Physiology of the Elite Rower

In this article I will try to provide an overview of the specific physiological characteristics of successful rowers. The article will grow in "chapters" as I complete them. Since data describing elite masters age rowers 35-80 years old really do not exist, (though we are working on it in the MARS study), I will focus on available data from young, elite men and women. I think it is a fair assumption that older successful rowers differ quantitatively but not qualtitatively from their young counterparts. I will draw much of the the information below from three excellent resources. Drs. Fred Hagerman of Ohio University in the United States, Dr. Neils Secher of Copenhagen, Denmark, and Dr. J.M. Steinacker of Ulm, Germany. All three physiologists have tested and examined large numbers of elite level rowers in their respective countries and published excellent reviews of their findings. I have had the opportunity to meet and talk with Hagerman, and Steinacker, but not Dr. Secher. What you read below represents their years of work, not mine.

CHAPTER 1

The Rowing Stroke

To the unitiated, a casual view of a rowing race might suggest that rowing is primarily an upper body sport. The error of this impression is well known by rowers. The rowing stroke takes advantage of a freely sliding seat so that the drive of the oar is sequentially aided by forceful extension of the legs, extension of the trunk, and a contribution of the arms that is minor in absoute force contribution but critical in technical importance. Since the boat is accelerated as it moves in reaction to the sweeping arc of the oar, acceleration will be proportional to force times time. Therefore the rower must achieve an optimal combination of high stroke power and long stroke length. This combined high force and long impulse duration requirement tends to select for rowers of a specific size and length.

SIZE and SHAPE

Compared to athletes in other endurance disciplines, successful rowers are as lean, but heavier and taller, with long arms, and a tall sitting height. Hagerman has collected data on more than 3000 elite U.S. rowers since 1964. Data from female rowers has been collected since the late 70s. Heavyweight oarsman averaged 6 feet 3.5 inches tall, and 194 pounds (1.92 m and 88kg). Their female counterparts averaged 5 feet 11" and 169 pounds (1.8 m, 77 kg). More recently, the average height and weight of the mens' and womens' U.S. 1992 Olympic team is reported in the table below (from Hagerman). As a reminder, 1kg = 2.2 pounds. 1inch = 2.54 centimeters.

TABLE 1 Physical Characteristics of Elite Rowers-1992 U.S. Olympic Team

	N	Age	HT cm	WT kg	Body Fat %
WOMEN	25	24	178.6	73.6	15.4
MEN	35	26	194.1	88.1	8.7

By comparing the 30 year data with the table from the 1992 Olympic Team, it is appears that the height and weight of elite rowers has changed little in the last 3 decades.. However, bodyfat % has decreased over three decades, so that lean body mass is higher today than in 1964.

It is also worth mentioning that the very best oarsman, winners of international medals, tend to be slightly heavier then this average, generally over 200 pounds (91 kg). The apparent advantage afforded the larger athlete in rowing has led to the inception of a weight restricted "lightweight" class of male and female rowers. Light weight men are restricted to a bodyweight of 72.5 kg while lightweight women must not exceed 59 kg. Data from U.S National team candidate testing suggests that lightweight males average 6 feet tall (1.84m) while lightweight females are about 5'7" (1.7m). Body fat percentage in the lightweight categories is not surprisingly even lower than that observed in heavyweights. Elite lightweight males average 5-7% body fat while elite females are under 15%.

CHAPTER 2

Physiological Characteristics of Elite Rowers-Maximal Oxygen Consumption

In the Table below, I have reproduced data presented by Dr. Fred Hagerman on the characterstics of the 1992 U.S: Olympic Team. This will serve as a basis for further discussions on rowing physiology. The data represent mean values for the group. So, there is a distribution above and below this mean.

TABLE 2: Peak Physiological Data- 1992 U.S. Olympic Rowing Team

Simulated Competitive Test. 2000m Ergometer race

N	Power (watts)	HR (b/min)	VO2 (L/min)	VO2 (ml/kg/min)	Lactic Acid (mmol/L)
males, 35	467	189	6.25	70.9	17.4
females, 25	310	190	4.31	58.6	13.1

Power Output

I think the female values have probably improved in the last 4 years, in parallel to the much improved performance of U.S. Womens teams at Worlds. However, these values remain representative. For the men, the power output corresponds to an average time of about 6:02 for 2000 meters. Among the U.S. guys, a best time of 5:48 has been performed. For the women, the average power translates to an **average** time of 7:01 for 2000 meters by the 25 team members. In 1994 the average for the top 10 heavyweight women was 6:52.5. It is likely that no one on the U.S. heavy weight women's team will be below the 7:00 standard in 1996. I do not have comparable physiological data for U.S. lightweights at the moment, but I discuss their performance data in "Ergometer Analysis".

Maximal Oxygen Consumption

The absolute values for oxygen consumption, as an average are among the highest reported among endurance athletes. These valuse represent the average of 25 and 35 athletes. The VERY best males (in the lab) have achieved values of 7.0 liter/min at max. Let me tell you, that is an extraordinary absolute V02 value! The very best females are at 5 liters/min, also extraordinary. This is not terribly surprising since rowers are very large for endurance athletes, and oxygen consumption increases with body size. However, when maximal oxygen consumption of rowers is scaled linearly with bodyweight, the values are less impressive. While 71 ml/min/kg is quite a "respectable" value (Average males of the same age are at 45 ml/min/kg), it is far from the 80-87 ml/min/kg values that currently typify the world elite cross country skiers and runners. The best female cross country skiers are over 70 ml/min/kg compared to about 60 for the female rowers. Are rowers undertrained, or undertalented? One problem with this comparison is a matter of scaling. Maximal oxygen consumption does not increase linearly with increased body mass (Click here for more on this). So, dividing VO2 by bodyweight is not really appropriate. Without going into details here, it is more appropriate to scale VO2 max to bodyweight^2/3. In the table below, I do this and contrast the data with 1) untrained males of normal weight, as well as 2) at the weight of elite rowers , and) elite cross country skiers. This will give you some idea of where rowers stand relative to the two extremes. Well I suppose being normal is not really an extreme, but you know what I mean.

TABLE 3 Maximal Oxygen Consumption- Comparison with Untrained Males and Elite Cross Country Skiers

Group	Weight (kg)	VO2 (L/min)	VO2 (ml/min/kg)	VO2 (ml/min/kg^2/3)
Average untrained U.S. male	72	3.25	45	187.5
Big, untrained male	93	3.91	42	190
92 Olympic Rowers males, 35	88.1	6.25	70.9	315
Top5 5 male rowers, U.S. (est.)	95	6.8	71.6	326
Top 5 male Rowers world (est.)	95	7.0	73.7	335
Top 5 World Cross Country Skiers	75	6.5	86.7	365

Elite Rowers have a maximal aerobic capacity about 1.75 times higher than same-age untrained males. However, compared to world class skiers, the best rowers are about 8-10% lower in maximal aerobic capacity, even after accounting for bodyweight differences with allometric scaling. (See Far right Column in table above). This is based on available physiological data from around the world The reasons for this difference are unclear. From a strict probability standpoint, we could argue that the subset of candidates for elite rowing that meet the "size requirements" for success from which performers are ultimately pulled is smaller than the pool from which skiers (and runners)are drawn.

These sports have less restrictive size demands, biomechanically. So, maybe the ultimate rowing athlete has not yet been discovered! Considering how good elite rowers are right now, I don't think I want to face him when and if he is!

Chapter 3: Skeletal Muscle Characteristics

Muscle Fiber type Mitochondria, and enzyme charectersitics

As observed repeatedly in runners, cross country skiers and cyclists, successful rowers are characterized by an above average percentage of type I (slow) fibers in their leg musculature. Several studies suggest that the Type I percentage is about 70% compared to 40-50% in the population at large. Furthermore, even among rowers, fiber type composition seems to be a descriminating variable. The more successful rowers have an even higher Type I composition. In internationally successful rowers, the percentage has been measured as high as 85% . The remainder are almost all type IIa fibers with almost no IIb fibers present. In general, it is concluded that the presence of substantial percentages of IIb (fast, low mitochondria) fibers in endurance athletes is indicative of either insufficient training years, or inadaquate intensity of training. Some older studies on national team females indicated more IIb fibers compared to elite males. However, the intensification of women's training programs in the last 5-10 years has probably narrowed or eliminated this descrepancy. With intense endurance training over a period of years, the fast IIb fiber subtype appears to convert to the fast IIa subtype that is characterized by greater fatigue resistance.

In trained rowers, the density of mitochondria is high, expressed as the ratio of mitochondria to fiber areas. This adaptation is evident in **both ST and FT fibers**. Measurements of oxidative enzyme activity reveals that successful rowers demonstrate the expected high levels of these enzymes in their rowing muscles. In contrast, glycolytic activity (a factor in **anaerobic** capacity), evaluated as the activity of the enzyme lactate dehydrogenase, is not different among groups of oarsmen. However, the better oarsmen possess a greater percentage of the "heart" subtype (LDH isoforms LDH_{1-3}) which has a lower affinity for pyruvic acid. In addition, muscle capillary density is twice as high in successful rowers as untrained. All of these characteristics contribute to a high work capacity and a reduced rate of lactate production at high workloads. The increased capillary density enhances the rate of lactate removal from the active muscle.

During my "rowing career", I have heard comments from presumably expert coaches that suggest that fast twitch fibers are important for "explosive leg drive" or "fast hands". I have tried to keep a straight face during these conversations, but this is simply wrong!. Even at high stroke rates, the contraction time of the rowing muscles is sufficiently long to allow slow twitch fibers to generate maximum force. Therefore, there is no advantage to possessing a high percentage of fast twitch fibers. To the contrary, they are conspicuously absent in the most successful rowers. I frequently blame my failure to row faster on my substantial endowment of fast fibers (varified by biopsy).

Muscle Size and Strength

The above characterstics are completely consistent with the expected metabolic profile of endurance trained muscle. However, rowers show abnormally large cross-sectional areas of individual muscle fibers, both fast and slow, when compared with the same fiber types in other endurance athletes. This is at odds with the general pattern of endurance adaptation (small muscle cell diameters mean reduced oxygen diffusion distances). Closer analysis of the task demands of rowing may help explain this difference. The stroke frequency of competitive rowing is quite low when compared to the contraction frequency employed in cycling or running. In contrast, the peak musclular force is substantially higher. The rower must adopt a pattern of work output that relies on relatively few periods of high force production with longer "rest" intervals between contractions. This pattern of activity is consistent with the development of larger muscle fibers, in appropriate response to the task demands. The extremes of aerobic capacity and muscle power necessary to ensure success in rowing are probably influenced by both genetic inheritance, and intense and specialized training.

Rowers tend to be stronger than other endurance athletes based on typical strength tests such as leg extensions. However, this greater strength often is associated with their inherantly greater size and muscle mass. Quoting Dr. Fred Hagerman, *"This increased strength should, in no way, be interpreted as translating into greater rowing power."* Dr. Secher says the same thing, *"Oarsmen are strong, reflecting thir large body dimensions, but their muscle strength is not correlated in any simple way to their rowing strength."* This premise is supported by several studies that indicate that strength data do not correlate well with rowing ergometer performance.

Only when a simulated rowing position is used does the strength of the best oarsmen distinguish itself from less qualified oarsmen. This supports the concept that even simple strength measurements are significantly dependent on skill. Secher has performed studies which suggest that oarsmen are unique in their ability to develop force with both legs simultaneously. This is a unique movement pattern in endurance sport. In untrained subjects and subjects trained in other disciplines, 2-legged strength is approximately 80% of the sum of the strength of the left and right legs measured seperately. This gap decreases in rowers due to their specific training.

I have gone back to the data I have on 500m, 2000m and 6000m ergometer performances from US national team candidates. The 500 meter is the closest performance measure we have that reflects anaerobic capacity. Even at this short distance, aerobic metabolism contributes significantly, but the 500m is a reasonable test length at any rate. Now what would the absolute best measure of "maximum functional strength" be for the rower? I think it would be the maximum power developed in the first five strokes from a dead stop in the boat. But, since that's not practical, we go to the erg. When I did just this type of test on collegiate rowers and compared it with power output maintained for 45 seconds, the correlation was about .90, which is very high. So, one maximal stroke is enough to predict performance reasonably well in a 250 meter sprint. This makes sense. Strength and anerobic capacity are both dependent on muscle mass. I accept that 250 meters and

500 meters on the erg are both reasonable measures of **anaerobic capacity**, so I hope you do. Now here is the important question. Muscle strength is strongly related to anaerobic capacity (500 meter time). But, is 500 meter performance time strongly correlated to 2k performance time? The answer is YES and NO. Yes, they are related if you take a range of people from untrained to elite oarsmen, or combine lightweight and heavy weight men and women into one very heterogenous group. But, NO they are not related when you look within a specific group of well trained rowers. When I determined the relationship between power output/kg for 500 meters and 2000 meters among 25 heavyweight men, the corrrelation was a weak 0.50. In the top 10 heavyweight women it was 0.07 or basically zero! Among the men, 500 meter power varied by 30 percent, while 2k power only varied by 10 percent.

To conclude this section, I will mention two studies performed by Hagerman and colleagues. The first, published in 1983, compared off-season and in season physical characteristics in 9 members of the men's US Olympic team. Ergometer performance power increased 14% from OFF season to IN season. Conversely, leg strength was significantly higher during the OFF season. This dissociation between maximal strength and peak rowing performance was more recently supported by a study completed in 1993, but as yet unpublished. This study compared physiological and performance variables in a group of rowers who performed weight training plus aerobic conditioning during the off-season to a group that did only aerobic conditioning. Dr. Hagerman concluded from the results that *"not only does supplemental weight training fail to improve physiologival and competitive performance, but more importantly it appears that weight training may actually detract from these performances."*

In elite level rowers, both men and women, it appears that there is an **optimal** level of muscular strength associated with success. This level appears to be achieved by the stress of intense rowing training. At this level, there is no evidence that supplementary weight training provides additional benefit. What is not clear from these data is whether the same is true for non-elite and older rowers. It is also reasonable to expect that supplementary strenght training in very limited doses can provided protection against injury due to muscular imbalance. These are important questions that I hope to learn more about in the future, as we try to find the best use of our often limited training time as masters athletes.

Ventilation and Rowing performance (examined specifically within the larger general article on ventilation)