Physiological Measurements

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Some or all of these responses will be measured, depending on the time available for testing, the types of tests conducted, and the objectives of the testing.

1. Exercise Tests

During the 25 years that our research group has evaluated elite rowers we have used a variety of tests to measure specific physiological responses. Currently we use exercise tests to simulate competitive efforts, evaluate anaerobic threshold, and observe responses to a standard submaximal exertion.

Simulated Competitive Effort (Max Test)

This has been the most consistent test we have used over the years and perhaps the most revealing. The test consists of a 2000 m all-out effort.

Since the physiological responses are obtained during simulation of a competitive effort, the results of these tests are probably the most applicable. Physiological data including ventilation, VO_2, heart rate, and lactates are usually the highest for these tests and although maximal respiratory, metabolic, and cardiovascular data are normally reported in the laboratory using a progressive exercise test to exhaustion on a treadmill or bicycle ergometer, it is our belief that the peak or highest values are indeed maximal. What is more important is that these peak or maximal values are obtained during an exercise that attempts to duplicate as close as possible a competitive effort.

We are now attempting to standardize these tests by consistently using the Concept II ergometer. The maximal test involves rowing 2000 m simulating as close as possible a competitive effort on the water for this distance. Depending on whether you are male or female, it usually takes between 5:30 minutes and 8:00 minutes to complete the 2000 m on the Concept II. The max test is performed with the speed ring vents closed and the chain placed on the small sprocket.

Direct Anaerobic Threshold (AT) Test

This test resembles a standardized progressive resistance test designed primarily to measure VO_2 max with the exception that during the early stages of the exercise the resistance is increased very slowly so that AT can be estimated by changes in ventilation, CO_2 output, and VO_2. In this test, when AT is reached, the athlete is then instructed to work maximally until exhausted. In this way both AT physiological and maximal physiological responses can be observed.

The following represent the AT procedures:

Time (minutes)	**Power (Watts)**
0-1	125
1-2	150
2-3	175
3-4	200
4-5	225
5-6	250
6-7	275
7-8	300
8-9	325
9-10	350
10-11	375

As seen in the suggested protocol the power output is carefully controlled before and beyond the AT level. However, once eleven minutes of exercise has been completed the athlete is instructed to row as hard as possible until maximal physiological responses are obtained. This usually occurs in minutes 11-12 for heavyweight men and earlier for heavyweight women and all lightweights, and since we are using either a semi-automated or automated metabolic measuring system, it is possible to determine when maximum values have been achieved.

Maximal-Submaximal Exercise Sequence

This test protocol was developed and first used in 1989 and has provided important information for the coach and athlete concerning training responses, especially changes in the utilization system. Following a maximal 2000 m effort on a Concept II ergometer on the previous day, the athlete performs two consecutive five minute ergometer efforts on the Concept II, the first at 70% of maximal power output recorded in watts on the previous day and the second at 85%. All ergometer tests are performed with the new speed rings, vents are closed, and the chain is placed on the small sprocket. Heart rate is monitored at the end of each minute of exercise and for each minute of a five minute recovery period following these submaximal efforts. A small blood sample is taken via finger prick at five minute recovery following each exercise and analyzed for lactic acid. It is important that the athlete not perform a vigorous warm-up prior to the first effort and that recovery following each submaximal effort be in a quiet sitting position. Heart rate is also observed at the end of each minute of the five minute recovery period.

The 70% test should elicit end-exercise heart rates in optimally trained rowers ranging from 140-150 b/min and lactates between 1.0-3.5 mmol/L while the 85% test should produce heart rates between 160-170 b/min and lactates between 3.5-5.0 mmol/L.

Once the maximal test has been performed then no further max testing is necessary. This initial max test becomes the baseline and the 70% and 85% tests can then be performed periodically during the training period to determine the effects of training. Since an abundance of utilization training is used these submaximal tests will provide an excellent means of charting training responses. As training progresses the heart rate and lactate values should gradually decrease for the standard exercises.

Submaximal testing has recently been revised so that now athletes perform three consecutive submaximal rowing tests on the Concept II ergometer at steady-state, again with the speed ring vents closed and the chain placed on the small sprocket. The testing protocol is based on a maximal 2000 m performance and dictates five minutes of rowing at approximately 60% of maximal power followed by another five minute test at 70% max power, and then ends with a final five minute test at 80% max power. Heart rate is monitored at the end of each minute of exercise for all three tests and blood samples are taken immediately after each of the first two tests and then after a five minute recovery period following the 80% test. As soon as the blood sample is taken following the 60 and 70% tests, the athlete begins the next test. The athlete should stretch well before the first test but should not warm-up on the ergometer; also no warm-downs should be performed as activity will affect lactate values.

The following is a detailed description of test protocol:

Category	60%		70%		80%	
	500m split	Stroke rate	500m split	Stroke rate	500m split	Stroke rate
Male Heavy	1:47	18-20	1:42	20-22	1:37	22-24
Female Heavy	2:03	18-20	1:58	20-22	1:53	22-24
Male Light	1:55	18-20	1:50	20-22	1:45	22-24
Female Light	2:11	18-20	2:06	20-22	2:01	22-24

Suggested heart rate and lactate ranges are as follows:

Percentage of maximum	HR (beats/minute)	LA (mmol)
60%	120-140	1-2
70%	140-160	2-4
80%	160-180	4-6

Results can be used to monitor training and determine relative aerobic and anaerobic fitness. It is recommended that some form of submaximal testing be conducted on a periodic basis in order to accurately plot training effects.

2. Body Composition

The ideal body weight, that weight which includes only a minimal amount of body fat, is an important factor. Excess weight, in the form of fat, is generally detrimental to performance. Accurate estimation of fat free weight (lean body mass), and fat mass (% fat), can be obtained by the underwater weighing procedures or skinfold determinations. Percent body fat values provide an objective guideline for adjusting body weight towards a more optimal lean/fat ratio as required by a sport. Percent body fat for rowers during the competitive season is as follows: heavyweight men, 8-10%; heavyweight women, 15-18%; lightweight men, 7-10%; and lightweight women, 12-15%.

3. Power

Power is measured and reported specifically in a variety of ways: horsepower, watts, ft.-lbs./min, kgm/min, and kilocalories/min. Power is defined as the rate of doing work. For exercise purposes power may be easily estimated by simply noting either the accumulated revolution data or direct display of watts or kcals on the rowing ergometer for a given time period or the final speed and percent grade of the treadmill at the end of a maximal exercise. If the maximal exercise test is progressive then noting the time to exhaustion is important. Also, if an individual is more fit they should be able to work at a higher percentage of their maximal physical work capacity for a longer period of time than their more unfit counterpart; this observation can be used to estimate power.

4. Pulmonary or Minute Ventilation

V_E is measured in liters per minute. This is the volume of air expired for a period of one minute and is equal to tidal volume (depth of respiration) x respiratory rate (number of breaths per minute). Maximal exercise values for highly conditioned male athletes can exceed 200 liters/min. Maximal V_E values for women can exceed 180 liters/min. This measurement increases proportionally to the body size of the individual, will become higher as respiratory fitness improves, and is elevated as metabolism is increased. If an individual can respire large volumes of air in a given time period it reflects exceptional lung power and excellent contraction capabilities of respiratory muscles.

5. Maximal Oxygen Consumption of Uptake

VO_2 max is measured in liters per minute or milliliters per kilogram body weight per minute. Maximum oxygen consumption is one of the best measures of general endurance fitness as many exercise physiologists believe that this variable, along with cardiac output, is probably the single most important limiting factor in one's ability to do prolonged work. This factor represents the combined ability of the respiratory and circulatory systems to pick up and deliver oxygen to the working muscles. It is therefore a measure of aerobic capacity. The measurement can be reported as an absolute value (liters/min) or as a relative value adjusted to body weight (ml/kg/min). Relative VO_2 is important during exercise when an individual is required to lift or move the body through a given distance over a prolonged period of time. Outstanding male distance runners and cross-country skiers have achieved O_2 uptake values in excess of 5.0 liters/minute and 80 ml/kg/min; their female counterparts have achieved the highest values among women athletes exceeding 4.5 liters/minute and 70 ml/kg/min. Recent research seems to indicate that to compete successfully as an international oarsman, absolute VO_2 should be about 6 liters/minute and relative values should be between 65-70 ml/kg/min. For women these values should range between 4.0-4.5 liters/minute and between 50-60 ml/kg/min. The absolute values are lower for lightweight rowers (4.5-5.5 for men and 3.5-4.0 for women) but since rowing technique dictates a sitting position perhaps the absolute VO_2 measurement should be considered the most important. Oxygen consumption is trainable and increases significantly in response to either single long sustained submaximal exercise bouts or many shorter intermediate bouts of running, swimming, cross-country skiing, cycling, or rowing.

6. Average Oxygen Consumption

This value can be reported either in absolute or relative terms (see VO_2 max), and may be even more important to the endurance-type athlete than VO_2 max. With the exception of the first minute of a high intensity exercise, during which aerobic metabolism is still increasing, it is important for a rower to achieve as high an average minute by minute O_2 consumption as possible. In this way, energy is derived more efficiently and the deleterious metabolic by-products (i.e., lactic acid) of anaerobic metabolism are significantly reduced. It is therefore important for oarsmen or oarswomen rowing a 2000 m piece, which is hopefully simulating a 2 km competitive row, to maintain as high an O_2 consumption as possible, particularly if the responses are representative of maximal power output on the ergometer. Because of the variability of aerobic metabolism during the first minute of simulated rowing, average O_2 consumption is the mean or average VO_2 for minute 2 through the end of exercise. An international caliber oarsman and oarswoman, with the exception of the first minute of exercise, should be able to maintain 98% or greater of their maximal oxygen consumption during this part of the test.

7. Heart Rate

The heart rate is measured in number of beats per minute. Heart rate increases proportionally with the intensity of the exercise and it is one of the easiest physiological variables to measure. It relates important information concerning the adaptability of the cardiovascular system to exercise. Heart rate can be used to determine the severity of an exercise and to indicate recovery ability of an athlete. It is often used as an indirect measurement of an individual's physical fitness and their response to a stress. Maximal heart rates for oarsmen usually range from 175-200 beats/minute while oarswomen's maximal heart rates are slightly higher ranging from 175-210 beats/minute.

8. Oxygen Debt

Oxygen debt is measured in liters or milliliters. This term originated from early research and is a misrepresentation of what really happens physiologically. We have no means of storing large quantities of O_2 in the body and therefore we have no source for borrowing it. Perhaps a better description of this measurement would be the ability to tolerate an O_2 lack or deficit. Oxygen debt is the volume of O_2 that is consumed during the recovery period following exercise above that ordinarily consumed at rest in the same time period and represents that O_2 which cannot be supplied during the exercise to sustain muscular contraction. The O_2 debt increases proportionally with the intensity of the exercise and indirectly represents anaerobic capacity. The total amount of O_2 needed to carry out a maximal endurance exercise always exceeds the amount that the athlete can consume (VO_2 or aerobic capacity). The athlete must therefore be able to tolerate or incur a temporary O_2 deficit during the exercise based on the inability of the O_2 transport system to keep pace with the total O_2 requirement of the exercise. During a submaximal exercise the O_2 requirement can be met almost fully by aerobic energy sources, but when the muscles begin to work at maximum energy levels their metabolic needs quickly exceed their ability to produce energy aerobically and thus the muscles must rely to some degree on their anaerobic energy sources. Anaerobic metabolism produces lactic acid and this substance has been found to increase proportionally with O_2 debt. Although some of the O_2 consumed during recovery following a maximal exercise is used to replenish small amounts of O_2 stores and energy sources, the largest portion is used to convert lactic acid onto glycogen. The recovery O_2 or O_2 debt apparently recharges our energy stores. At least 40-60 minutes are needed to achieve complete recovery following severe exercise if the athlete recovers in a sitting or reclining position. However, the recovery process can be accelerated by performing a mild or light exercise during recovery. This warm-down procedure seems to promote a more rapid oxidation of lactate by permitting the respiratory and circulatory systems to remain slightly elevated and thus transport the lactic acid more quickly to the muscles and liver where it is oxidized. A maximal endurance exercise of 5-7 minutes in duration should produce oxygen debts ranging from 10-20 liters.

9. Mechanical Efficiency

This parameter is specifically defined as a ratio:

$$\frac{\text{energy (work or power) output}}{\text{energy input}} \times 100$$

and is therefore expressed as a percent. In human energy cost studies, efficiency is indirectly estimated by calculating power output (watts, horsepower, kilocalories) on the treadmill or rowing ergometer and then placing this value as a common quantity (kilocalories) in a ratio with energy input, which is estimated by the amount of oxygen consumed. Since VO_2 can be converted to kcal, it is quite simple to get an estimation of efficiency. For our purposes, efficiency measures are valid and comparable only if each individual is working at prescribed equated or standard levels of exercise. Obviously the higher their efficiency value, the better. However, if a person works at only 70-75% of their maximal physical working capacity, efficiency measures could be higher since aerobic metabolism predominates in easier steady-state types of exercise. Therefore, obtaining a high efficiency value at maximal work or power output is a good indicator of potential excellence in performance. The highest efficiency values for human subjects range between 30-32% (competitive cyclists). Highest efficiencies recorded for rowers range from 20-24%.

10. Anaerobic Threshold

Anaerobic threshold (AT) is usually measured as that percent of maximal O_2 consumption or work below which no significant amounts of lactic acid are produced. In other words that point just before skeletal muscle metabolism shifts significantly from aerobic to anaerobic or that work level below which aerobic mechanisms can totally meet the energy demands of the exercise, and above which anaerobic metabolism becomes increasingly more important as exercise intensity is increased. As a result, the anaerobic threshold is an important factor to consider when an exercise lasts longer than one to two minutes, since the higher the anaerobic threshold, the longer a person can stay below the anaerobic threshold while exercising at an intensity close to maximum and thus delay the deleterious effects of anaerobic metabolism (production of lactic acid). When the average healthy adult engages in submaximal exercise below approximately 50% of max, there is little anaerobic metabolism. Thus, a relatively small O_2 deficit is incurred with only a minimum amount of lactate produced in the skeletal muscles and accumulating in the blood. However, as exercise intensity increases above 50% max, anaerobic metabolism plays an ever-increasing role in order to meet the higher energy demands. As a result of elevated anaerobic metabolism, lactate levels in the exercising muscle, and consequently the blood, begin to rise.

Obviously a highly conditioned endurance athlete has a higher anaerobic threshold than an untrained person, and recently it has been suggested that, although VO_2 max is an important limiting factor in long-term exhaustive exercise, one's ability to perform at a high percentage of one's VO_2 max without a significant involvement of anaerobic metabolism may be just as important. It therefore appears that an elevated anaerobic threshold leads to better sustained athletic performances. Outstanding distance runners have achieved anaerobic thresholds exceeding 90% of max while our research with oarsman has revealed a range of 75-98% depending on when AT is measured. This variable is usually lower during the off-season and should peak at the height of the competitive season. Knowledge of anaerobic threshold could also serve to regulate training more precisely; the measurement of heart rate compatible with the anaerobic threshold would provide a control factor which could be used during training to reflect the relative use of aerobic and anaerobic metabolism in a workout.

11. Blood Lactates

Blood lactates are measured in mg% (mg/dl), or mmol/liter. During severe exhaustive exercise, O_2 consumption cannot keep pace with the energy needs of the muscle cells. As a result, the cells become increasingly more dependent on anaerobic metabolism. Where CO_2 and water are the by-products of aerobic metabolism and can easily be eliminated or handled by the body, extensive use of anaerobic energy sources produces large amounts of lactic acid, which build up in the working muscles and overflow into the blood. There seems to be a high correlation between extensive use of anaerobic energy sources and elevated levels of venous blood lactates. Elevated lactate levels have been associated with acute muscular fatigue and pain. Blood lactate levels measured during recovery can provide useful information regarding an athlete's efficiency in oxidizing the lactate to glycogen. The 5 minute recovery lactate measurement, since it takes time for the muscle lactate to diffuse into the blood, is taken as the maximal value produced during exercise. An end-of-recovery lactate measurement indicates oxidative efficiency of resynthesis processes to convert lactate to glycogen. A dominance of slow-twitch muscle fibers will probably improve this oxidative resynthesis. Lactic acid levels for oarsmen and oarswomen following 2000 m of maximal ergometric rowing ranged from 10-20 mmol/L. Lactic acid concentrations following competition have been higher; 20-28 mmol/L for men and 15-20 mmol/L for women.

12. Muscular Strength and Power

These factors are measured by an isokinetic dynamometer (Cybex II) which evaluates muscular output at pre-selected controlled velocities from isometric (0°/sec) to fast and more functional speeds (up to 300°/sec) and the results are reported in foot-pounds or foot-pounds per minute. Torque (force) achieved through a range of motion and the speed at which the specific torque is achieved complete the performance evaluation. Slow contractile velocity specifically tests muscular strength and joint stability. The dynamometer evaluates strength at every point throughout the range of motion in maximum effort contractions. Peak power is then calculated from the single muscle group's force-velocity curves over the range of contraction frequencies studied. Standard testing procedure dictates beginning with a specific contractile velocity setting of, for example, 30°/sec, the subject repeats up to three maximal voluntary contractions at a given speed with full recovery between contractions. Strength is measured at each point throughout the range of motion and displayed (in foot-pounds) on a recorder. This procedure, repeated at increasing velocities (60°, 90°...300°/sec), enables assessment of strength levels at higher speed contraction rates when the proportion of muscle mass (numbers of fibers recruited) is less.

Local muscular endurance or power endurance assesses the ability to sustain high levels of muscular performance over time. Measurements include a tracing of the fatigue curve and digital read-out of the total work performed over selected time intervals during sustained maximal dynamic contractions; this test requires each athlete to perform repetitive contractions at 180° or 240°/sec. If recordings are made during a one minute endurance test at regular intervals (e.g., every 10 sec) then a detailed fatigue curve may be determined.

Muscle strength applied at high contraction rates (power) is paramount to successful performance in explosive events of short and moderate duration. It is important for an oarsman and oarswoman to exhibit high muscular power outputs at the faster, more functional speeds (180°/sec and higher) and, at the same time, perform well on the one minute power endurance test with consistent power results at each measuring interval and displaying little power drop-off during the later stages of the test.

The functional power measurement for rowers is very important and it has been estimated that the strength and power measurements at 240°-300°/sec are the most applicable measurements since these are the speeds in which the power phase of the rowing technique is carried out.