# 25 The Physiology and Technique of Hard Riding



## Abilities of Cyclists

Cycling is by far the most energetic activity you can undertake. Other activities may produce more force, as does weight lifting, or more muscle power over a short period, as does track sprinting or most swimming events, but there is nothing that approaches the long-term, high-power demands of cycling. In these events, the cyclist is working as hard as possible in the most efficient way for many hours at a stretch -- for 4 hours for a 100-mile race, for 12 or 24 hours for long-distance events, and even for several days in the longest events, interrupted only by the amount of sleep that the cyclist chooses. Stage races may require only 6 hours a day, but the biggest has 22 racing days in a month.

The contrast with many other activities becomes more apparent when cycles of motion are considered. Many weight trainers consider 20 or 30 repetitions adequate. A long swimming race may require 500 strokes. A marathon run requires about 30,000 paces. The 200-mile ride, which is probably cycling's equivalent to the marathon, requires 50,000 pedal revolutions. Even the century ride, which cyclists of all types complete, requires 25,000 revolutions. The world's record of 507 miles in a day probably required over 100,000 revolutions.

These demands for energy, and the ability of first-class cyclists to meet them, exceed the boundaries of our physiological knowledge -- at least as it is published in scientific journals. We do not have sufficiently accurate explanations of exercise physiology to enable us to recommend training practices for hard riding that are based on laboratory knowledge. Rather, we are still at the stage where the known capabilities, techniques, and experiences of hard riders are the base data for extending our present physiological theories of short-term exercise into the realm of long-term, high-power exercise. As a result of this inadequate knowledge, when current exercise physiology has been applied to engineering design for cyclists, such as in the design of bikeways, the results have been contrary to experience. One ludicrous result is the published criterion for bikeway grades, which states that the highest hill that most cyclists can climb is 34 feet high.

Cyclists should be skeptical of all recommendations that have been made by exercise physiologists, for these are generally based on scientific theories that do not apply to the conditions of cycling. Scientists typically continue to apply generally accepted theories to particular situations, even when the data for one situation (cycling in this case) refute the theory. In cycling, practical experience still outruns science.

# Known Facts about High-Performance Cycling

Cyclists are able to exceed 25 mph on the road for up to 8 hours, and to exceed 20 mph for up to 24 hours. Competitors in these events, like sporting cyclists in general, ride with cadences between 90 and 110 rpm. Cyclists eat and drink while cycling. Cyclists who take early leads in massed-start events (as opposed to unpaced time-trial events) rarely are in position to contend in the final sprint. These are the known facts that must be explained by any legitimate theory of cycling.

## Cycling as Understood by Exercise Physiologists

Exercise physiologists base much of their thinking on the theory that success depends upon efficient technique. Each of the abilities that a person possesses is a limited resource; the competitive athlete can succeed only by efficient use of that resource. Since top competitors don't differ greatly in physiological resources, those athletes who use their resources inefficiently will be beaten by those who use their resources efficiently. This general theory is supported by the even more general evolutionary view: that physiological processes have evolved toward efficiency because animals that are efficient in their use of the resources available to them are more successful than those that use their resources inefficiently.

Therefore, exercise physiologists typically conducted experiments based on this principle of efficiency. Since the oxygen-transport system (heart, lungs, arteries, and veins) is highly stressed in most events that last more than a few seconds, exercise physiologists typically measured the amount of oxygen consumed and calculated the efficiency with which it was used. Since the oxygen is used to oxidize food products (measured in calories), which are also a limited resource, the measurement of oxygen consumption also leads to calculations of food efficiency.

A typical early experiment sought to discover the cycling technique that produced the highest efficiency (the most power for the lowest rates of oxygen and food consumption). The answer was cycling at 55-60 rpm. However, when the physiologists set trained athletes the task of producing the power for 25 mph (a level that is easily attained by trained athletes) using 60 rpm (a very easy cadence), the subjects collapsed in about 10 minutes, the equivalent of about 4 miles. The collapse should have been expected, because the cycling condition is riding at 25 mph in a gear of 140", a task that we know is impossible. The world's 25-mile record was set on a smooth and level racing track by using approximately 112" at 90 rpm to obtain 30 mph, an extremely high gear and moderate rpm by most standards. This collapse at only 5% of the time and distance that competitive cyclists actually attain should have signaled that something was wrong with the theory, but the exercise physiologists didn't raise the question; they just recommended cycling at 60 rpm.

I was one of the cyclists who raised an uproar over this incompetence. As a result, exercise physiologists started to experiment with trained cyclists who were allowed, at some times in the experiments, to use the cadence that they preferred and to even, in some experiments, ride their own racing bicycles instead of the laboratory ergometers. However, the dogma of efficiency still dominated physiological thought. So we got results such as that of Hagberg, Mullin, Giese, and Spitznagel (Journal of Applied Physiology, August 1981). These authors measured several physiological variables while the cyclists rode their own racing bicycles on a sloped treadmill at different work loads and cadences. They concluded that "competitive cyclists when tested on their road-racing bicycles are most efficient at an average pedaling rate of 91 rpm." That conclusion is false. For the most significant measures of efficiency (oxygen consumption, air flow, ratio of oxygen consumed to carbon dioxide produced, and the products in the blood of anaerobic exercise), the cyclists showed highest efficiency at cadences 10% to 20% below their preferred racing cadences. The data are clearly shown in the paper; the dogma of efficiency prevented the scientists from seeing the facts that they recorded.

I pointed out this discrepancy between facts and conclusions to the editor of the Journal of Applied Physiology, suggesting that my hypothesis better explained the facts that had been measured than did the theory of efficiency. The editor refused to publish the letter, with the excuse that it had no experimental support. Of course it had; its experimental support was the data measured by Hagberg and associates, data that had already been accepted by the journal.

There are two real reasons for the refusal: I am not a member of the exercise physiology profession and my hypothesis runs counter to the current theory.

# A More Reasonable Physiological Theory

I offer here my extension of current physiological theory, as developed through my experience in, and with, hard riding. I describe the techniques for getting more miles faster that have been proved by general use by cyclists, and offer an explanation for these techniques that should improve your use of them, so you should get the most miles fastest that your body can produce.

It is rather complicated, so I will start with an outline and then go into details. The human body has two different sets of muscle fibers to produce power, and it consumes three fuels. All fuels are ultimately consumed by reaction with oxygen from the air, a multi-step cold process that is not like burning fuel in a furnace. The step that finally provides energy to both kinds of muscle fiber is the activation of phosphate compounds into the high-energy form adenosine triphosphate (ATP). ATP is the material that directly powers the molecular ratchets that contract the muscle fibers.

However, the fuels are not neatly assigned so that each muscle fiber has its own fuel. Furthermore, one fuel can be stored in two places with rather different capabilities. This power-production system is supported by a fuel-production system for each fuel and by a fuel-and-oxygen-transport system. Each of these systems has its own speed limit, and each fuel-storage place has its own capacity limit and replenishment rate. Furthermore, cycling is not a natural activity -- the human body did not evolve for it. This has the small disadvantage that cycling technique must be learned by overcoming the body's natural tendency to run or to walk. It also has the great advantage that by designing the bicycle for efficient cycling, human intelligence has so outsmarted evolution that we can produce more power for a longer time than by any other method. Lastly, in order to get the most advantage from understanding this process, the cyclist must be careful to understand the difference between riding to arrive or to win (hard riding or racing) and riding to improve capability (training). One part of hard-riding technique consists of selecting a pedaling style and a power level to meet the demands of the road and the competition without exhausting any one system. The other part of hard-riding technique consists in managing the replenishment of fuel supplies to increase the endurance of each system. Training technique consists of cycling to stress each system in turn to its limit, thus giving the body the incentive to develop toward its limits of ability.

The two kinds of muscle fiber are distinguished by whether they tend to use the aerobic or the anaerobic chemical processes to produce mechanical power. (These are also distinguished by their "twitch speed," but because both speeds are fast enough for cycling it is more useful to consider the predominant metabolic processes.) The aerobic process uses oxygen and fuels that are taken directly from the blood to produce energy. The two fuels are fatty acids and glucose (also called blood sugar or dextrose). In this process these fuels become completely oxidized to carbon dioxide and water, producing lots of ATP (36 molecules of ATP for each molecule of glucose, for instance). Fatty acids that circulate in the blood are the predominant fuel for low-power activities such as normal walking. Though the body usually stores enough fat for many days of normal activity, it usually does not convert this fat to fatty acids fast enough to power intensive activity. If more than just normal power is demanded, as it is in cycling, the fuel for the additional power is largely glucose. Glucose is therefore the special athletic fuel. It circulates in the blood and is stored in the form of glycogen, both in the muscles and in the liver. For moderate power levels the muscles use blood glucose, which is replenished by glycogen conversion in the liver, by digestion of food carbohydrates, and by direct eating of foods containing glucose. These aerobic processes combine the fuels and the oxygen that circulate in the blood. If either fuel or oxygen is insufficient, the process won't work. Most exercise theory is based on activities in which oxygen is in shorter supply than fuel, but cycling is a very special exercise in which running low on oxygen is much less of a problem than running out of fuel.

When not enough oxygen is available, the anaerobic fibers can operate without it. Because resting muscles have a low blood flow, they do not have sufficient oxygen and glucose for intense activity. Even muscles that are in use may be asked to produce more power than the blood flow can support. Therefore, for emergency starts and intense efforts, the muscles use a fuel that is stored in the muscle itself: the storable form of glucose called glycogen. This process uses the first few steps of the normal glucose aerobic process, but cannot go further because there is not enough oxygen. Hence it is fuel inefficient: the amount of glycogen equivalent to a molecule of glucose makes only 2 molecules of ATP, instead of 36 for the full process. If a moderate level of exercise continues to use the same muscles, some of the partially processed glucose is usefully consumed as increased blood flow brings more oxygen. The rest is dumped into the bloodstream to be removed later by the liver.

Unfortunately, the muscles store enough glycogen for only about 10 minutes of intense activity. Because glycogen is merely the storable form of glucose, it is not replenished as long as the muscles keep taking the blood glucose for exercise, or even for normal movements. Therefore, muscle glycogen is not stored until the body rests, and the normal replenishment rate is only about two-thirds of capacity per night's rest. Therefore, muscle glycogen is the emergency fuel, to be used only when necessary.

The ATP molecules provide the direct energy for muscle operation.

Muscle consists of layers of protein material that can slide over each other but are connected together by a molecular ratchet, rather as the two parts of a car jack are locked together by the mechanism that lifts the car one tooth at a time. Just as you operate the jack handle once for each ratchet tooth, the muscle requires one molecule of ATP to move two adjacent layers one molecular-sized "tooth" distance, after which the layers lock together again unless the resisting object moves enough to allow the muscle to take up another "tooth distance," which requires another molecule of ATP.

These power-production processes are supported by supply systems for each ingredient, each of which has its own characteristics. Fatty acids are originally supplied by the digestion of food fat, and the surplus is stored as body fat. The supply of body fat exceeds any normal exercise need, but the body does not readily release it at the rate necessary for normal cycling. How much power can be produced from the fatty acids normally available from the blood is unknown. Body fat is the emergency supply for periods of starvation, and in women for the needs of pregnancy and lactation, so the body is stingy about releasing it. However, fatty acids from foods are directly available, and because the fat portions of foods take longest to digest, their fatty acids become available to sustain power production when the carbohydrate portions of the meal have been exhausted. The amount of glucose in the blood is maintained by the conversion of liver glycogen until this supply is exhausted. The supply of liver glycogen is sufficient to sustain about 1« to 2« hours of hard cycling when supplemented by the normal amount of fatty acids. The additional glucose (also called dextrose) that is necessary for typical cycling events is supplied directly from food that is being digested while riding. The glucose becomes available through three processes: a few foods (particularly man-made athletic foods) contain glucose; glucose is the result of simple breaking of the typical sugar molecules; and glucose is produced by more complex conversions of other food ingredients, particularly starch. Glucose eaten directly at times of glucose shortage is available at the muscles within a few minutes; the recovery is remarkable.

Normal food sugars become available as glucose after about half an hour or so, other carbohydrates somewhat later, and protein in excess of immediate need later still. Because glycogen is the storable form of glucose, it does not become available for storage until the body has a glucose surplus, which means after exercise has ceased and digestion has progressed. Muscle glycogen is stored in the muscle and may be used for either anaerobic or aerobic processes, depending on whether there is enough oxygen available from blood flow. Muscle glycogen is sufficient to sustain less than 10 minutes of very hard cycling, although it is possible to increase the supply somewhat by depleting it by hard exercise several days before a critical event and then loading up with lots of carbohydrate-rich foods in the intervening days. All fuels require oxygen for processing, although if glycogen is processed anaerobically the need for oxygen is delayed. Oxygen is supplied by the air, collected by the lungs, and transported by the circulatory system. The amount normally circulating in the blood will sustain hard cycling for only a few seconds, so the blood must circulate constantly and rapidly to replenish the oxygen supply.

This analysis explains the course of fatigue during hard exercise. The first material to be exhausted is oxygen. After a few seconds of exercise the athlete is limited to the power that can be produced by the oxygen-collecting and oxygen-distributing capacity -- that is, by the heart and the lungs -- supplemented by the anaerobic processing of muscle glycogen, which produces a further but delayed demand upon the oxygen supply. No wonder cardiovascular (circulatory) fitness is the objective of so much athletic training; it is the critical limit in many sports.

However, there is much more to consider. The subjects attempting to ride at 25 mph in 140" gear collapsed because their muscle glycogen became exhausted. The required power at the required cadence could no longer be produced. Lowering the power to about 80% of the maximum power sustainable by the circulatory system, but still keeping the cadence at a level for maximum oxygen efficiency, allows the muscle glycogen to be used more slowly and more efficiently. The glycogen is then used aerobically, which allows it to produce up to 18 times more energy, so that the athlete can use this energy to supplement the power produced from blood glucose and fatty acids for much longer. The cyclist may run low on fatty acids, but if he does his muscles will consume glucose instead. The runner can operate in this mode for about 2 hours before collapsing when his supplies of glucose and glycogen are consumed.

The standard technique for preventing collapse is to eat glucose and other food sugars that are quickly converted to glucose. But even if a runner consumes as much food as he can while running, he becomes painfully exhausted in 5 hours or so. It appears to be practically impossible to run hard all day in the way that many hard-riding cyclists can ride all day -- and the difference is not in the gross amount of calories required, because the calorie-consumption rates are not very different.

There are at least two kinds of fatigue in this analysis. Simple fatigue is caused by the lack of fuel. Replenish blood glucose, and probably fatty acids, and the aerobic muscle fibers are ready to go again. Wait overnight (or preferably two nights) for muscle glycogen to build up, and the anaerobic fibers are ready again. If exercise is resumed the following day, particularly if the athlete has not eaten enough to produce a surplus of glucose, the muscle and liver stores are only partially full, so the athlete will start out fine but will weaken early. Under extreme demands, when the muscles run short of normal fuel, they consume themselves, breaking down muscle protein into glucose and fatty acids for fuel. The result is weakness, inflammation, and pain -- the kind of fatigue that lasts for days. This is about the limit of knowledge in conventional exercise physiology.

This conventional knowledge does not explain how cyclists can complete the normal hard ride or the normal national-class race of over 100 miles, can ride hundreds of miles in a day, or can race day after day in stage races. One thing is obvious: If these rides were attempted using the normal experimental technique for exercise bicycles, the cyclists would fail just as soon as the subjects on the exercise bicycles. The laboratory technique does not reproduce that used by hard-riding cyclists. The laboratory technique is to pedal hard slowly (55-60 rpm), because that maximizes oxygen efficiency. But oxygen is freely available, and the hard-riding cyclist rarely uses the full capacity of his heart and lungs because this causes him to become exhausted rapidly. Other sports may demand the maximum rate of oxygen uptake, but cycling rarely does. So economizing on oxygen is pointless.

Maximizing oxygen efficiency also maximizes fuel efficiency, because the oxygen is used to convert fuel to energy. However, maximizing fuel efficiency is also not what actual cyclists do. In fact, the hard cyclist deliberately chooses to pedal considerably faster than the most oxygen-efficient cadence to avoid getting tired. In short, fatigue is delayed by working harder and burning more calories! This works because even though force and speed are interchangeable in producing mechanical power in machines, their effects are not physiologically equivalent. The runner cannot trade off muscle force for muscle speed, because the muscles must support the body's weight: however, the bicycle enables a person to outsmart nature. The cyclist does not have to put all his weight on the pedals; the bicycle's design allows him to turn the pedals faster with less force if that would be a better way to produce the required power.

The bicycle has three characteristics that allow the cyclist to trade off muscle force for muscle speed. The first is that the bicycle supports the cyclist's weight, so that the cyclist can press on the pedals with any fraction of his body weight that provides optimum results. As a result, we find that the force the cyclist applies to the pedals varies greatly during a ride, but is only rarely as much as full body weight. The second characteristic is that the normal pedal circle (13«" in diameter) uses a greater range of leg muscle extension and contraction than running or walking -- about as much muscle stroke as is possible without excessive flexing at the knee. This greater muscle stroke allows high muscle speeds without such a high cadence that vibration and other inefficiencies absorb much of the greater power produced. The third characteristic is selectable gearing, which allows the cyclist to use the optimum cadence regardless of the bicycle's actual speed.

Low muscle force and high muscle speed allow greater endurance than high muscle force and low muscle speed because of the way the muscle operates. One reason is that when a muscle produces a steady force at constant muscle length it does so by the repeated activation of large numbers of small fibers, each of which operates for a short time. As each muscle fiber is activated, it has to take up the slack of the muscle structure around it; this requires power. So a muscle pulling steadily at a fixed object consumes chemical power even though it produces no mechanical power. The faster the muscle moves, the less the proportionate inefficiency of this process. However, this is only a small effect.

I hypothesize that the major reason for the greater endurance of muscles under low-force, high-speed use is in the sequence in which the muscle fibers are recruited as the force is increased. Muscle force is controlled by the number of fibers recruited by the central nervous system. If you want to push harder, your brain and spinal cord recruit more fibers. Because muscle glycogen is an emergency fuel that takes a long time to replenish, it makes no sense for the body to recruit the anaerobic fibers for easy tasks.

Instead it probably recruits the aerobic fibers that consume fatty acids and glucose directly from the blood until the force required exceeds what these fibers can produce. This leaves the supply of muscle glycogen available for emergencies. The speed of muscle contraction is not controlled by the brain, but by the movement of the resisting object. (Positioning movements are a special case in which two sets of muscles oppose each other to position a limb. This requires brain control, but pushing or pulling against an object such as a bicycle pedal requires only the control of force.) Therefore, an increase in the speed with which the muscle is contracting does not cause the brain to recruit more fibers. Faster movement of the resisting object (a pedal in this case) simply requires that each fiber that is activated by the brain operate its molecular ratchet faster, which uses fuel at a higher rate because each movement of the molecular ratchet requires a molecule of ATP.

Because higher muscle force requires more fibers but higher muscle speed does not, and because the more fibers recruited the greater the proportion of anaerobic glycogen-using fibers, a high-force, low-speed regime will exhaust the muscle glycogen supply much more quickly than a low-force, high-speed regime that produces equal mechanical power. And because the high-force, low-speed regime requires that the glycogen-using fibers be recruited to supply the high force that is required, the moment that the muscle glycogen supply is exhausted the cyclist no longer has sufficient strength to turn the pedals, even though lots of glucose may be left. The experimental subjects required to ride hard at 55-60 rpm were attempting to ride at 25 mph in 140" gear, a feat we know to be impossible. The subjects collapsed because the pedal force that is required to do this requires both aerobic and anaerobic fibers. Once the muscle glycogen that powered the anaerobic fibers became exhausted, the subjects could no longer exert the force required by the experimental conditions. Had the experimenters then changed the conditions to normal cycling conditions, the subjects would have found that they were no longer exhausted but could continue for many miles.

Of course, employing the glucose-using and fatty-acid-using aerobic fibers exhausts their fuels also, but glucose is readily replenished. If glycogen use is avoided by the low-force, high-speed pedaling style, most of the power above the normal level comes from glucose. Hence the necessity for replenishing glucose by eating sugary foods in large quantities while riding. Remember that you have an emergency supply of glucose in the liver glycogen also, so again save that for emergencies. Eat to replenish blood glucose before you get hungry and before you get the bonk, which are the symptoms of depleted liver glycogen. Then you have protected the reserve for real emergencies. As the cycling journalist Velocio discovered a century ago, eat before you get hungry and drink before you are thirsty. If you can do most of your riding on your current food and water intake, you have ample reserves for whatever hardships the road, the weather, the competition, or a failure of arrangements may bring your way.

Unfortunately it is impossible to eat enough carbohydrates to replace the glucose required for continuous hard riding. The normal club cyclist on a very long trip gradually gets weaker and weaker until his speed drops to about 12 mph, at which speed the rate of glucose consumption matches that of glucose replacement. However, cyclists can train themselves to do better, as is shown by the performance of long- distance hard-riding tourists, 24-hour racers, and stage racers, each of whom greatly exceeds the carbohydrate calorie input rate. Rides of over 480 miles in 24 hours and of over 200 miles a day for extended periods are known, and I have participated in a ride of over 100 miles and 7,000 feet of climb a day for more than a week -- a ride in which the participants got stronger and stronger.

I hypothesize that cyclists with this degree of training increase the proportion of their power that comes from fatty acids from body and food fats. In the normal person who exercises seldom, fatty acids largely fuel the constant power load of normal activity, whereas glucose largely fuels the extra power required for unusual activity. (There are exceptions. Glucose is the only fuel for the brain and the heart, which operate all the time.) I hypothesize that if the body can be convinced that damn hard riding is normal activity, then it will adjust to a higher average rate of fatty acid consumption, thus freeing glucose for an even higher level of physical activity. Again, body fat is an emergency reserve that should not be touched until an emergency (such as famine) occurs, so the body is loath to burn body fat unless conditions are critical.

The "long-lasting" effect of meals with lots of fat suggests that eating more fat at breakfast provides fatty acids to fuel afternoon cycling, but at the expense of sprint power in the morning (because the digestive system is overloaded at that time). This is fine for tourists but bad for racers. The answer is to develop the body's ability and inclination to convert body fat to fatty acids and to use fatty acids for a greater proportion of the normal cycling power from early morning on. I hypothesize that the body's fat-fuel processes decay with low levels of physical activity, just as its other power-production processes do. Because glucose and glycogen can supply the power for the moderate levels of occasional exercise, the fat-fuel processes do not become stressed enough to develop until glucose and glycogen run very short. Moderately hard daily riding may produce the change, but when the cyclist is limited to hard riding for only a few days a month it takes painfully long, hard rides on those days to accelerate the fat-fuel processes significantly. I have had to retrain this system several times in my life, and those times have been painful.

# Difficulty in Training the Brain for High Cadence

This discussion has emphasized that high pedal cadence makes hard riding possible by reducing the need for consuming glycogen, which is irreplaceable during the ride. However, attaining a consistently high cadence despite other distractions is one of the most difficult skills in cycling. Beginning cyclists start at 40-60 rpm and continue until they are tired out and must slow down. I believe that this is a principal reason for the fact that few of those who start cycling become cyclists. They never learn to ride the easy way, so they always find quite ordinary trips too hard for them to complete, whether alone or with a club. And if they ride with a club, they have the additional discouragement of seeing everybody else disappear over the horizon with great ease. What is most remarkable is their resistance to advice, cajolery, and even threats of being left behind when cyclists attempt to encourage them. Even if they shift down on command, with the first distraction they shift up again to ride at 60 rpm in pain, or they slow down and drop back from the group. At the same time, the cyclists who are coaching them become exasperated and angry at what they see as stupid stubbornness that makes the situation worse.

In my opinion, pedaling is an unnatural act that requires overcoming certain control characteristics that have been built into the human brain by evolutionary selection since our ancestors first adopted upright running and walking as the usual modes of locomotion. By supporting our body weight, the bicycle enables us to outsmart nature by trading off lower muscle force for higher muscle speed. But to do so consistently when concentrating upon the road, the terrain, the traffic, and the competition requires that we use our intelligence to outsmart our own built-in control habits that have been developed for our natural walking and running modes.

We have been evolutionarily optimized for walking, running, and agility. We walk at low cadence with most of our weight carried by bones and joints, thus using low muscle forces that give us the maximum miles per calorie. We run at the maximum power our circulatory system can maintain with high cadence and large muscle forces but medium muscle speed because of low muscle stroke. For traversing irregular ground we can lift our feet further than is necessary for walking or running, so we can obtain greater muscle stroke, but when we do so we greatly increase the muscle forces because of the greater knee bend. Hence we cannot traverse irregular ground, or a steady climb, at the high cadence of running, because the combination of high muscle force and high muscle speed (produced by the combination of long stroke and high cadence) would require more oxygen than our circulatory system could supply.

We have not developed a larger heart, lungs, and circulatory system to support running up hills for at least two reasons. The first is that running up hills has been of lesser importance than running over relatively flat ground or walking. The second reason is that were we to do so our glycogen supply would run short very quickly. In other words, development of the ability to run over irregular or hilly ground would produce a different kind of creature altogether, one in which it probably would have been impossible to combine our other advantages.

These operating modes are built into our brain so that we unconsciously operate in one or the other of them. This control system is extremely strong; otherwise too many of our ancestors would have died from insufficient mobility. They would have been caught by tigers, or have starved before reaching new food supplies. Modern humans consider the built-in behaviors that we have to control, like sex and aggression, to be very strong. How much stronger is a built-in behavior that so universally affects our motion that we have never before realized it to be controlling us?

The bicycle allows a fourth operating mode because it supports the cyclist's body weight at the pelvis, thus removing the formerly fixed relationships between body weight and muscle force and between leg position and muscle force. The cyclist can, if desired, produce high power by moving the feet through their full range of motion while retaining low muscle force and achieving high cadence. The design of the bicycle evolved through trial and error to allow just this style of operation. However, this fourth operating mode provides inappropriate clues to our control system. The low muscle force represents walking, and the full range of leg motion represents the hill-climbing walk, so the beginning cyclist's brain sends a message to operate at walking cadence, which is 120 steps a minute or 60 rpm.

Because the built-in control system is so strong and so unrecognized, the beginning cyclist doesn't realize that it should be overcome. The experienced cyclist, who has overcome it, does not realize why it is so difficult to overcome. The usual beginning cyclist can learn to overcome the normal control system only by painful experience. If beginners persist in trying to ride reasonable distances at reasonable speeds (which are far greater than the distances and speeds considered reasonable by the average person) they sooner or later find that weakness and pain force them to gear down, and the results are unexpectedly beneficial. After several such painful experiences the brain is ready to accept the new instructions. If cyclists are not instructed, after many such experiences they might find it out for themselves.

It seems to me that the multi-gear bicycle has distinct disadvantages for beginners. Certainly beginners with multi-gear bicycles can climb hills easier, but they spend much more time and effort riding on level ground in gears that are too high for them. Though a bicycle with gears between 38" and 100", in the present fashion of cheap 10-speeds, is good for a very strong rider, one geared between 30" and 72" would seem better for a weak beginner. I predict that more people would graduate from being people-on-bicycles to being cyclists if they started on a low-geared bicycle and increased the top gear only when they became strong and supple enough to spin out in the gear they started with. For instance, although I had been a hard rider, pass stormer, and racer, even when I still rode about 7,000 miles a year my best gear for level time-trialing was less than 85" unless I got in some special racing training.

A few beginning cyclists learn more easily. I rode my first 200-mile day on my first sporting bicycle only because I broke my derailleur cable early in the morning (on an old-fashioned double cable that could not be replaced in the field), so I had to lock my derailleur in 72" gear to surmount the mountains. As a result, I went much farther than I thought possible once I reached the more level ground, and I later fell asleep at the dinner table through weariness without pain. But then I was a youthful athlete. I had been swimming competitively and cycling for years, and swimming's rapid flutterkick may well have made the high cycling cadence feel more natural.

# Individual Selection of Optimum Cycling Technique

This discussion of the scientific basis for hard riding should enable you to understand the reasons for using the hard-riding technique, and that knowledge should guide you to apply the reasons as principles instead of just cookbook recipes. Of first importance is to discover the amount of pedal force you can maintain throughout a given ride. This will be somewhat greater for short rides than for long ones, because you expect to use up a portion of your glycogen during the ride. But during most of the ride you will apply a lower force that does not use any significant amount of glycogen. Having decided on the pedal force to experiment with, raise the cadence until you are breathing hard but are not out of breath. This may well increase bicycle speed so that the increase in air resistance increases the pedal force more than you think advisable. If so, decrease the gear and the speed until you reach a gear, cadence, and speed that can be maintained on the level for the expected duration of the ride. This is what you use for level-road, no-wind time-trialing, with a little bit more power toward the end when you realize that your reserves are lasting.

Though this is scientific and illustrates the principles, it is not very accurate. Accurate estimation of the appropriate pedal force requires experience with your own physical condition. In any case you have no accurate means of measuring pedal force to confirm your estimate. The practical way to accomplish this is first to learn the appropriate cadence by counting your pedal revolutions against a watch. (I usually count for 15 seconds and multiply by 4.) Get used to the feel of riding at 90-110 rpm, so you can use this rhythm as your standard. This may be faster than the optimum, but the errors caused by distractions and weariness will slow you down, which is exactly what you must avoid. So learn to spin faster than necessary. Having established the cadence, experiment with gears until you find the highest gear in which your leg muscles don't get painfully tired before the end of the ride. Even this procedure is not completely adequate, because the appropriate gear varies with your physical condition. With my present highly variable cycling schedule I am often surprised to find that during time trials over familiar courses the gear I find best is as much as 10% different from the gear I initially estimated, and in making that estimate I considered how I felt that day. Naturally, a rider in consistent condition has less variability to worry about.

This fine adjustment also takes care of hills and wind. Learn to assess your pedal force and the sensations in your leg muscles continually so that you become sensitive to overload force. Never let the cadence drop (unless a hill is too steep for your lowest gear). Never let the force get above standard unless you plan to use part of your glycogen reserve to obtain a particular result, such as surmounting a hill, or going over rolling terrain without slowing down, or making an unsuccessful break in a race. If conditions deteriorate, pedal force tends to increase, so change down sufficiently to keep pedal force constant and slow down to maintain or barely increase the cadence. As conditions improve, speed up and then raise the gear until normal cadence and pedal force are again reached. If you have trouble staying with the group, try to raise the cadence and not the pedal force, because you can recover from the oxygen debt of excessive cadence but you cannot recover the glycogen used by excessive force. On the other hand, if conditions become so much easier that you don't want to produce maximum power, as when riding comfortably in the middle of the group or when descending a hill on which speed is limited by the turns, reduce your force considerably before raising the gear to reduce your cadence somewhat.

This precise control of force and cadence requires a gearing system in which you can change one gear at a time without getting into inappropriate gears halfway through a double shift, and without making mistakes when distracted and tired. The only gearing system that does this over a reasonable range of gears is the system in which the ratio between chainwheels is half that between adjacent sprockets. This system practically requires handlebar-end shift levers so you can shift both derailleurs simultaneously and can shift even when you want your hands on the bars. (See chapter 5.)

These techniques enable you to save your glycogen "sprint reserve" for the times when it will bring success. Use the reserve to surmount short rolling hills without slowing down by increasing the pedal force in the same gear. Stand up at this time if you find it more comfortable. A series of short rolling hills really separates the well-conditioned and skillful riders from everybody else, so if you are in good condition take advantage of it. At another time you may want to make a break on the level. Increase your pedal force and increase the gear, perhaps allowing your cadence to drop a little so that you don't get out of breath as your speed increases. On a long climb, plan to climb most of it at slightly above-normal force and cadence, which require reducing the gear more than most riders do, just so long as you can stay with the competition; otherwise recognize that you must drop back. If you can make a break on a long climb, do so by first protecting your reserve by low-force, high-cadence climbing until the appropriate time, then increase pedal force and raise the gear to establish your lead. Once the lead is big enough, or as big as you can establish, don't forget to return to the original force and cadence to prevent early failure and getting caught. By following this technique, I have frequently beaten riders with considerably greater basic strength.

This does not cover all the exercise processes; if it did, the cyclist who had ridden for hours would not have an "oxygen debt." When the ride is over, we would expect heart rate, breathing, and temperature to return quickly to normal, because the cyclist cannot have been operating anaerobically for so long. Yet after a very hard ride of long duration, a cyclist's heart rate, breathing, and temperature may remain at abnormal levels for an hour or longer. Clearly, then, the body has some chemical chores to do to recover from the hard ride, but we do not know what these are.

# Difference between Training and Racing

Training is not the same as performance riding. In performance riding you ride to get the most out of your present physical condition, which requires riding as easily as you can for the required speed. Training is meant to improve your present physical condition to yield better performance in a later event, which is best done by overstressing each system in turn so that it gets stronger. Of course, this makes you more tired sooner. Amateur racers who train much more than they race should learn to observe and analyze their weaknesses relative to the competition's, and should concentrate their training on stressing the systems that are weakest. Amateurs should also, of course, choose a racing program to exploit their strengths. In estimating their weaknesses they should consider their condition relative to the competitors' in the chosen events, and not relative to the specialists in other types of events. Because of the necessity of staying with the bunch in massed-start racing and in some touring and hard-riding events, it is more important to correct weaknesses than to amplify strengths. Neither the sprinter, the pacer, nor the climber can exploit an advantage unless they can stay with the bunch. Only when riders get in a position to exploit their best characteristics are those characteristics worth anything. Training the best characteristics is of lower priority than first developing the ability to reach the position where an advantage can count. Professional racers who race so much that they do little if any training during the season have the different problem of selecting races to suit their strengths and then using them to also train their weaknesses. This is a problem I have never faced and cannot give reasonable advice about.

## Training

The training to improve a weak system must be of the type that stresses that system. There is no one training routine that will develop every cyclist to a competitive level, or any one routine that will always work for any one cyclist. All cyclists are different, and each one changes both with development and in accordance with recent cycling experience. For general club cycling and touring, regular cycling is the best training. It is enjoyable, and it covers the mix of needs fairly equitably in relationship to the cycling terrain the cyclist faces.

However, the cyclist who wishes to improve his performance beyond the club-cycling level must train according to personal needs. This does not mean giving up enjoyable club cycling, for with a little forethought many types of training can be performed on enjoyable rides. But it does mean that the cyclist must evaluate his particular needs, plan his training time to fulfill them, and select rides and companions that will allow for training.

Each phase of training must be devoted to improving one specific system. This does not mean that only one system can be trained during one ride, but it does mean that at any one time one system is being deliberately stressed more than the others in order to make the body feel the need for improving that system. The technique is to modify the normal cycling style to overload the system to be trained, while retaining enough reserve capacity in the other systems to ensure that the desired system can be compelled to work at its maximum capacity. Simply modifying one's cycling style is insufficient -- the modification merely enables the cyclist to exercise a desired system. The cyclist must still work very hard to ensure that the system actually is exercised to its full capacity. There are at least seven systems to be exercised:

Assuming that you have already developed your basic riding skills and abilities to achieve minimum club-riding performance, I recommend the following types of training to improve each specific system.

## Anaerobic fibers

The objective is to increase both the power and the number of sprints available per day. Interval training, which is alternating cycles of full-power and half-power riding, loads both aerobic and anaerobic fibers during the full-power phase, and then allows the circulatory system to replenish the oxygen and to metabolize or remove the anaerobic waste products during the half-power phase. Each sprint should be pushed hard as long as you can maintain pace, and you should deliberately reduce to half-power once your speed falls significantly. The half-power phase should last until the heart and breathing rates have stabilized again, when the next sprint should be started.

Some people advocate weight training to increase strength. It helps as a winter activity, but I believe that when interval training is available, that is superior except for special conditions. Track sprinting is much more a strength activity than road-racing sprinting, so track sprinters may well benefit from continued weight training. Women seem to have insufficient strength in their back and shoulders to withstand the forces that their legs can develop when trained, so they benefit from weight training of the upper body. However, most road-racing sprints are not a matter of initial maximum strength but of using the strength remaining after an exhausting ride, conditions that interval training more closely duplicates.

## Aerobic fibers

The objective is to increase the amount of pedal force available for long periods without using the anaerobic fibers. This allows higher speeds at maximum cadence through using higher gears, and allows easier hill climbing at the low cadence dictated by available gears. I think it necessary to express a specific caution here. Many racers and racing enthusiasts read of the enormous gears used by the professional international stars at critical times (such as 53 x 13, or 110") and believe that they should copy this practice. This is inadvisable. The stars use such large gears only because they have developed sufficient strength to exceed maximum cadence under racing conditions in smaller gears. The cyclist of lesser strength is much better served by lower gears that allow him to spin at maximum efficient cadence. The training technique is to ride against adverse conditions of grade or wind in gears slightly too high. This riding condition must be continued after the initial anaerobic strength has been exhausted.

This ensures that the aerobic fibers are producing the power. Though severe initial sprints will exhaust the anaerobic fibers, processing the anaerobic waste products requires additional oxygen after the sprint ceases, thus preventing full exercise of the aerobic fibers until this process is complete. Therefore a gradual increase of power from the start is probably as good, and it feels much better, so that for significant aerobic conditioning the hill climb should start after 15 minutes of exercise and should last for at least 15 minutes more to have significant effect. Because those cyclists who have longer hills to climb appear to develop superior hill-climbing ability, a longer climb is better if available.

## Unconscious coordination

The objective is to ensure that the central nervous system will habitually call for high cadence despite any distractions, and that the various muscles will be activated appropriately during each portion of the pedal revolution. The training technique is first to develop proper leg action at medium cadence in medium gears (that is, under conditions in which the cyclist can pay attention to style) by consciously thinking about style.

Develop full ankle movement. Keep the knees moving in the straight-ahead plane. Apply force to the pedal in the direction in which it is moving to the greatest extent possible -- that is, forward at the top, down in front, backward at the bottom, and pulling up at the back. Consciously relax the rest of the body. Once medium cadence is achieved, raise the cadence gradually until you can spin at 110-120 rpm with a good, relaxed style, limited only by the unavoidable bouncing produced by the oscillating leg masses. This takes as long as any other aspect of training, but it also helps the circulatory system as well, so don't skimp on it.

## Circulatory system

When you have aerobic-fiber staying power and suppleness, you can really start developing speed power. Of course, the high-cadence training for suppleness has also trained the circulatory system, because excessively high cadence brings the cyclist into an oxygen-inefficient operating style which, even in medium gears, gets one out of breath. To redirect the attention from excessive cadence (for the purpose of developing coordination) toward merely high cadence (for developing circulation), increase the gear and increase the speed so that the legs have to develop a lot of power. But do not increase the gear to the maximum that you can sustain. Stay a little undergeared so that the circulatory system is stressed harder than the leg muscles system -- you should feel a bit of pain in your lungs. As in aerobic muscle training, this must be started gradually and maintained for significant time in order to be sure that you are working aerobically. Aerobic exercise experts say that 12 minutes is sufficient, but even if that is sufficient for mere aerobic fitness it is insufficient for cycling events. You cannot consider yourself fit for cycling events until you can keep your lungs hurting a little for at least 30 minutes and preferably for 1 hour or 25 miles.

## Conscious skill

The skills of managing your body and your bike in relationship to terrain, weather, and competition are discussed in chapters 34, 35, 37, and 40.

## Digestion

The objective is to develop the ability to consume and digest food while riding hard. It requires hard rides of at least 3-4 hours, consuming food at approximately 1-hour intervals, preferably without stops or with minimum stops. No training effect will be achieved until you reach the time at which glucose would have been exhausted, which for most cyclists occurs between 1« and 2«

hours after the start of continuous hard riding.

### Fat conversion

The objective is to compel the body to convert fat at a rate high enough to support cycling power, at least in conjunction with the intake of food. This requires considerably longer hard-cycling periods than are needed for training digestion alone -- say 8-12 hours. I think that shorter-duration exercise merely encourages greater eating, thus replenishing during each night both the glucose (both that in the blood and that stored as glycogen) and the small amount of body fat that was consumed by the day's exercise. Long continued exercise, I estimate, compels the body to consume more fat faster. This produces the cycling endurance primarily desired, but also produces a long-lasting reduction in body fat. This is desirable both because thin cyclists climb and accelerate much faster and because thin people live longer and better.

# Use of Heart Rate Monitoring Equipment

For many years some cyclists have measured their heart rates and used this information to guide their training. The easiest method is to measure the resting heart rate upon waking. A low value implies that the cyclist is in good condition, while a higher value implies that the cyclist has some physical problem --possibly overtraining the previous day or stress from other causes or simply a minor infection that would otherwise be unnoticed. The more difficult method is to measure the heart rate immediately after some training exercise and the speed with which the high exercise rate returns to normal. For cyclists this requires taking the pulse while riding the cool-down phase of a training exercise -- not the easiest measurement to take. Measuring the heart rate during the training exercise was practically impossible. The development of portable electronic heart rate monitors has made all these measurements practical for those who care to spend the money.

The question is whether knowledge of one's current heart rate improves one's cycling performance, either in training or in racing. There is, of course, the question of providing a greater safety margin for those with heart disease, but that is a medical question that I will not consider. Simple knowledge of facts, such as one's current heart rate, is worthless without a useful theory for understanding their significance as a guide to one's actions. The initial impetus to heart rate monitoring came with the successful one-hour record by Francesco Moser under the training advice of Dr. Francesco Conconi. Conconi's theory was that he could discover how hard a cyclist could ride continuously by studying the relationship between heart rate and power output. As long as the cyclist was operating aerobically his oxygen consumption and heart rate increased linearly with power output, but when the cyclist tried to increase power and entered the anaerobic range the relationship between heart rate and power changed. Conconi worked with Moser to increase his maximum aerobic power and to select the gear which would provide proper cadence at that power, thus maximizing his chance for a successful ride. That theory requires measuring both heart rate and power over a considerable range of speeds, and repeating these measurements as the cyclist's condition changes. That is not very practical, and it applies only to short-distance, level-road time trials; its value for massed-start racing or hard touring is much less.

For various reasons, those who advocate the use of heart rate measuring equipment make a much simpler recommendation. They recommend a maximum heart rate based on age and possibly as modified by estimated physical condition, and advocate training at that heart rate. Some also advocate selecting the gear that will allow you to produce the maximum speed for that heart rate. Some also try to make their recommendations attractive to people without scientific knowledge by making inaccurate simplifications.

One such simplification is that aerobic exercise consumes fats while anaerobic exercise consumes sugars, and that exercising below a particular heart rate consumes fats while exercising above that heart rate consumes sugars. We already have more accurate theories than these, and there is no theory to support these recommendations. The gear-selection theory, in particular, is wrong because it doesn't consider length of ride or variability of conditions, both physical and competitive. It is merely another variation of the traditional method of exercise physiologists (selecting the most oxygen-efficient cadence), whose defects I discussed above.

Knowing your current heart rate may influence your training by indicating roughly how hard you are working. The cyclist who is inclined to slack off will see a lower heart rate and will be motivated to work harder. Contrariwise, the cyclist who is too enthusiastic at the moment may see that he is working harder than normal and slow down to avoid overtraining and burnout. However, heart rate is no measure of how well you are riding, and high-performance cycling requires more than mere aerobic conditioning. Because of the inadequacies of mere heart-rate theory, trying to use heart rate information as the major guide to training or racing will probably produce recommendations that are not as good as the advice that is given earlier in the present chapter.

The use of heart rate measuring equipment, for those without medical indications for its use, is probably more of a psychological aid to maintaining a consistent training routine than a scientifically sound basis for training or racing. A cyclist who pays attention to the various aspects of his condition, and trains accordingly as described in the training advice given above, probably can do better than one who depends on knowledge of heart rate as a guide for his training or racing.