NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 11-90

OXYGEN CONSUMPTION DURING UNDERWATER FIN SWIMMING WEARING DRY SUITS

LCDR JOHN A. STERBA, MC, USNR

MAY 1990

NAVY EXPERIMENTAL DIVING UNIT

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Oxygen consumption ($\dot{V}O_2$) during underwater fin swimming was measured with divers wearing dry suits in near-freezing water. During the last 30 min of a 40 min swim, $\dot{V}O_2$ was measured in eight U.S. Navy divers swimming in a cold water (2°C) flume. Each diver swam seven times, evaluating seven pairs of fins determined to have a large enough foot pocket to be used with dry suits with thick insulation. Weight distribution, volume of dry suit gas, and dry suit diving experience were all controlled. Swimming depth was 3 m (9.8 ft) in a large area of constant flow in the cold water flume. $\dot{V}O_2$ consumption was calculated from loss of O_2 bottle pressure, measured on-line and corrected for depth and temperature, to units of ml/min, standard temperature, pressure, dry (~~STPD~~). VO_2 during swimming at 0.5 ± 0.1 (SD) kns, determined to be ideal for long distance swimming,
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averaged 1,252.4 ± 87.2 (SE) ml/min (n = 56) for eight divers, averaging seven pairs of fins. Corrected for body weight, $\dot{V}O_2$ was 15.8 ± 1.1 (SE) ml/kg/min.

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CONTENTS

Page No.

I. INTRODUCTION 1

II. METHODS 1

A. SUBJECTS 1

B. DIVING EQUIPMENT 1

C. CONTROL OF CONFOUNDING VARIABLES 2

D. OXYGEN CONSUMPTION 3

E. ACCURACY OF MEASUREMENTS 3

F. COLD WATER FLUME 4

G. PROTOCOL 4

H. DATA ANALYSIS 4

III. RESULTS 4

IV. DISCUSSION 5

V. CONCLUSIONS 5

REFERENCES 6

TABLES

Table No.		Page No.
1	Fin number, size, blade description, and manufacturer.	9
2	Oxygen consumption for fin swimming at 0.5 kns (mean ± SD, n = 8 subjects) for seven pairs of fins, with overall mean (± SE).	10

ILLUSTRATIONS

Figure No.		Page No.
1	Cold water swimming flume at the Navy Experimental Diving Unit, Panama City showing divers free-swimming and data aquisition area on the mezzanine.	11
2	Oxygen consumption vs. fin number during swimming at 0.5 kns (mℓ/min, mean ± SD, n = 8 subjects).	12
3	Oxygen consumption, normalized by body weight vs. fin number during swimming at 0.5 kns (mℓ/kg/min, mean ± SD, n = 8 subjects).	13

I. INTRODUCTION

There is an absence of published data on oxygen consumption ($\dot{V}O_2$) for underwater fin swimming wearing dry suits during diving in near-freezing water defined as a sea water temperature to -2.0°C (28.4°F), and fresh water to 1.7°C (35.0°F). This empiric data is not only useful for determining the metabolic rate of exercising divers, it is needed for the evaluation of closed circuit underwater breathing apparatuses (UBA) to assist in predicting both oxygen bottle duration and carbon dioxide scrubber capacity.

Claims of swim fin performance by manufacturers are without data from any reported physiological or human factors study. The few studies measuring the $\dot{V}O_2$ of underwater fin swimming, summarized by Lanphier (1), were done from 1954 to 1957 before the introduction of currently used cold water diving fins which have large foot pockets to accommodate the thick undergarment insulation for thermal protection of the feet. At the Navy Experimental Diving Unit (NEDU), an international survey was conducted of military cold water diving units in the United Kingdom, Canada and the United States, as well as diving fin manufacturers. Seven, large foot pocket fins of varying design were identified as being candidates for cold water diving. Table 1 describes each fin for size, blade type and manufacturer. The purpose of this study was to determine oxygen consumption during free-swimming using all seven pair of fins with experienced U.S. Navy divers. To conduct this study, a physiology laboratory with a cold water flume was designed and is briefly described.

II. METHODS

A. SUBJECTS

Eight U.S. Navy divers selected as experimental subjects were medically screened by history and physical exam before voluntary participation in this study. Each diver, although very experienced in cold-water dry suit diving, received specific training in dry suit diving, buoyancy control and fin swimming in the cold water flume. The U.S. Navy divers in this study were physically conditioned with underwater swimming and regular physical training prior to this study. Anthropometric data (mean ± SD) on the eight subjects were, age: 30.6 ± 4.7, weight: 80.3 ± 10.2 kg, height: 179.8 ± 6.1 cm, body surface area: 1.99 ± 0.13 m^2, and body fat: 20.2 ± 6.2 % determined by four-site skin fold thickness using a skin fold caliper (2).

B. DIVING EQUIPMENT

Underwater swimming performance, thermal balance and energy cost may be affected by the comfort, fit and flexibility between dry suits and undergarments. Therefore, the selection of one dry suit and undergarment was based on a formal survey of military cold water diving units and dry suit manufacturers (3), unmanned testing of undergarments (4-5) and manned evaluation of dry suits and undergarments at NEDU (6-7) and in the Arctic Sea (unpublished observations). In the U.S. Navy, the selection of both dry suits and undergarments, called diver Passive Thermal Systems (PTS), is by diver preference (8-9). Changes in fit between commonly shared dry suits, especially wrist and neck seals, can greatly affect diver comfort during free-swimming. In addition, anecdotal reports received by NEDU suggest that two-piece construction of undergarments may be less insulating compared to the better fit of one-piece construction undergarments. Therefore, both the dry suit and the one-piece construction undergarment were custom made for each diver-subject.

From the skin, outward, the following garments were worn: light weight polypropylene long underwear, single-piece construction vapor barrier nylon shell (Diving Unlimited International (DUI), San Diego, CA), and M-400 weight Thinsulate undergarment (DUI), with the flannel side next to the vapor barrier and outer surface of the Thinsulate made of vapor barrier nylon. Evaluation of the dry insulation of this M-400 Thinsulate undergarment at an equivalent suit squeeze of 1.1 psi (0.76 m, 2.5 ft of depth) was determined to be 0.68 clo, or 1.69 clo/cm (mean +/- SD, n=5) (3-4). The dry suit used was made of vulcanized rubber (model: Pro, military version, Viking America, Inc., Solon, OH). After purging all air from the dry suit just below the surface, each diver was individually weighted to be neutrally buoyant in the swimming position using a weight vest (Zeagle, model Alpha, Zephyrhills, FL) averaging 15.9 kg (35 lb) of lead shot. At 3 m swimming depth, only enough dry suit air was added to remain neutrally buoyant in the swimming configuration. The MK-15 MOD 0 closed circuit UBA was used with a full-face mask (AGA, Interspiro, Branford, CT) with reduced volume faceplate having lead counter weights (total = 1.4 kg. 3 lbs) for neutral buoyancy. Any leak in the dry suit, determined during the dive or incidentally noted after the dive during undressing eliminated that data from the study due to the additional thermal stress.

Swim fins are selected by U.S. Navy divers by personal preference (8-9). In Table 1, each fin is described.

C. CONTROL OF CONFOUNDING VARIABLES

From earlier studies, increasing underwater swimming speed has been demonstrated to increase oxygen consumption (10-14). For this study, the underwater swimming speed was predetermined to be 0.5 nautical miles/hr (kns). This was determined to be a typical swimming speed for long distance underwater fin swimming with dry suits by consensus of 10 U.S. Navy divers swimming in the cold water flume. Although all ten divers complained of over-exertion during a 30-min swim at 0.7 kns, oxygen consumption data will be reported for comparison.

To control for variation in drag underwater, one type of commonly used underwater breathing apparatus (UBA) was used, the MK-15 closed circuit UBA. With drag increasing underwater with swimming near any surface, divers swam alone in the center of the cold water flume.

Preliminary testing demonstrated that ten U.S. Navy divers could not maintain depth control with fin swimming at 1.5 m (5 ft) due to large buoyancy changes in the dry suit at such a shallow depth. Swimming at 3 m, which is a common depth for long distance swimming, corrected this buoyancy control problem.

The diet was not modified by excessive carbohydrates or lipids to attempt to improve the metabolic response to cold water. An adequate breakfast the day of an experimental dive was ensured. Hydration was encouraged and any exercise or diving within 24 hours was prevented to avoid dehydration. Caffeine consumption was kept to a minimum but could not be eliminated in these subjects. Alcohol consumption was limited and not consumed 24 hours prior to diving. All dives began at the same hour of the day to avoid any potential influence of circadian rhythm. A minimum of 48 hours elapsed between experimental dives for each subject to allow complete recovery.

Even though changes in kick frequency might affect the energy cost of underwater fin swimming, it was not controlled. The U.S. Navy divers in this study were very experienced in underwater fin swimming and it was beyond the scope of this project to change how they swam underwater without rigorous retraining.

D. OXYGEN CONSUMPTION

The MK-15 closed circuit UBA has been used to calculate $\dot{V}O_2$ based on changes in oxygen bottle pressure (15). In this study, the calculation of $\dot{V}O_2$ was based on changes in oxygen bottle pressure corrected for the diver's swimming depth, temperature of the water, and the exact internal (floodable) volume of the oxygen bottle. Equation 1, below, calculates $\dot{V}O_2$ corrected to units mℓ/min, standard temperature pressure dry (STPD). The values of $\dot{V}O_2$ were also normalized by body weight (mℓ/kg/min) for each subject.

$$\dot{V}O_2 = \Delta P/\text{min} \cdot V_b/14.7\ \text{PSIG} \cdot 273/(T+273) \qquad \text{Eqn 1}$$

where: $\dot{V}O_2$ = oxygen consumption, mℓ/min, STPD
ΔP = change in oxygen bottle pressure, corrected for depth
V_b = oxygen bottle's floodable volume, 2868 ml
PSIG = pounds per square inch, gauge
T = water temperature, °C

Since oxygen is not added for lost volume in the breathing circuit, any leaks from the full face mask or off-gassing from the MK-15 UBA would not affect accuracy of $\dot{V}O_2$ calculation. Oxygen is only added for a change in oxygen content below a set point of PO_2 equalling 0.7 atmospheres absolute (ATA). The diluent bottle was filled with 55% O_2, 45% N_2, approximately a PO_2 of 0.7 ATA at 3 m. The diluent bottle was turned off after purging the MK-15 UBA breathing volume before data collection.

E. ACCURACY OF MEASUREMENTS

Oxygen bottle pressure was measured using a submersible, solid state pressure transducer (Druck, Inc., model PTX-160/D, Newfairfield, CT) with an accuracy of +/-0.1% full scale deletion. Water flow in the flume was measured using a portable liquid flow meter (Swoffer, model 2100, Seattle, WA) with a reported degree of accuracy of ± 0.04 kns. Water flow in the swimming area at 3 m was repeatedly measured with an overall accuracy of ± 0.1 kns for maintained flows of 0.5 and 0.7 kns.

F. COLD WATER FLUME

The cold water flume shown in Figure 1 measures 4.6 m deep, 4.6 m wide, and 9.2 m long with the swimming area being 4.6 m deep, 2.3 m wide and 4.6 m long. The entire column of water is circulated by two, 1.7 m diameter propellers which control water flow in increments of 0.1 kn to a maximum of 1.5 kns. The swimming area was designed to allow two divers to be separated by 2.0 m in the constant flow area. Turbulent water flow was outside the swimming area. In this study, each diver swam alone in the center of constant flow at a depth of 3 m at 0.5 and 0.7 kns.

G. PROTOCOL

The diver quickly dressed into the dry suit assisted by two tenders and entered the water under 10 min to avoid unnecessary heat stress. After entering the water, purging the dry suit, and assuming a prone position, a randomly selected pair of fins unknown to the diver was securely placed on the diver using fin keeper straps. After a 10 min period to ensure the O_2 bottle temperature equilibrated to the 2°C (35°F) water, the diver descended to 3 m and trimmed buoyancy for free-swimming. The MK-15 UBA was purged with diluent, the diluent valve was turned off, and the MK-15 UBA breathing volume and oxygen bottle pressure stabilized before oxygen bottle pressure measurements were made. Oxygen bottle pressure was monitored and data stored using an automated diver monitoring system (DMS) described elsewhere (16-17). Preliminary testing determined rectal core temperature to remain stable (37.1 ± 0.3(SD)°C, n = 8), therefore it was not measured.

The cold water flume, Figure 1, took one minute to arrive at a steady state speed of 0.5 or 0.7 kns. The first 10 min of underwater swimming was not considered steady state for data analysis. Following this 10-min period, 30 min of oxygen bottle pressure data was collected for calculating $\dot{V}O_2$. A separate study with the same protocol was done with all eight divers using fin #7 swimming at an increased speed of 0.7 kns.

This experimental protocol was approved by the Committee for the Protection of Diver Subjects at NEDU.

H. DATA ANALYSIS

The slope of the change in oxygen bottle pressure was calculated by least squares for the 30-min period of free-swimming. The $\dot{V}O_2$ (mean ± SD) is reported for all eight divers, each using seven pairs of fins (n = 56) for 0.5 kns and with fin #7 for 0.7 kns (n = 8). Analysis of variance determined any differences in $\dot{V}O_2$ between fins at 0.5 kns with significance accepted at $p < 0.05$.

III. RESULTS

For swimming at 0.5 kns, Table 2 lists $\dot{V}O_2$ in units mℓ/min and mℓ/kg/min (mean ± SD) for each of the seven fins for all eight divers. For all fins combined, $\dot{V}O_2$ (mean ± SE) was 1,252.4 ± 87.2 mℓ/min or 15.8 ± 1.1 mℓ/kg/min. Figure 2 and 3 illustrate the $\dot{V}O_2$ data at 0.5 kns in units of mℓ/min and mℓ/kg/min, respectively, for individual fins. There were no significant differences between fins for $\dot{V}O_2$ or $\dot{V}O_2$ normalized by body weight.

At 0.7 kns, $\dot{V}O_2$ was 1,864.1 ± 447.5 mℓ/min/kg or 24.5 ± 7.3 mℓ/kg/min (fin #7, mean ± SD, n = 8 subjects). However, 0.7 kns was considered subjectively to be too fast for sustained swimming longer than 20 min by the eight subjects during the 30 min swim.

For comparison, 0.5 nautical mile/hr (kns) equals 16.4 yd/min, 15.0 m/min, or 0.6 statute (land) miles/hr. Likewise, 0.7 kns equals 23 yd/min, 21.0 m/min, and 0.8 statute miles/hr.

IV. DISCUSSION

At the same swimming speed, 0.5 kns, the value of VO_2 from swimming with dry suits (1.25 ℓ/min) was approximately 56% higher than reported by Lanphier (0.8 ℓ/min) for divers wearing only minimal protective clothing (10). Comparing the VO_2 in our study to the same $\dot{V}O_2$ in Lanphier's study, divers with minimal protective clothing swam at 0.8 kns, 60% faster than our study (0.5 kns). The high value of VO_2 in our study is attributed to increased drag and decreased swimming efficiency from wearing thick undergarment insulation, the dry suit, a heavy weight vest, and the cumbersome MK-15 UBA.

In our study, well conditioned divers complained that 0.7 kns was difficult to maintain for swims longer than 20 min, despite only a moderately high value of $\dot{V}O_2$ (1.9 ℓ/min). The $\dot{V}O_2$ of maximum effort during stationary fin swimming against a submerged trapeze has been reported by Morrison to be 2.5 ℓ/min (13). This closely approximated the mean $\dot{V}O_2$ for divers free-swimming at 1.2 kns with minimal protective clothing (10). Above 1.2 kns free-swimming, divers were noted to tire rapidly (10). For comparison, divers of average size and reasonable fitness have been reported to have maximum $\dot{V}O_2$ of at least 3 ℓ/min (1). Our results indicate that despite only moderately high $\dot{V}O_2$ at 0.7 kns, underwater fin swimming with restrictive garments and equipment may give the sensation of near-maximal exertion.

Differences in $\dot{V}O_2$ between various fin types in Figures 2 and 3 were anticipated based on diver preference following fin swimming in the cold water flume and open-water experience. The lack of statistically significant differences may be due to a small sample size for each fin (n = 8 subjects) and the variability in water flow of ± 0.1 kn in the cold water flume. The market survey and selection of these fins suitable for dry suit diving may assist others investigating underwater swimming performance wearing dry suits. Overall, divers unanimously agreed that the COMEX PRO fin had too small of a fin blade. All six other fins were found to be ideal for long distance cold water fin swimming.

V. CONCLUSION

The $\dot{V}O_2$ for underwater fin swimming wearing dry suits in near-freezing water is 1,252.4 mℓ/min or 15.8 mℓ/kg/min at a swimming speed of 0.5 kns, subjectively determined to be ideal for long distance swimming.

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Table 1
Manufacturers Key

Fin #	Fin Name	Size	Blade Type	Manufacturer
1	Alpha	X large	Unvented, Center flexible vein, 10.2 cm wide	Dacor Corporation Northfield, IL
2	Turboflex	X large	Vented, 3 vents, no vein	Dacor Corporation Northfield, IL
3	Turtle	One size	Vented (3 sets of 2 vents), no flexible Vein	International Divers Inc. Baymon, Puerto Rico
4	Plana Avanti	X large	Non-vented, 2 (2.5 cm) veins	USA, Seaquest Inc. Carlsbad, CA
5	Seawing	X large	Vented (2 small, 1 large), no veins	Scubapro, Inc. Rancho Dominiquez, CA
6	Comex Pro	One size	No vents, no veins, small blade	Comex Pro Marseille, Cedex 2 France
7	Power Plana	X large	No vents, no veins	USA, Seaquest Inc. Carlsbad, CA

Table 2
OXYGEN CONSUMPTION
(mean ± SD, n=8 subjects)

Fin #	$\dot{V}O_2$ (ml/min)	$\dot{V}O_2$ (ml/kg/min)
1	1,300.1 ± 297.6	16.4 ± 4.1
2	1,263.7 ± 239.1	16.0 ± 4.1
3	1,152.4 ± 156.3	14.5 ± 2.5
4	1,261.4 ± 194.1	16.1 ± 4.1
5	1,099.2 ± 196.1	13.8 ± 2.6
6	1,353.4 ± 183.6	16.9 ± 1.7
7	1,336.4 ± 198.2	16.7 ± 2.3
Overall mean ± SE	1,252.4 ± 87.2	15.8 ± 1.1

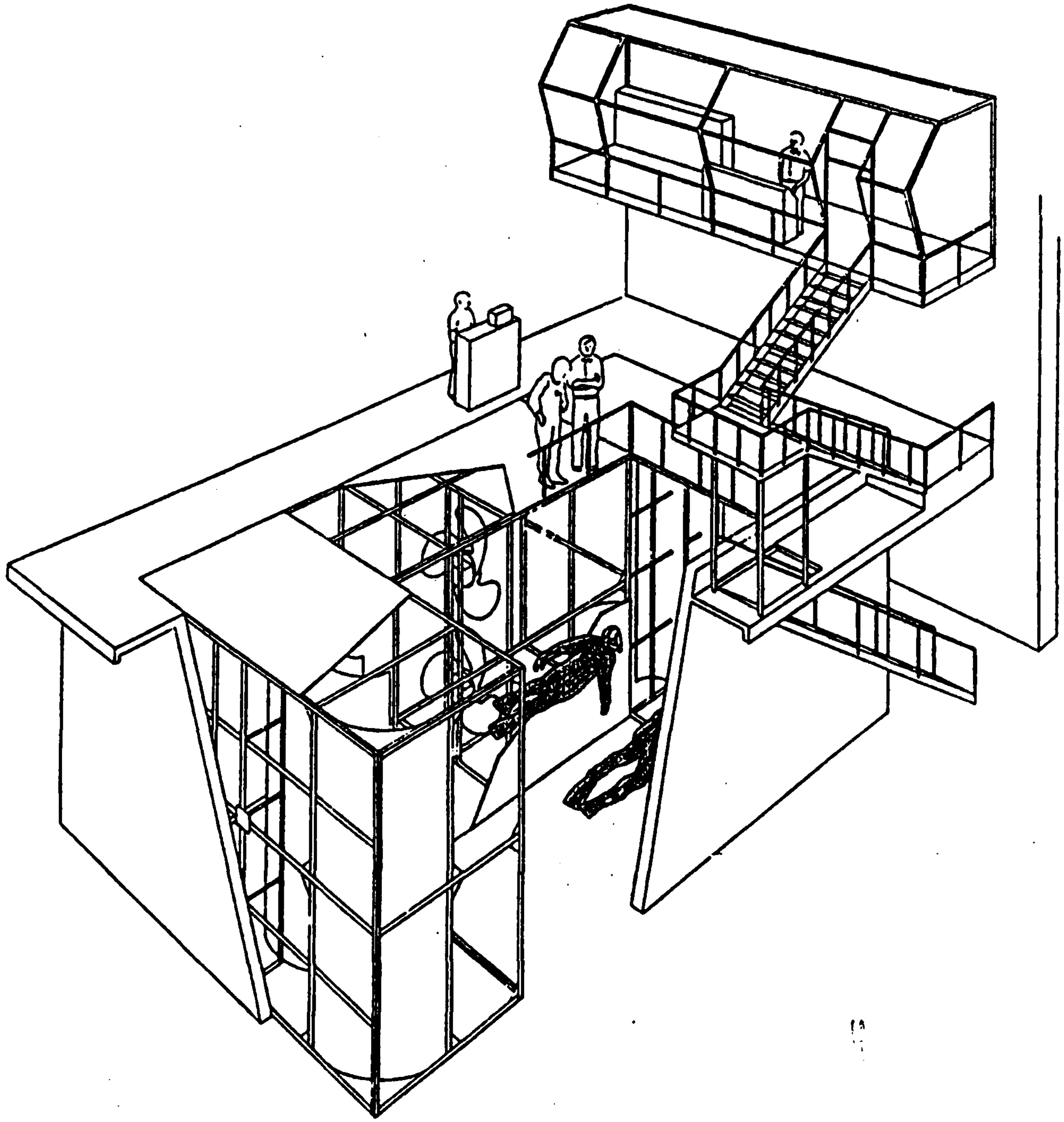

FIGURE 1. Cold water swimming flume at the Navy Experimental Diving Unit, Panama City showing divers free-swimming and data aquisition area on the mezzanine.

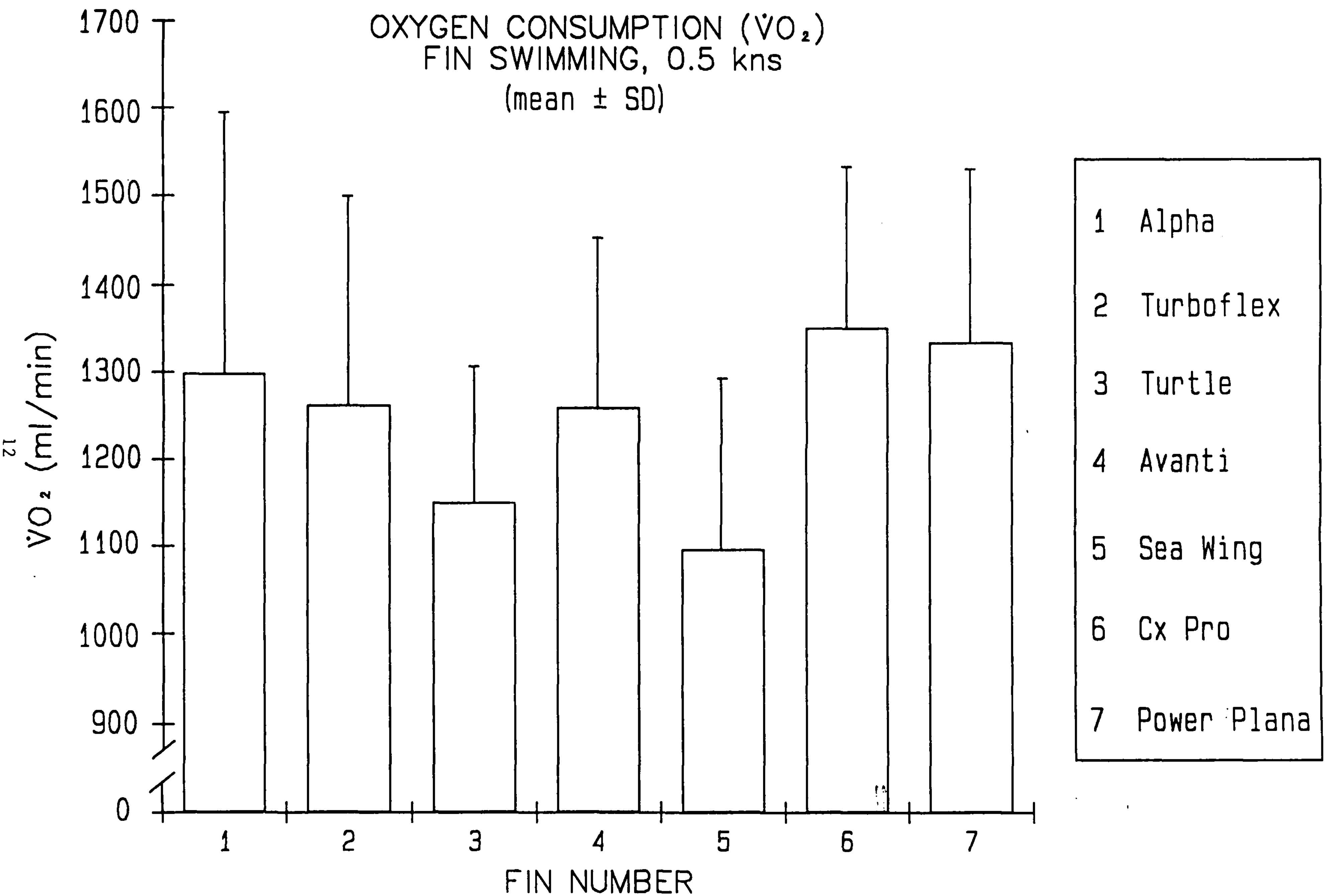
OXYGEN CONSUMPTION (V̇O₂)
FIN SWIMMING, 0.5 kns
(mean ± SD)
V̇O₂ (ml/min)
1700
1600
1500
1400
1300
1200
1100
1000
900
0
1
2
3
4
5
6
7
FIN NUMBER
1 Alpha
2 Turboflex
3 Turtle
4 Avanti
5 Sea Wing
6 Cx Pro
7 Power Plana

FIGURE 2.

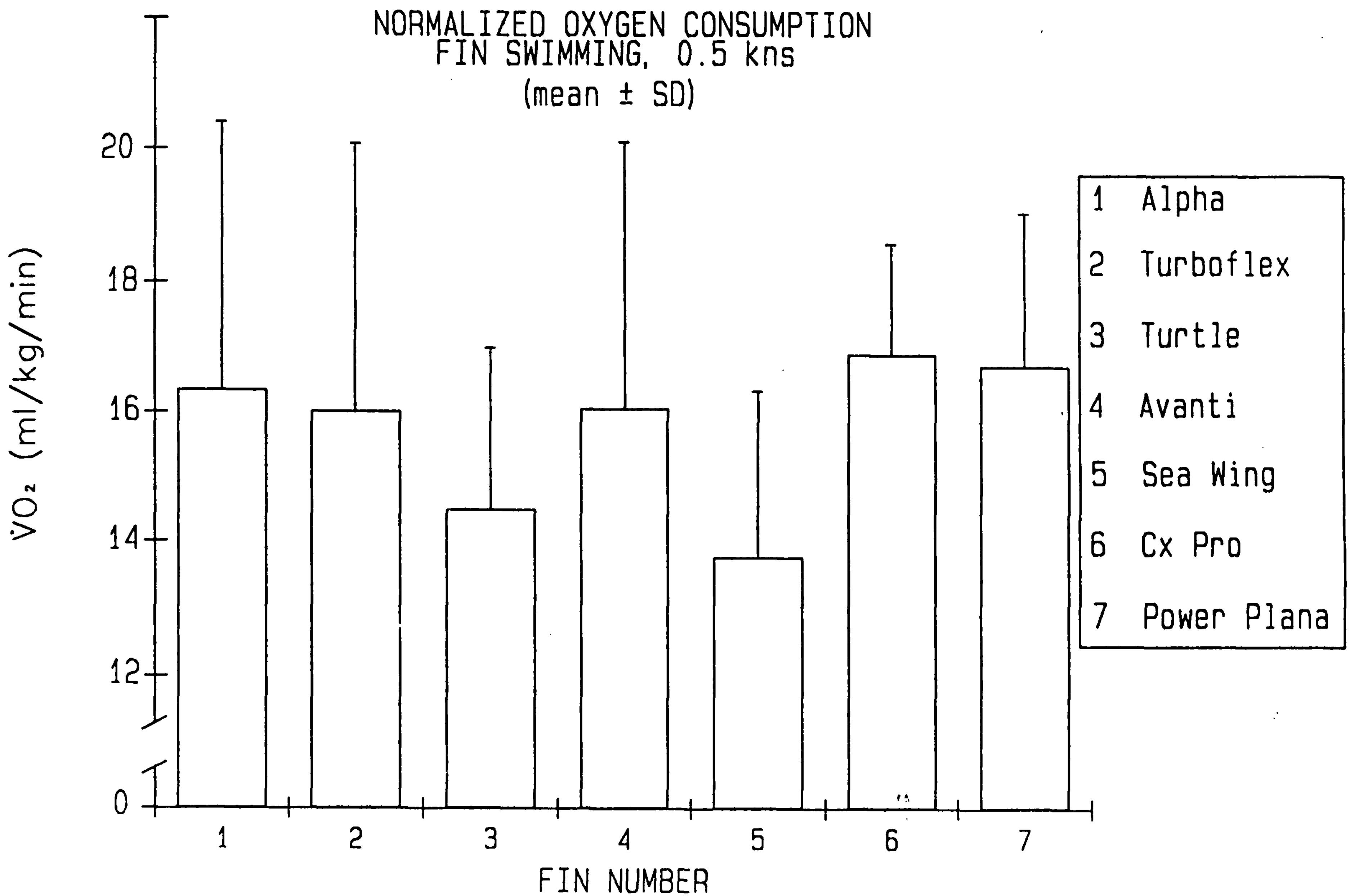
NORMALIZED OXYGEN CONSUMPTION
FIN SWIMMING, 0.5 kns
(mean ± SD)
V̇O₂ (ml/kg/min)
20
18
16
14
12
0
1
2
3
4
5
6
7
FIN NUMBER
1 Alpha
2 Turboflex
3 Turtle
4 Avanti
5 Sea Wing
6 Cx Pro
7 Power Plana

FIGURE 3.