over the splits or its backward velocity was decreased by the splits, resulting in less thrust (Tables 2 and 5). These fins were kicked at high frequencies, thus the relatively small amount of water accelerated rapidly leads to low efficiency. The lack of improvement in thrust or economy of fins with venturis, vents, trauth, etc. would be expected from the Lighthill model (16,17) as they would not increase the velocity of water down the fin, and in fact may decrease it, thus leading to lower thrust during the power phase.

It has been suggested that larger more rigid fins produce greater thrust (13, 14). This implies that the diver must have enough leg strength and power to overcome the resistance of the fin. Similarly the hamstring muscles of men are weaker than the quadriceps, thus the power stroke should generate more thrust than the recovery stroke (25). The design of a fin should not preclude a straight up-down kick to maximize the surface area to accelerate water so fins should not be too wide to prevent this type of kick. There was a positive correlation between fin stiffness (EI) and hip angle, reflecting a deeper kick, and resulting in a greater distance of travel per kick. Swimming with a rigid fin in the down stroke and a flexible fin in the up stroke may be advantageous; however this type of fin was not available for testing.

Large rigid fins have been suggested to have greater maximal thrust, and thus a diver using these fins may generate more pulling power and faster speeds (13,14). Previous studies have reported maximal thrust of 64 to 78 N with the maximal sustainable thrust of 40 N (2,26). The maximal values measured in the present study are greater (140 to 170 N). The proposition that rigid fins develop more thrust and speed was not supported by this work. The maximal velocity and thrust were developed by both rigid and flexible fins, with the limitation of the rigid fins being the ability of the diver to generate a high frequency, and the limitation of the flexible fins being limited by the diver's maximal leg kick frequency. Although a previous study suggested that a fin that is too flexible or too rigid did not perform as well as a fin that was intermediate in rigidity (12). This was not supported by this study as the most rigid and most flexible fin had similar performances.

Based on the physics of fin swimming using the Lighthill model (16, 17) and the VdotO_2, velocity and thrust data, it is clear that some fins have better performance (Attack, Apollo) than other fins, however this can not be ascribed to a single fin characteristic. It is clear that the venturis, vents, trauths, splits in the tested fins did not improve the performance of the fin. Further work is needed to develop the optimization of fin characteristics, by lowering drag (kick depth-rigidity) and maximizing efficiency (kick frequency-flexibility), to minimize energy requirement and maximize performance of fins. It would appear that the Lighthill model (16, 17) could be used to predict fin performance, but that it would have to be tested empirically.

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