The Physiology of Being in Shape…
The Adaptive Processes that Allow an Athlete to Push Through the Challenges of Vigorous Exercise at Ever-Increasing Intensity

By
Coach Ed Nessel, R.Ph, MS, MPH, PharmD

Every person associated with prolonged vigorous activity realizes that with continuous training (appropriate or not) something positive happens over time that allows the body to withstand increasingly-demanding physical challenges. Even if armed with only a superficial smattering of understanding physiology, the coach and/or athlete realize that somehow dedicated continuous exercise brings improvement in movement.

Climbing the mountain to being in shape is commendable but not enough. Who climbs without wanting to reach the peak? Like grabbing correctly for foot- and hand-holds on the slippery mountain face, grabbing hold of the correct physiology is the surest way to get to the top. The top here means reaching the maximum potential of the person doing the "climbing."

Getting in "shape" is neither easy to attain nor to explain. The human body is a wondrous machine with complicated systems able to produce great quantities of energy both quickly and over extended periods of time. This permit's the body to try and adapt to whatever is physically challenging it and enlarge its capacity to handle increasingly more vigorous exercise. Unlike a manufactured automobile engine which has the exact parts needed to produce a certain amount of predicted energy and power, the human body's components can be made to produce more by having them induced more through utilizing specific physiologic protocols over time. In every instance of adapting to exercise, three main elements, the holy grails of athletic training as I see it, are brought into the picture and must be addressed to a greater or lesser extent depending upon the chosen venue and type of sport for participation: endurance, strength, and power. The correct pathway to physiologic condition is to build on endurance then go for strength and finally, most every athlete's goal: power.

Endurance

This is where it all starts if the coach and/or trainer and athlete approach getting in shape correctly. It takes the greatest amount of time and the most effort to develop all the physiological adaptations the body needs to capture endurance. It is not a simple goal; it is an ongoing process. When we speak of endurance we must include both the muscular and cardio-respiratory systems. When dealing with muscular tissue, endurance becomes specific to individual muscle groups. Each racing stroke has its nuances and particular muscle and energy demands and needs to be mixed appropriately with other elements. A breaststroker swimming mostly freestyle is being training incorrectly, even early in the season. Correct muscle training is highly specific since nearby muscle fibers that are not utilized in condition sets will not gain appropriately enough in endurance. It is more beneficial to work specific strokes on specific days or to simply mix free and stroke in what I call "twitch swims" for most training sessions.

My research over the years has shown that it the kick that gets you to the wall in close races. On average, the fraction of total energy consumed in a race for distance freestyle is about five percent for the legs, sprint freestyle about 10%; strong backstroke demands between 20% and 25% legs, and butterfly requires strong hip action to go along with between 25% and 35% kick. The slowest stroke, breaststroke, requires the most from the kick where the legs drive the body forward demanding between 50% and 60% of total stroke energy. Knowing this, we must give the legs their due at each practice. They can be pushed hard and with less recovery between efforts. Some swimmers can naturally isolate leg pain and deal with it better than others. All must understand their importance to fast swimming: "no kicky…no swimmy." We need to build kick sets to work the specific muscle groups of the legs and to increase their endurance capacity over varying distances. An absolute minimum of 1000 yards in a training session should be devoted to kicking; some sessions doubling that would not be excessive with the majority of that being event-specific as stated above: a breastroker needs to kick breaststroke, a flyer must work the dolphin kick., etc, etc. Of course, logic and appropriate training would suggest that there be recovery sessions that allow intensely-worked muscle groups an easier time of it.

When dealing with cardio-respiratory endurance, we speak more of the body as a whole. Though cardio-respiratory and muscular endurance overlap since the body is the complete unit of movement, the former becomes the more important aspect of physical fitness. When physical condition is suspect and fatigue sets in too quickly, muscular strength diminishes as does neuromuscular coordination, concentration and alertness. To prevent this and to correctly train the athlete we need to increase the mechanisms required to harvest and utilize energy supplies for prolonged movement and to concomitantly increase the distribution of nutrients and oxygen throughout the body to sustain this movement. It may seem quite unfair that what takes the body so long to develop is most easily lost with de-training. In swimming we use the expression “losing your air” because air is what is mostly perceived to be in short supply and which becomes of primary concern while moving quickly through water over a distance of 100 yards/meters or more.

Muscle tissue is composed of two gross-types of fibers, slow-twitch and the larger fast twitch. The fast twitch fibers are further divided into all-out fast-action (Fb, which have no blood supply and are whitish in color) and a somewhat slower fast twitch (Fa which has some blood going to it and is reddish in color). The larger fast-twitch fibers are the ones that contain the potential for developing most of the strength and power. Where there is no blood supply there is greatly diminished endurance since no respiration, no waste removal and no continuous supply of nutrients can occur. The slow-twitch fibers have the greatest blood supply and are the ones most induced by endurance training. They can grow up to 22% larger than the fast-twitch fibers under this type of stress. Even the slower-type of fast-twitch muscle fiber, with more oxidative capacity than pure fast-twitch, can be made to enlarge and somewhat convert over to endurance. Along with this change in fiber type, we can see a second adaptation to endurance training: an increase of up to 15% more capillary induction (blood supply) to slow-twitch fibers with all of the advantages mentioned above. This can show itself when a sprinter trains mostly endurance (if you can force him to do it). Some of his power fibers will switch over to fire more slowly but for longer periods of time; this will lessen his power output and corresponding all-out speed somewhat but add endurance so his event selection can expand somewhat, and he will stay stronger longer.

A third muscular adaptation to endurance is the increased formation of myoglobin. This is an iron-containing protein combining with and carrying all-important oxygen to the muscles’ contractile fibers. With appropriate aerobic training, muscle myoglobin can be increased in muscle fibers by an amazing 80%. The more oxygen myoglobin can bind, the redder it becomes which adds additional color to these fibers already coming from the blood supply.

Oxygen needs to go where it can do the most good, and that is right to the mitochondria where all the energy to move muscle and the body is manufactured. The greater the number of mitochondria the muscles can produce the greater their oxidative (respiratory) capacity. And this increased number of mitochondria (the fourth adaptation to aerobic training), allows for increased energy production throughout the specific muscles being trained. Again, specificity of training. Only those muscles being trained regularly will produce more mitochondria. This is the goal of much of our training: work the main muscle groups needed to power the athlete through his event's requirements, but don't ignore the ancillary groups that can be used to support the whole body through various movements. Total body development is key to superior athletic performance.

It takes vigorous exercise to better induce mitochondria to enlarge, multiply, and perform efficiently. But the coach and athlete need to understand this important adaptation: as the production of mitochondria progresses to where they split and double in amount (they do not all do this at the same rate) those doing the splitting temporarily lose their ability to provide energy. The athlete can feel as though something is wrong…that he is undergoing a set-back in training where he feels heavy or sluggish or fatigues more easily. This is only a temporary condition until all the new mitochondria mature and become able to donate to the aggregate energy supply.

The fifth adaptation to occur in aerobically-trained muscle is their enhanced ability to utilize free fatty acids (FFA's) for energy, sparing more of the carbohydrate stores until later in the event or training session for fueling speed.

The cardio-respiratory system's response to endurance training is even more encompassing. TWO major systems (called the oxygen transport system) are induced to adapt to delivering oxygen and energy in greater supply per unit time. The cardiovascular system adapts by having the heart increase in size (weight and volume), the left ventricle's wall increase in thickness and the ventricle chamber itself growing larger. This cardio hypertrophy (increase in size) due to endurance stress allows for greater filling between beats (diastole), and the increased muscularity of the ventricle's walls permit's the heart to push out more blood with more force (positive inotropic effect) with each contraction (systole), producing an increased stroke volume (SV). We call this an "athletic heart." The heart is enlarged but done so appropriately due to its adaptation to increased circulatory demands. Usually, the larger the athlete the larger the heart with greater stroke volumes. As training continues, the heart rate (HR--chronographic effect) goes down at rest and in sub-maximal activity because it becomes more efficient at filling and pumping out blood. But a well-trained heart can also produce an increased maximal heart rate (HRmax) when demand requires. Several studies have shown that an average of one beat/minute per week is dropped as cardiac condition improves. After six months or more of dedicated aerobic training some responding athletes can drop their resting heart rates by 20 to 3o beats per minute or more. But we also see in older athletes (60 years old and greater) that many have developed the ability to safely increase their maximum age-appropriate heart rate when exercising intensely to allow more blood to go to the various organs of demand. All-in-all, cardiac output CO-how much oxygen-carrying blood leaves the heart per minute) is determined by multiplying stroke volume times heart rate: CO = SV x HR.

There is another determinant to condition: how much oxygen is extracted by the various tissues. This is quantified by determining the difference in oxygen content between arterial and venous blood and is signified by: a-v02diff. If we put all these formulae together we have the best laboratory method of determining a person' aerobic condition:
Maximal oxygen consumption (VO2max) which shows the highest rate of oxygen consumption attainable for an individual during maximal or exhaustive exercise. In fully-matured athletes, the highest attainable VO2max is reached within eight to 18 months of dedicated effort which indicates that athletes have genetic limits to maximal oxygen consumption. When VO2max is reached during very intense training, exercise quality is nearly over due to the end of the body's ability to supply oxygen to the exhausting muscles. The body may be able to hold on for a short time past this marker but that will deplete any anaerobic reserves present, and we need to bring in mental toughness.

VO2max is usually highest in the sport-specific activity for which the athlete is training. Running hard will NOT help you in the water, but we do see moderate positive cross-over effects established in the various energy systems when going from swimming to other activities. Unfortunately, the more time spent in a gravity-free environment (swimming) the less the body can fight gravity on land without feeling the physical stresses at the articular areas (joints).

The swim sets that can stress the aerobic oxidative enzymes the most without completely wiping out the athlete training hard are any repeat distances where the rest is less than the time it took to swim. Utilizing a quick rule of thumb, taking five seconds rest per length swum or kicked will provide the necessary aerobic challenge to develop the oxidative enzymes necessary to increase endurance. Distances of no more than 300 yards/meters work best with the stated rest-to-work ratio. Many coaches will argue that offering their swimmers the opportunity to take one minute's rest after each 300 yards effort is much too long and won't challenge the athlete sufficiently, but in fact it will provide enough time to allow sufficient recovery to push several repeats with enough effort to produce all the adaptations mentioned earlier. When we shorten the repeats to 75's or 100's with only 15 to 20 second's recovery, the rest becomes more in line with what coaches and athletes deem appropriate. We can also get the necessary muscle fibers involved without completely exhausting them if we mix freestyle and stroke in different ratios throughout the set. Backstroke compliments freestyle very well (both long axis movements) while breaststroke and 1-arm, alternate arm and two-arm butterfly work the core in similar fashion (short axis movement). Of course, any mix that proves appropriate for specific events would train the swimmer correctly. The use of swim fins has proven very beneficial when the athlete and coach understand the physics of their use. Going beyond the obvious of being able to hold stroke for more yards with fins, moving through water more quickly with their use produces oxidative demands greater than swimming and kicking without them. Of course we don't want to create fin-addicts, but utilizing fins appropriately can only produce beneficial results.

As touched upon earlier, an increase in blood flow to many organs is a concomitant positive inducement from endurance training. This increase is one of the most important factors for increased aerobic endurance capacity and performance. It is due to four major factors: (1) increased capillary innervation to muscle, (2) existing capillaries are opened wider, (3) a redistribution of blood which translates into more blood being directed to the muscles, and (4) increased blood volume. This last adaptation allows for increased stroke volume which allows for increased VO2max…there is a cascade effect where each physiologic adaptation is related and contingent upon another.

The more intense the training the greater the increase in blood volume. Blood plasma volume increases due to the kidneys spitting out more anti-diuretic hormone (vasopressin) and aldosterone. These are secreted to retain water which increases blood plasma. Aerobic exercise also increases the formation of plasma proteins, mostly albumin, which controls osmotic pressure in the blood by retaining more fluid. Aerobic training also make more red blood cells (RBC) but as more of these are produced, more plasma is generated. Thus by virtue of dilution, we see the RELATIVE red-blood-cell concentration go down along with the hematocrit which is an important marker of oxygen-carrying red cells available. What someone ignorant of sports physiology would see would be a picture of relative anemia…"sports anemia." Where in reality there is no anemia because the ABSOLUTE number of red blood cells has been increased from base line because of aerobic training.

The other major group of organs enhanced by aerobic training, the respiratory system, can be enhanced to a greater percentage increase than cardiovascular function. Exchangeable air and the ability to do so increase astoundingly within a few months of dedicated training and continue to rise to the athlete's innate potential. Though respiration while at rest or with easy movement does not increase in functionality with aerobic training, the ability to exchange air (tidal volume) definitely rises consistently during maximum aerobic effort as does the respiratory rate; this is because of increased usage of respiratory tissue, its flexibility in function, increased activity of the skeletal respiratory muscles of the chest (intercostals) and the increased vascularity for enhanced O_2 and CO_2 respiration. What works best to enhance this in the water is to have the swimmer hold his breath while streamlining and kicking hard under water then having to kick and swim at the surface forcing the body to deal with increasing amounts of the one element that will limit all movement…the buildup of CO_2. This waste product of oxidation causes the brain to center only on being able to rid itself of it…at the cost of everything else. But having the body also develop physiologic buffers to combine with and neutralize CO_2 allows the swimmer to push on in a challenging set to prepare for the "combat" of racing. I do not recommend breath-holding while swimming. This causes the athlete to rush the strokes to get to the next breathing cycle. Getting the best air-exchange during most of the event is the smart physiologic play. This will allow a stronger finish since all swimmers slow down toward the end of their race. I would opt for my swimmers slowing down LESS than anyone else…if we are ahead, it is harder to get caught; if behind, we have a fighting chance to get our hands on the wall quicker.

Strength

Though strength-gaining (resistance training) can be sought along with the rigors of capturing endurance, it is not advisable to seek both with the same intensity at the same time. Putting in serious time at resistance training can actually hinder the development of endurance. But adding it gradually to the overall regimen of building the body will only serve to quicken what I call being in shape. Why seek out strength? Why devote time and effort to even visit the weight room? Because a stronger athlete can do the same tasks with less effort. This translates into less fatigue over time. Strength is synonymous with muscle, but we must also create strong area of the body that are intimately involved with muscle. The integument (connective tissue around the joints) must be made to adapt to handling increasing resistance otherwise inflammation can ensue along with tearing and weakening. Tendons (connecting muscle to bone) must be allowed to adapt to handle stronger and thicker muscle fibers made bigger by strength training; if not, they will be pulled from either the muscle or the bone as the too-strong muscle goes through its function of contraction.

To build strength, the intensity of exercise has to increase and only through a limited number of repetitions with more rest and recovery in between sets. The more the resistance, the greater the stress on muscle tissue. And when muscle is first stressed and intentionally "injured" (broken down), satellite recovery tissue (myogenic stem cells) is called into play to accelerate muscle repair and regeneration. The initial breakdown leads to rebuilding to a greater size causing first hypertrophy (enlarged muscle fibers due to positive protein synthesis) and then hyperplasia (actual splitting of muscle fibers which then enlarge to produce an absolute greater number of fibers). But Nature also provides a protective mechanism embedded within muscle tissue to prevent tissue damage if too much force is generated…autogenic inhibition. Resistance training can inhibit this inhibition…a good reason to take care in the weight room to prevent musculoskeletal injury.

There are two kinds of hypertrophy: transient and chronic. The former only lasts a few hours and is caused by fluid being pumped into the exercising muscle groups. Chronic hypertrophy is the type that lasts and takes the longest to develop since it is caused by actual increased tissue development over time.

Muscles were made to contract, but they have to elongate to get to recovery position for the next contraction. It is this elongation, eccentric movement, under stress which produces both the most muscular discomfort and the greatest enlargement of muscle tissue per unit time. The discomfort is something we call delayed-onset-of-muscle-soreness (DOMS) and which can manifest itself anywhere from four to 48 hours after intense exercise.

Resistance training also causes the body to produce more nervous tissue innervation directly into the muscle fibers in the form of motor-neuronal units. This happens early on in strength training (the first 10 weeks). Then the above-mentioned hypertrophy and hyperplasia lead the way to increased strength with the neuronal innervation still of some importance but now diminishing. When more of these units are functioning, more muscle fibers can contract simultaneously to produce more force. Nature has also provided that not all our muscle fibers contract at the same time with the same intensity. If this were not the case, our ancestor wouldn't have had any innate endurance to allow them to run for the trees and not be eaten by saber-toothed tigers. But with resistance training, we cause more muscle fibers to contract at the same time for more immediately-developed force. This premise allows some athletes to become quite strong yet not have a huge muscular build.

Power

This is our destination: to become powerful athletes. We become truly physiologically in shape when we can move through the sport-or-activity-specific requirements with speed and grace. The grace comes from repeated efforts at mastering complicated muscular movements. To repeat efforts is to cause more myelin to be wrapped around the neurons innervating muscle. The more the myelin, the more easily the body can perform neuro-muscular movement. Training for power should be as sport specific as possible. Athletes have usually worked very hard to get here…all to make it look so easy while competing.

$$\textbf{P (power)} = \frac{\textbf{Force x Distance}}{\textbf{Time}}$$

Power is the explosive aspect of strength; it is the product of strength and speed of movement. Usually as strength increases, power ensues quickly with appropriate training. The more power we can develop the faster we can move through water. But how the athlete trains in the weight room or on the field or in the pool will dictate how much power he can be made to develop. Moving heavy resistance is not enough. Moving heavy resistance quickly but under control is what develops power. Sufficient rest and recovery within power-training bouts and between them is even more important than trying to build strength. Maximum power can not be generated if the power fibers are not allowed sufficient time to completely or almost completely recover. A good measure is being able to move an ever-increasing resistance through an exercise in one second and to bring back the weight under control in the same amount of time. The longer it takes to move a heavy resistance the less the power element is brought into play.

Some athletes are gifted from birth with a greater percentage of fast-twitch muscle fibers. Most of us have about 25% pure fast-twitch throughout our musculature. Fast-twitch are the largest fibers in muscle and react the quickest when voluntarily caused to contract. The fastest fibers have no blood supply so their constant ability to produce energy and remove waste is greatly limited. But the slower type of fast twitch fiber, as mentioned earlier, can be made to increase blood innervation which does two things: (1) it increases the power ability of the athlete to hold for a longer time (a good thing), and (2) the absolute amount of potential power able to be generated is somewhat diminished (not a good thing). The positive aspect, again, of all this is that the increased power produced, though not at the absolute maximum, can be held over a longer period of time so the athlete has the ability to pursue his power event stronger and longer to the finish. Fast-twitch (power fibers) also retain their ability to produce power much longer (up to six months) during de-training than slow-twitch fibers which noticeably lose their functional aerobic endurance within two weeks of inactivity.

When pushing the body through bouts of power-generating activity, the athlete is also intentionally creating chemical buffers at the cellular level. Lactic acid is knowingly formed, created as a result of anaerobic (lack of oxygen) energy production. The body is stimulated to form bicarbonate buffers (-HCO3) to absorb this acid, eliminate it through the kidneys, and delay paralyzing acidosis. This physiologic adaptation will only occur when the body is pushed way past its comfort zone. Quality athletes are formed only when pushed way past their comfort zone…over and over again.

Getting in good condition is a relative thing. Almost everyone has the innate ability to rise to their optimum level, but most who commit to enhancing their physiologic condition will stop short. For those who have “seen the light,” they will have to work longer and harder to continue on to capture the three elements of physiologically being in shape: Endurance, Strength, Power.