# Underwater fin swimming in women with reference to fin selection

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Pendergast D, Mollendorf J, Logue C, Samimy S, Underwater fin swimming in women with reference to fin selection. Undersea Hyperb Med 2003; 30(1): 72-82 - Underwater swimmers use fins, which provide thrust to overcome drag and propel the diver. The type of fin used has been shown to affect diver performance, however data are lacking for women. The oxygen consumption ($\dot{V}O_2$) of swimming as a function of speed, velocity as a function of kick frequency, maximal speed (v), maximal $\dot{V}O_2$ and the maximal thrust were determined for 8 female divers swimming at 1.25 m depth in a 60 m annular pool. $\dot{V}O_2$ increased as a function of v as; $0.52 + -0.485\ V + 2.85\ V^2$ ($r^2 = 0.996$) and $0.12 + 1.52\ V +1.275\ V^2$ ($r^2 = 0.999$) for high (5 fins) and low (3 fins) groupings, respectively. Splits, vents and flanges did not significantly affect $\dot{V}O_2$. Kick frequency increased linearly with v, with unique slopes for each fin. Maximal $\dot{V}O_2$ was not affect by fin type ($1.46 \pm 0.05$ l/min). Velocities that could be stained aerobically were $0.60 \pm 0.02$ m/sec on average, with the most flexible fin higher (0.71 m/sec). Maximal v averaged $0.87 \pm 0.03$ m/sec, with the most rigid fin lower (0.77 m/sec). Maximal thrust was not affected by fin and averaged $104 \pm 9$ N. It can be concluded that female divers preferred the most flexible fins, which were also the most economical. This is most likely due to low leg power, which could also explain the absence of differences in maximal thrust and velocity.

*SCUBA diving, oxygen consumption, kick frequency, thrust, fins*

## INTRODUCTION

Sport diving has become a popular recreation, and is becoming more popular among women. An important component of diving is underwater swimming using fins for propulsion. As fins come in a wide variety of shapes, materials and designs and all of which are reported to improve the diver's performance, fin selection can impact diving performance and success. Fin selection is often subjective, but performance is dependent upon the diver having the leg power to kick the fin and the metabolism to sustain muscle contractions over the period of the swim.

To swim at a given speed the diver must provide a thrust per kick, which overcomes drag, and propels the body forward. The total thrust is met by the thrust per kick times the frequency of kicking, thus there is a relationship between the distance the body goes per kick and the kick frequency as a function of velocity. To swim with fins, women would have to be able to generate a force with a flutter kick to propel the fin and generate sufficient thrust to over come

drag. It is well documented that women have significantly lower muscular force than men, particularly the hamstring group (1, 2), and thus the type of fin best for women may be different than for men.

The capability to sustain muscle contractions is dependent upon the diver's ability to supply energy at the rate dictated by the energy cost of locomotion (economy, $VdotO_2/v$). Previous studies have demonstrated that although women have lower maximal aerobic power, even when corrected for body weight (1), their surface and underwater swimming economy are greater, thus requiring less energy to swim at the same speed as men. Diver's performance 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.

To date most studies on underwater swimming have focused on male divers, particularly when evaluating fins (3, 4, 5). The energy cost of underwater swimming at or near the surface has previously been reported (4, 6, 7, 8, 9) and the values ranged from 1.3 to 2.5 l/min while swimming at speeds of 0.5 to 1.2 knots, maximal $VdotO_2$ of 3.1 to 4.2 l/min and rapid fatigue at higher speeds, however these data were for men. It has also been shown in men that the energy cost of swimming is negatively correlated with fin surface area, but not flexibility, while maximal speed was negatively correlated with flexibility (10, 11). Maximal thrust has been shown to be 200 N in men with higher thrust in curved (129 N) than straight fins (107 N) (3), however no comparable data are available for women.

More recently it was reported that female divers expend less energy than male divers (30-40%), however the effect of fin selection on economy was not evaluate in women (12). A firm conclusion about the best types of fins for women cannot be made from previous studies, where the data were mostly on men. The purpose of the presently reported study was to evaluate performance of women swimming with commercially available fins, with different physical characteristics, that are widely used in diving.

## METHODS

### Subjects

The subjects for this project were recruited from the local diving community through contact with dive shops. Eight female divers were studied. The divers were all SCUBA certified and had been diving for between 3-15 years with an average of 32 self-reported hrs/yr of diving. The average ages of the subjects were $24 \pm 5$ years, heights $169 \pm 11$ cm, weights $67.7 \pm 15.8$ kg, and body fat $20 \pm 6$ %.

### Protocol

The Institutional Review Board of the University approved the study and the divers gave informed consent prior to participation. The divers completed a history and were given a physical exam prior to participation. The divers participated in a series of seven 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, which consisted of a ¼ inch foam neoprene wetsuit and weight belt that made them neutrally buoyant, 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 20°C and

the water temperature was maintained at 25ºC (previously determined to be thermally neutral during exercise).

### Energy Cost Measurements

The energy cost of swimming over a range of speeds that could be achieved using primarily oxidative metabolism ($VdotO_2$) was determined 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 using a calibrated impeller type flow meter (PT-301, Mead Inst. Corp., Riverdale, NY). 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 (9 to 14 min). After completion of the first maximal swim, the diver was given a 20-30 min rest and then an addition swim was completed in each session (about 2 hours). Two fins were tested per session. A repeat measurement on one fin was determined for each subject for reliability of $VdotO_2$ ($r^2=0.92$), including maximal $VdotO_2$.

$VdotO_2$ was measured using a previously reported pressurized bag-in-box system (12). The entire system was maintained at the diver's pressure by the regulator worn by the diver during collection. Expired ventilation was determined, at atmospheric pressure, by a calibrated dry gas meter (Harvard, USA) and $O_2$ and $CO_2$ fractions using a calibrated mass spectrometer (MGA 1100, Perkin Elmer, CA, USA). $VdotO_2$ (STPD) was calculated by standard methods.

### Kick Frequency and velocity measurements

This test established the relationship between kick frequency and velocity. The divers swam using SCUBA in the pool at 1.25 m depth for 20 m. They started at their slowest kick frequency and increased the frequency progressively until their maximum (13). The average velocity was determined and plotted as a function of kick frequency. The velocity/kick frequency gave the distance the diver's body traveled per kick, and represents the thrust per kick cycle (both legs). 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 (13).

### 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

The fins were purchased from a commercial dive shop and their physical characteristics 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 surface area was calculated as the area of a trapezoid. The fin mass was determined by weighing each fin on an electronic scale (Toledo Scale model 8142).

## Table 1. Physical characteristics of the tested fins

| Fin | Material | Flanges | Vents | Ribs | Length | Tip Width | SA | Mass | EI |
|-----|----------|---------|-------|------|--------|-----------|----|----- |----|
| | | | | | m | m | $m^2$ | kg | $N*m^2$ |
| Attack | FG | wide; ½ L | No | No | 0.59 | 0.22 | 0.11 | 1.00 | 5.45 |
| Apollo | R | elliptical | No | No | 0.30 | 0.20 | 0.07 | 0.98 | 1.32 |
| Blades | R/P | narrow; fl | No | Yes | 0.37 | 0.19 | 0.08 | 0.82 | 2.45 |
| Jet | R | wide/tapered | Yes | Yes | 0.26 | 0.23 | 0.06 | 1.01 | 1.92 |
| Quattro | P/R | wide/tapered | No | No | 0.37 | 0.21 | 0.07 | 0.88 | 1.95 |
| Ocean | P | wide/tapered | Yes | No | 0.35 | 0.23 | 0.07 | 0.88 | 1.95 |
| Compro_ | P | wide/tapered | Yes | Yes | 0.33 | 0.24 | 0.07 | 0.86 | 2.72 |

Where: FG = fiberglass; R = rubber; P = plastic; SA = surface area; EI = stiffness

To classify each fin's stiffness, the fins were hung as cantilever beams with weights at the TE using a previously described method (14). The fin stiffness using this method is reported as an EI-value in Table 1.

### Statistical Analysis

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

## RESULTS

Fins come in many designs with quite different physical characteristics (Table 1).  Fin selection is most often made on the basis of the diver's perception of the effectiveness of the fin, fit or appearance.  In this study the female divers subjectively ranked the flexible fins highest and the more rigid fins the lowest.

### Energy Cost of swimming

The average data (±S.D.) for $VdotO_2$ as a function of velocity are shown in Table 2 for each of the 8 fins studied. Three fins with the same $VdotO_2$ (Attack, Apollo, and Apollo taped)

had significantly lower vales that the other five fins (Blades, Jet, Quattro, Ocean, Compro), which were not different from each other. The average data for the high and low VO2 groups of fins are shown as a function of velocity in Figure 1. The data were fit best by a second order polynomial and the equations were: $VdotO_2 = 0.52 + -0.485 V + 2.85 V^2$ ($r^2 = 0.996$) and $VdotO_2 = 0.12 + 1.52 V + 1.275 V^2$ ($r^2 = 0.999$) for the high and low $VdotO_2$ groupings respectively.

**Table 2. Average (± s.d.) oxygen consumption (l/min) as a function of velocity (m/sec) for tested fins**

| Fin | | Velocity | | | |
|---|---|---|---|---|---|
| | | 0.4 | 0.5 | 0.6 | 0.7 |
| Attack | mean | 0.810 | 1.080 | 1.350 | 1.640 ** |
| | s.d. | 0.060 | 0.110 | 0.210 | 0.320 |
| Apollo | mean | 0.797 | 1.020 | 1.333 | 1.641 ** |
| | s.d. | 0.045 | 0.137 | 0.219 | 0.261 |
| Apollo taped | mean | 0.756 | 0.961 | 1.150 | 1.471 ** |
| | s.d. | 0.098 | 0.151 | 0.139 | 0.159 |
| Blades | mean | 0.920 | 1.161 | 1.438 | 1.717 |
| | s.d. | 0.104 | 0.111 | 0.169 | 0.212 |
| Jet | mean | 0.920 | 1.161 | 1.440 | 1.755 |
| | s.d. | 0.140 | 0.211 | 0.270 | 0.280 |
| Quattro | mean | 0.950 | 1.316 | 1.671 | 2.061 |
| | s.d. | 0.130 | 0.210 | 0.326 | 0.426 |
| Ocean | mean | 0.890 | 1.126 | 1.406 | 1.721 |
| | s.d. | 0.110 | 0.150 | 0.155 | 0.154 |
| Compro | mean | 0.953 | 1.217 | 1.473 | 1.773 |
| | s.d. | 0.146 | 0.124 | 0.164 | 0.252 |
| Mean | | 0.850 | 1.130 | 1.408 | 1.716 |
| s.d. | | 0.131 | 0.121 | 0.124 | 0.178 |

* significantly higher than the average value
**significantly lower than the average value
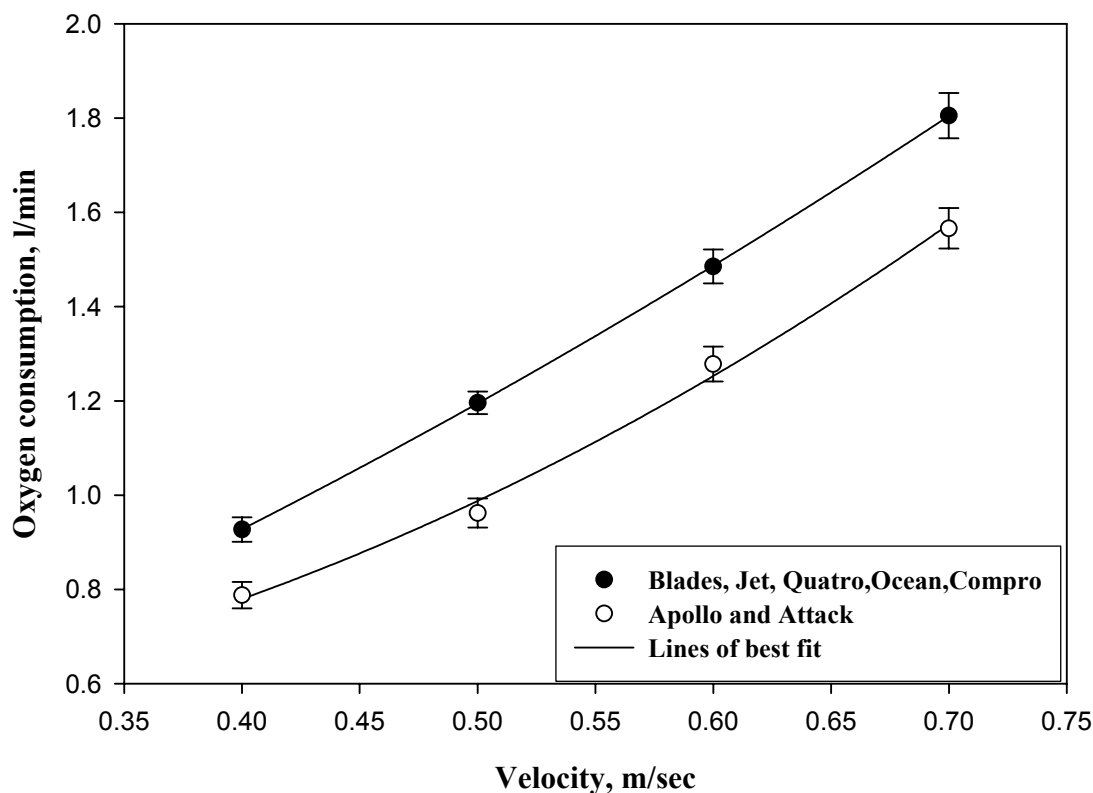
**Figure 1.** The average (± s.d.) steady state oxygen consumption for the groups of fins with the highest (●) and lowest (○) $VdotO_2$ are plotted as a function of velocity. The best-fit lines for a second order polynomial are shown (see text for equations).

Of the most economical fins there was no difference in the Apollo fin when swum with or without (split taped closed) the split, suggesting that the split was ineffective in improving economy. The primary difference in the Apollo fins, compared to the other fins studied, is that they are very flexible. Interestingly the other economical fin was the Attack fin, which had the greatest surface area and was the least flexible fin studied.

Fin economy was not affected systematically by vents as $VdotO_2$ of 3 fins with vents (Jet, Ocean, Compro) were not different from fins without vents (Blades, Quattro); with other physical characteristics being similar. Similarly fins with ribs (Blades, Jet, Compro) had similar VdotO2 levels to fins without (Quattro, Ocean). The width and length of the flanges did not appear to make a difference as well since fins with full or ½ length, wide or narrow or straight or tapered had $VdotO_2$ values that were not different from each other.

The maximal aerobic power, the velocity at maximal aerobic power (velocity that could be sustained aerobically) and maximal tethered force (thrust) are shown in Table 3 while swimming with each fin. Average $VdotO_2$max for all fins was 1.462 ± 0.046 l/min, and were not significantly different among the fins. The maximal aerobic speeds for all fins averaged 0.61 ±

0.04 m/sec, while the Apollo taped was higher (16%) than the remainder of the fins, which were not statistically different from each other.

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

|  | Attack | Apollo | Apollo T | Blades | Jet | Quatro | Ocean | Compro |
|---|---|---|---|---|---|---|---|---|
| **Aerobic Power (l/min)** | | | | | | | | |
|  | 1.407 | 1.446 | 1.547 | 1.483 | 1.436 | 1.494 | 1.463 | 1.419 |
|  | 0.229 | 0.187 | 0.292 | 0.145 | 0.207 | 0.309 | 0.234 | 0.254 |
| **Aerobic Velocity (m/sec)** | | | | | | | | |
|  | 0.61 | 0.64 | 0.71* | 0.60 | 0.60 | 0.57 | 0.58 | 0.60 |
|  | 0.09 | 0.08 | 0.11 | 0.10 | 0.10 | 0.10 | 0.09 | 0.10 |
| **Maximal Tethered Force (Neutrons)** | | | | | | | | |
|  | 90 | 111 | 102 | 116 | 111 | 109 | 101 | 92 |
|  | 42 | 46 | 44 | 36 | 71 | 40 | 60 | 36 |

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

**Maximal Thrust**

The average maximal thrust that could be developed by all fins was $104 \pm 9$ N.  The Attack and Compro fins generated significantly less force (16%) than the other 6 fins (Apollo, blades, Jet, Quattro, Ocean), which were not different from each other ($108 \pm 6$ N).  The Attack and Compro fins were the most rigid fins, but their other characteristics were generally not different from the remainder of the fins. The absence of differences among flexible and rigid fins, where you would expect greater thrust from the rigid fin, suggests that the subjects were limited by leg power.

**Kick Frequency-velocity**

The data for the maximal velocity that can be achieved as a function of kick frequencies (Kf) are shown in Table 4 for each fin.  The average values of max d/K and Kf at the max d/K were $0.86 \pm 0.08$ m/k and $49 \pm 5$ k/min.  The max d/K increased as a function of stiffness (EI, table1) (d/K=0.06 EI+0.72 (r=0.93)).  Similarly the d/K at max V increased linearly with stiffness (EI) (d/K=0.04 EI + 0.57(r=0.94)).

**Table 4.  Analysis of kick frequency and velocity relationship for all fins**.

| Fin | Max d/K | Kf Max d/K | V max | Kfmax | d/K at v max |
|---|---|---|---|---|---|
| Attack | 1.04* | 43** | 0.9 | 72 | 0.87 |
|  | 0.21 | 8 | 0.13 | 18 | 0.30 |
| Apollo taped | 0.82 | 56* | 0.91 | 79 | 0.66 |
|  | 0.13 | 11 | 0.12 | 24 | 0.2 |
| Apollo | 0.82 | 55* | 0.89 | 85 | 0.66 |
|  | 0.14 | 13 | 0.14 | 25 | 0.17 |
| Blade | 0.90 | 48 | 0.86 | 80 | 0.69 |
|  | 0.20 | 8 | 0.13 | 26 | 0.17 |
| Quattro | 0.85 | 47 | 0.85 | 76 | 0.71 |
|  | 0.20 | 10 | 0.18 | 26 | 0.19 |
| Compro | 0.83 | 42 | 0.77** | 78 | 0.66 |
|  | 0.14 | 9 | 0.14 | 32 | 0.23 |
| Jet | 0.80 | 47 | 0.85 | 80 | 0.67 |
|  | 0.15 | 9 | 0.17 | 29 | 0.18 |
| Ocean | 0.81 | 53 | 0.84 | 79 | 0.67 |
|  | 0.15 | 10 | 0.13 | 25 | 0.20 |
| Mean | 0.86 | 49 | 0.86 | 79 | 0.07 |
| s.d. | 0.08 | 5 | 0.04 | 4 | 0.07 |

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

The d/K for the Attack fin was significantly higher (21%) than the remainder of the fins, which were not different from each other (0.83 ±0.03 m/K). The Kf at the max d/K were highest for the Apollo and lowest for the Attack. The maximal velocity (aerobic + anaerobic metabolism) averaged 0.87 ± 0.06 m/sec, with a max Kf of 79 ± 4 k/min.  The maximal swimming velocity was highest for the Attack (13%) with all other fins being similar (0.67 ± 0.02 m/sec). The maximal Kf were not different among the fins, and only the Attack fin's d/K at v max was significantly greater than the other fins (24%).

The major difference in the Kf-v relationship among the fins was that more flexible fins had to be swum at 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.

**DISCUSSION**

The data from the present study demonstrate that the most economical fins (15 %) for women were the two Apollo fins and the Attack fin, with the other fins being similar to each other.  The Apollo fin with the split taped (solid blade) was significantly better at the two faster

speeds (14%) than the Apollo and Attack.  The energy cost to travel one meter was 31 ml at slow speeds and increased as a function of velocity to 34 ml/m at 0.7 m/sec.

The energy cost of swimming was 14 to 18% lower in women than men (14) irrespective of speed or fin.  Previous studies have reported similar finding for both surface (15) and underwater swimming (12).  This difference has been shown to be due to lower torque in women, secondary to lower body density, particularly in the lower extremities (15).  This conclusion is supported by the data from the present study, as women had 20% body fat compared to values previously reported for male divers of 12% (14).

The maximal velocity of swimming is dependent upon the energy cost of swimming and the metabolic power.  The maximal aerobic power of the women was not affected by fin type and averaged 1.462 l/min.  This value is 39% less than reported for male divers with similar experience using the same measures. After correction for lean body mass (79.96 Kg and 54.16 Kg, respectively) $VdotO_2max$ between men (14) and women are not different (30 and 27 ml/min/kg), indicating that the fitness of the female and male divers were similar.  Since the economy of swimming is not dependent upon body weigh in air the absolute energy cost and maximal aerobic power determine swimming performance, thus energy cost and maximal $VdotO_2$ are lower in female than male divers.

The maximal aerobic speeds of women were faster for the most economical fins (7%), which was due to higher economy and similar $VdotO_2$ max. among the fins.  Compared to men (14) the maximal aerobic speeds was 21% lower, as the 39% lower $VdotO_2max$ was partially offset by the lower energy cost of swimming.

The energy cost of swimming (economy) is determined, in part, by the body drag.  The drag that the diver must overcome has to be overcome by a propulsive force or thrust.  The thrust produced during a kick cycle by male divers has been shown to be greater in the more economical fins and related to the distance the body travels per kick (V/kick frequency) (14).  Although drag or thrust was not measured directly in this study, the maximal d/k was significantly greater in the Attack fin (30%) than the other fins, however the economy was similar in the Attack and Apollo fins although their d/k was 21% lower, suggesting other factors influence economy in women.  The d/k for women was 15% lower than men (14) for all fins and speeds, but the economy was better.  The average kick frequencies at the maximum d/k for all fins, and at all speeds, were similar in women and men (50 and 52 k/min) (14).

Women have been shown to have lower leg strength and power than men (1), thus it is reasonable to suggest that they would be able to generate less maximal thrust than men.  Lower leg power in women prevents deep vertical kicks, particularly with large rigid fins, with women compensating by kicking less deeply or turning the edges of the fin vertically to reduce the drag (as seen on the video tapes of these studies).  The combination of lower thrust, less vertical displacement and increased drag during recovery would require a higher kick frequency in women to meet the overall thrust requirements.  A high kick frequency increases the internal work and thus the energy requirement (16) as moving a small mass of water rapidly is less efficient than moving a large mass of water slowly (17).

A significant positive correlation between fin stiffness (EI) and thrust was observed and previously reported (14), reflecting a deeper kick, and resulting in a greater distance of travel of the body per kick.  Previous studies in male divers have shown that fins that are curved on the underside give better economy than straight fins (10), presumably due to more thrust in the power phase.  These fins however may lose power (drag) during the recovery and transition phases and thus average power would be lower, as seen for the Compro fin in this study.

It has been previously reported that large rigid fins have greater maximal thrust, and thus a diver using these fins may generate more pulling power and fast speeds (10, 11). Previous studies in male divers have reported maximal thrust of 64 to 78 N with the maximal sustainable thrust of 40 N (3, 18). The maximal values measured in the present study for women were 104 ± 9 N, 29% less than men (14), and were not significantly different among the fins. The proposition that rigid fins develop greater maximal thrust and speed was supported by this work, as maximal velocities of 0.91 m/sec were observed in rigid fins (Attack) compared to flexible fins (Apollo), which had a 14% lower d/k.

Based on the physics of fin swimming using the Lighthill model (16, 19) and the VdotO$_2$, velocity and d/k data, it is clear that some fins have better performance (Apollo taped, Attack, Apollo) than other fins, but this cannot be ascribed to a single fin characteristic. It is clear that venturis, vents, trauths, or 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. Women have reduced metabolic power and thrust, compared to men, however their energy cost of swimming is less, both of which are due to the lower body weight and density. It is clear however from the subjective opinion of the divers and quantitative data, that a more flexible fin was better for the female divers in this study, however increasing leg power could change these findings, as this seemed to be the major factor in the performance of the fins for female divers.


## ACKNOWLEDGMENTS

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