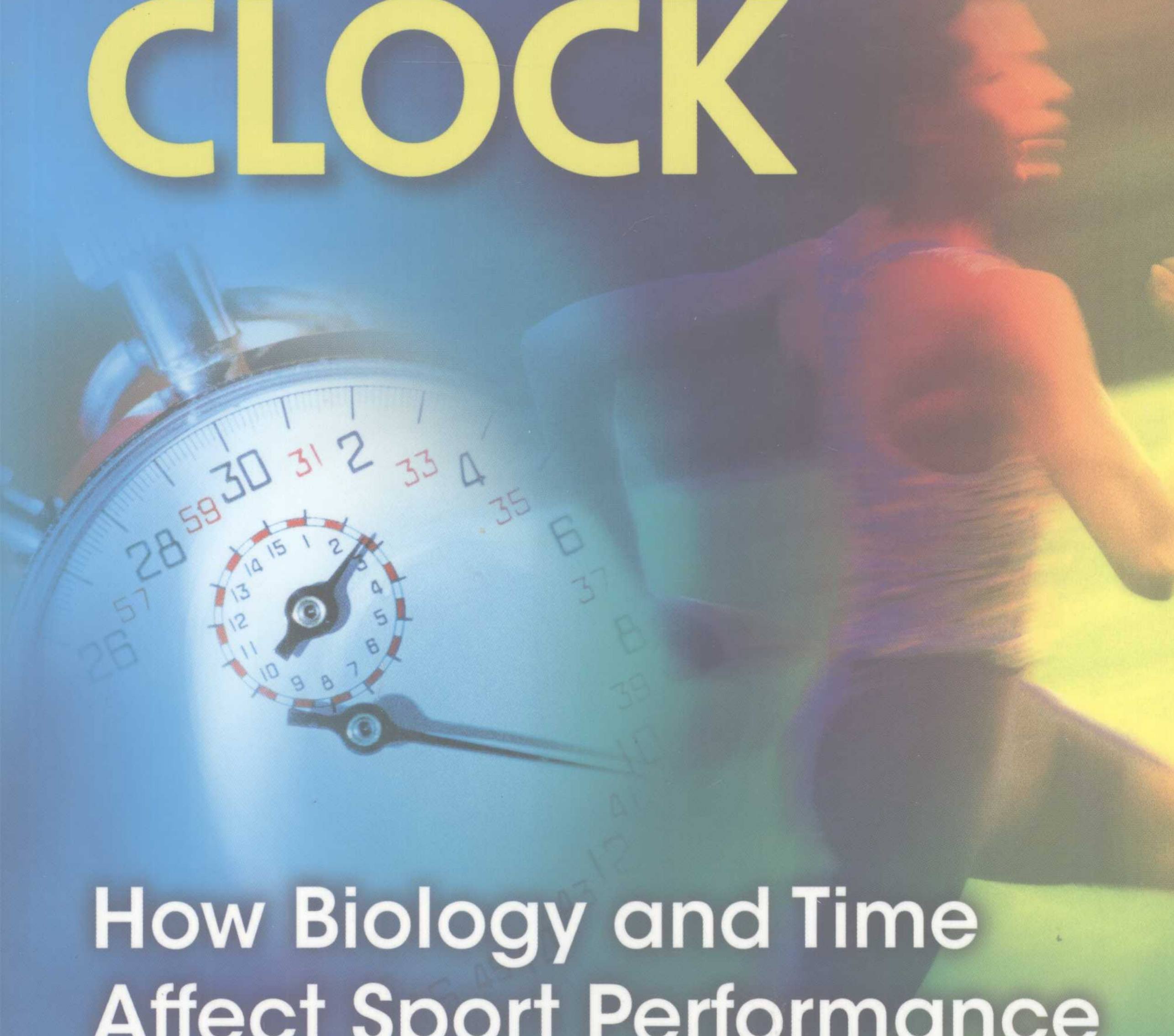
THE ATHLETE'S CLOCK



How Biology and Time Affect Sport Performance

THOMAS W. ROWLAND, MD

FOREWORD BY TIM NOAKES

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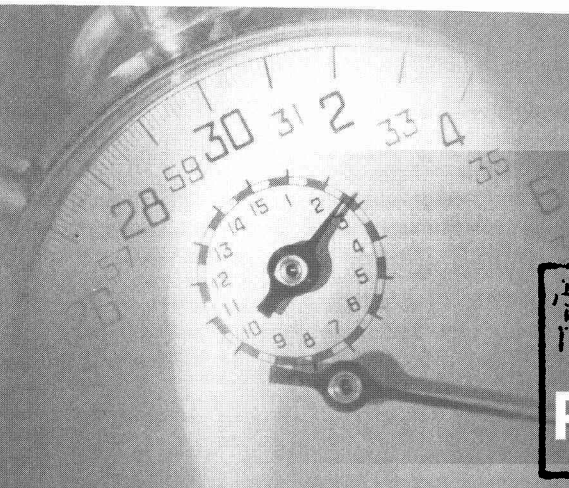

How Biology and Time Affect Sport Performance

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THE ATHLETE'S CLOCK

FOREWORD

Once upon a time the understanding of exercise physiology was easy. The key to all forms of exercise performance was the heart, whose function determined how far and how fast humans can run, swim, or cycle. Once the heart's limiting capacity is reached, the muscles become oxygen deficient, releasing poisonous lactic acid. The lactic acid interferes with normal muscle function, causing the anguish we recognize as fatigue. According to this explanation, the best athletes are those with the largest hearts, best able to pump the most blood to their active muscles and produce the highest rates of oxygen consumption during exercise.

It is a theory based on work done by the British Nobel Laureates Sir Frederick Gowland Hopkins in 1907 and Professor Archibald Vivian Hill in the 1920s. This idea has been widely promoted and vigorously defended by legions of exercise scientists ever since. Most humans with any interest in exercise science believe this theory to be the only possible truth.

But for the first time in 90 years, the past decade has witnessed the appearance of some cracks in the walls of this fortress of belief. We now know that some things are not easily explained by this traditional Hopkins-Hill model. If the model is the final truth, then there really is no need for athletic competitions. Medals can simply be given to those with the largest hearts and the greatest capacity to consume oxygen. But the problem is that the very best distance runners (the Kenyans and Ethiopians, for example) do not have any greater capacity to consume oxygen than do lesser runners who finish far, far behind. Thus something other than simply a big heart and a large capacity to consume oxygen must explain truly exceptional athletic performance.

Indeed, this theory invites the simplest question: If the heart limits all forms of endurance exercise performance, why do cyclists in the Tour de France or runners in the Olympic marathon race at submaximal levels of heart function? If the heart is indeed the factor limiting their performances, then those athletes' hearts must begin to function at maximal effort the instant the race begins. But their hearts do not. Hence, something else is involved.

Probably the most damning evidence against this traditional theory is the simplest and most obvious—so obvious, in fact, that it has been ignored for the past 90 years: Can the Hopkins-Hill model explain how athletes pace themselves not just during races but also during training?

If the control of exercise performance resides in the exercising muscles under the action of this toxic lactic acid, then why do athletes begin races of different distances at different paces? If lactic acid is the sole determinant of an athlete's pace, then there can be only one exercise pace for each individual regardless of the distance she plans to cover. The pace must be that at which the effect of the poisonous lactic acid is just being felt. Going any faster will cause more lactic acid to be produced, slowing the performance. But slowing down will cause a drop in lactic acid levels in the muscles, removing its inhibitory effect and leading to an immediate (but temporary) increase in performance. Soon, however, the higher intensity will lead to increased lactic acid production in the muscles, reversing the process.

If the model is completely unable to clarify how different paces are possible during exercise, it has even greater difficulty explaining what happens near the end of the exercise as athletes begin to speed up in anticipation of the finish—the classic end spurt. The end spurt is most obvious at the finish of each stage of the Tour de France but is present in all running races longer than 800 meters. How is it possible for an exhausted athlete to speed up at the end of a race when he is the most fatigued? This common phenomenon indicates that our understanding of fatigue—classically defined in all textbooks of exercise physiology as the inability to sustain the desired muscle force (or running speed)—is utterly incapable of explaining what happens in the real world of competitive sport. If athletes speed up at the end of races when they should be the most tired, they cannot be fatigued, according to this hallowed physiological definition.

And even more confusing is this: As they sprint for the line in the final moments of their end spurts, athletes do not activate all the available muscle fibers in their exercising limbs. They always finish with muscular reserve. Which raises these questions: Why not? What is holding them back? And even more intriguing is this: If an athlete finishes second, milliseconds behind the first athlete, what was holding her back? Why did she not risk death by exercising just a little harder in order to win the race? The conclusion must be that she chose to come in second rather than to go faster even if going faster would not have killed her.

Then the final piece of evidence against this purely peripheral control of exercise performance is that certain substances can have a marked effect on human exercise performance even though they act only on the brain. The most obvious example is amphetamines, a class of drugs that dramatically improve performance by acting on the brain to reduce the uncomfortable sensations of fatigue.

In the face of such compelling evidence, one could expect that supporters of this traditional explanation would acknowledge that their model might not be absolutely correct. Science is supposed to be a courteous activity conducted by decorous men and women according to time-honored principles of fair play and respect for differing opinions, all for a singular goal: the pursuit of a perfect truth. Sadly, the reality is sometimes different. Modern science, and perhaps even more so in exercise science, is a war waged on opposing sides by men and women with varying measures of self-importance. Those most certain of their opinions are usually also the most belligerent.

Those intrepid nonbelievers who question soon attract the scorn of the majority. The result is that it is much easier to stay quiet or to choose conformity. It is into this hostile arena that the genial Dr. Thomas Rowland and his sagacious book have made their entry.

Dr. Rowland, a pediatric cardiologist, is lean and athletic—a lifetime athlete. His small, linear frame identifies him as an ectomorph. According to 1940s Harvard psychologist William Sheldon, the defining characteristic of the ectomorph is cerebrotonia—a greater capacity for deep thinking than for urgent acting. Shakespeare understood that their need to think and to understand more deeply places the ectomorph on the social edge. Of Cassius who plotted his assassination, Julius Caesar is allowed to observe this:

> Yond Cassius has a lean and hungry look,
> He thinks too much; such men are dangerous.

Much better to surround oneself with the soft bellied:

> Let me have men about me that are fat,
> Sleek-headed men and such as sleep a-nights.

In *The Athlete's Clock*, Rowland plots the assassination not of an autocratic emperor. Instead, he invites us to question some of our most hallowed concepts of human athleticism. He wishes to understand how research in sport science helps us better understand how time, aging, our internal biological clocks, and associated controls like the central pattern generator (CPG) influence human athletic performance.

His overarching questions are these: Is the control of physical effort over time—sporting performance—under the conscious control of the athlete? Or do subconscious controls of which we have little knowledge really determine how well we can perform in sport? Thus he poses this question: Are the forces of destiny—or the finish time in a 10K road race—under our conscious control?

Rowland begins by providing evidence from laboratory studies showing that the pacing strategy during more prolonged endurance exercise may be regulated by subconscious controls that produce the uncomfortable symptoms that we recognize as fatigue. He wonders whether these sensations arise "from the unconscious portions of the brain, which, having sensed physiological information indicating high-exercise stress, depress force of muscle contraction and block the desire to continue, all in the name of preserving safety?" He acknowledges that few exercise scientists and even fewer athletes are impressed by any explanation that proposes that human athletes are not in exclusive control of their own sporting performances. In answer, he provides a body of current evidence that allows readers to arrive at a more informed opinion.

The function of those controls is to regulate the frequency and power of the muscle contractions, expressed in running as stride frequency and stride length. Runners achieve this by acting on a CPG that sets the stride frequency and stride length and hence the pace. This simple explanation is revolutionary. Defenders of the Hopkins-Hill model speak not in terms of how a CPG might regulate exercise performance but exclusively in terms of how the heart's nutrient supply to the exercising muscles regulates their function and therefore establishes the runner's pace.

Not that this CPG is a novel evolutionary development unique to athletic humans. Instead, a similar controller subtends the identical function in the more primitive brains of the most ancient creatures like the lowly cockroach. The magic of this CPG is that it will always choose the most efficient combination of contraction frequency and contraction power regardless of the activity—running, swimming, or cycling—and the conditions of exercise. The CPG does its work without requiring any input from conscious thought, although there may be some limited capacity for conscious choice to influence the actions of the CPG in the short term.

What of sprinting speed? Could the peak rate of firing of the (subconscious) CPG determine how fast humans can sprint over 100 meters? Probably not that simple, since this excludes the role of the sprinter's muscles in producing the force necessary to propel the body between strides. Weak muscles and a superfast CPG will still produce a slow 100-meter time. But like distance runners, even 100-meter sprinters must pace themselves. According to Caribbean sprinter Steven Headley in an interview with Rowland, "You can't run all out for more than about 4 or 5 seconds. . . . I really don't know what causes me to slow at the finish. Sometimes I'm not even aware of it." Is this another example of the subconscious control of human athletic performance?

Clear evidence for well-defined subconscious controls is provided by the diurnal (24-hour) variations in human athletic performance. Even better examples are the responses of players in fast ball sports like baseball, tennis, and cricket, in which the ball must be struck on the basis of advanced cues occurring in the very earliest portion of its flight and in which conscious actions can play no part. In all these sports, the ball striker must hit the ball at a time when he does not know the ball's precise position in space (since he does not see it). Nor does he know precisely when the ball will reach the point at which he wishes to strike it. The marvel is that few humans are ever able to make these seemingly improbable actions successfully, let alone most of the time.

Thomas Rowland has written a magical book that is both timely and revolutionary. My wish is that it will open minds to a new possibility: that we know much less about the factors that regulate human athletic performance than in our simple ignorance we may believe. That is the hidden message of this rebellious, indeed heretical, book. It is a message that exercise scientists need to take seriously if we are to advance our profession as a solemn science that aims to detect, rather than to conceal, truth.

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INTRODUCTION

We are all time travelers, passengers on an unflagging moving present that carries us even further into the future.

—Michael Lockwood, The Labyrinth of Time, 2005

Hey, kids! What time is it?

—Buffalo Bob, The Howdy Doody Show, circa 1952

By now it was almost four o'clock, and I was not greatly surprised that he was late.

I was awaiting, with no little anticipation, the visit of an old boyhood friend whom I hadn't seen in decades. It was so long ago, in fact, that it struck me that instead of coming from Michigan, it was more like he would be arriving from a different time dimension altogether. John had been a fairly straight-and-narrow fellow in high school, but after graduation, his life had taken a rather bizarre and certainly unexpected turn. Maybe it was his participation in the 1968 Chicago riots that led John to suddenly drop out of society, moving into a barn in the Lower Peninsula and abandoning a promising future in law, family, and all the usual social conventions. And there he had been ever since.

I had heard enough of his story to expect some rather eccentric behavior. He would, for example, insist on sleeping outdoors (so as, in his words, "not to lose the magic"). But what I did not anticipate was that immediately on his arrival, this bearded, altogether cheerful soul would rapidly stride from room to room, covering up all the clocks with a towel or cloth. We were, it seemed, about to spend the weekend unaware of time. (His idea was not original. The 18th-century philosopher Jean-Jacques Rousseau, in a gesture of disdain for the constraints of time, is said to have tossed away his watch, predating Peter Fonda in the opening scene of *Easy Rider* by a couple of centuries. In Rousseau's case, it is tempting to suggest that this act might have been associated with his subsequent bizarre social behavior, progressive paranoia, and ultimate death with insanity.)

My mind recoiled. How would we know when to eat dinner? To go to bed? When would we know when the coffee shop was opening for my morning latte? We wouldn't know how long to cook the lasagna. Or when to meet our friends at the cinema. And—now seemingly of critical importance—when would John know it was time to leave?

For three days, I was off kilter, disoriented, confused. No question about it, this weekend had a lesson. Those of us who have stuck to the narrow path of a conventional life are slaves to time. Without its anchor, our daily lives are set adrift. (Adventuresome readers are invited to try this experiment for themselves. See what it's like to miss your daughter's piano recital, to burn a steak or two.)

Meaning of Time

Time is, quite literally, of the essence. Indeed, it creates the very boundaries of our lives on this planet. From the moment of our birth, the sand begins to flow without ceasing through the hourglass to mark the point of our exit. In between times, we mark time in all that we do—our sleeping, eating, working, vacations. Clearly, no other single factor so defines our existence.

No wonder, then, that the great thinkers—philosophers, mathematicians, poets, theologians, physicists—have struggled throughout history to understand the nature of time. Time is something we all know about. But what is it?

Aristotle was among the first to consider time as a fundamental feature of the universe. From this viewpoint, it proceeds linearly and continuously, without interruption or influence by outside events. It doesn't matter what you're doing—time marches on. It is like a geometric straight line. Here, likening time to a mathematical construct would reveal its absolute, or physical, nature.

This was a popular idea, since it obviously reflected what people saw before them—the regularity of the tides, seasons, migration of birds, and, most particularly, the progression of the sun, moon, and stars across the sky. This concept of time as an imperturbable progression was further embodied by the invention of the clock, which defined time in respect to astronomical events. This modern measurement of time has, of course, become extraordinarily precise, extending from highly exact astronomical observations to the frequency of vibration of the cesium atom, a clock with an accuracy of 5 parts per 10 million million. That's a margin of error of .0000001 seconds per day.

Others have been inclined to view the passage of time from the standpoint of human experience (*psychological* or *subjective* time). Human beings, among all the animals, are uniquely gifted with the ability to sense time. This is nowhere less apparent than when you are awaiting a flight delayed for three hours (we might call this *O'Hare time*). Subjective time can, of course, move much more rapidly, like when you are enjoying a party with good friends or winning at tennis (label this as *40-love time*). You'd have difficulty convincing yourself that the agonizing creep of time at the airport is identical to that on the tennis court. But viewed from the U.S. Naval observatory in Washington, D.C., the keeper of astronomical time, no objective difference exists between O'Hare and 40-love time.

Time can also be viewed from the perspective of sequence. Gottfried Leibniz (who lived from 1646 to 1716) thought of time that way. (He also invented calculus, the binary system on which today's computers are based, and—to his lasting credit—optimism in life.) According to this idea, termed the *relational theory of time*, events do not take place in time; instead, it's the other way around. Time is defined by the order in which events occur. By this concept, events in life become the cornerstone of existence rather than time itself. This argument runs counter to that of time as a physical, immutable, independent reality.

You could easily fill an entire library with what's been written about the nature of time. (Those who wish a concise, easily readable source can try the 1972 book *What is Time?* by the British author G.J. Whitrow from Oxford Press.) Among these discourses are many intriguing themes. For instance, Einstein's ideas on relativity spoke against time as an absolute, stating that the passage of time depends on the location and speed of the person looking at the clock. In effect, a clock traveling at extraordinary speeds will appear to slow down when compared to another clock at rest relative to the observer. Such arguments are inconsistent with a physical, independent characterization of time. They state that rather than being absolute and invariable, time is related to speed. Thus, they are more supportive of Leibniz's concept of relative time. (Until your Volvo can approach the speed of light, however, these can be considered theoretical, rather than pragmatic, arguments.)

And then there is the question of the arrow of time. Can time go backwards? Or is it unidirectional? In light of our daily experiences, this would seem a bit silly. Of course, billiard balls do not come flying out of their corner pockets, your mother-in-law's precious china dish that you dropped cannot suddenly reassemble itself, the faux pas you uttered at the boss' dinner party last night cannot be retrieved.

Others have not been so sure. Physical laws of motion, for example, work just as well in reverse as they do in forward motion. That is, if you filmed a system corresponding to the laws of Newtonian mechanics, you would never be able to tell whether the film was later being projected backward or forward. It is possible to calculate not only the future positions of the planets around the solar system, but also their locations in the past. In the laws of physics, there is no preferred direction of physical processes in respect to time.

Indeed, this question of the direction of time has been considered with a great deal of thoughtful deliberation, and a number of books have been devoted entirely to this subject alone.[1] In the end, it seems that common expectation holds true. Students of the subject have generally come to the conclusion that the passage of time, notwithstanding events in certain popular novels and films, cannot be put in reverse. It proceeds only forward. The most powerful argument for one direction of time comes from the second law of thermodynamics, which holds that the degree of disorder, or *entropy*, in a system increases as a function of time. Left to themselves, systems become more disorganized, not the reverse. Predictably, things run down. Other evidence of the one-way arrow of time has been witnessed in the course of biological evolution, the chronological order of geological events, and the extended trends of astronomical events (like the life spans of stars or the expansion of the universe itself).

Another interesting perspective of time is that in its linear progressive flow, there exists no such thing as *now*. Like its counterpart in mathematics, the point representing the present is dimensionless. It, in fact, does not exist. As soon as you consider the point of now as the present, it has become part of the past. Contrary to all you learned about Zen theory, not to mention *carpe diem*, by this account, you cannot live for the present because the present does not exist. There is only future and past. As Kai Krause has concluded, "Everything is about the anticipation of the moment and the memory of the moment, but not the moment."

The only way to make time stand still, as it were, is to think about it in terms of duration between two points in immediate time. That is, "I am now a student at the University of New Mexico." In this way, now becomes a state, a condition. And you could, I guess, remain a perpetual college student, thereby freezing time indefinitely.

And, finally, being linked so intimately with the essence of human existence, it comes as no surprise that poets and philosophers have waxed nostalgic on just how precious time is. Consider this quote from Fernando Pessoa:

> I sorely grieve over time's passage. It's always with exaggerated emotion that I leave something behind, whatever it may be. The miserable rented room where I lived for a few months, the dinner table at the provincial hotel where I stayed for six days, even the sad waiting room at the station where I spent two hours waiting for a train—yes, their loss grieves me. But the special things in life—when I leave them behind and realize with all my nerves' sensibility that I'll never see or have them again, at least not in that exact same moment—grieve me metaphysically. A chasm opens up in my soul and a cold breeze of the hour of God blows across my pallid face.[2]

Chronological Versus Physiological Time

In 1884, a group of international astronomers gathered in Washington, DC, to create worldwide time zones. Their goal: to eliminate the chaos and confusion that had previously existed as each locality in the world sought to create its own particular time measure. In the United States, for instance, each railroad company set train arrivals and departures by its own time standard. The year before this historic meeting, almost 100 different railroad times were in force.

The world was divided into 24 longitudinal time zones to put us all in synch. They chose Greenwich, England, on the outskirts of London, as the starting point, or the *prime meridian*. (Today on visiting this site, one expects to see something extraordinary, maybe a bright yellow line running north and south through the grounds, but, no.) What was formalized in the capital city of the United States was the original idea of the ancient Babylonians a couple of thousand centuries earlier. This was to divide the day into 24 hours, with 60 minutes to an hour, and 60 seconds to a minute. This is all related, of course, to astronomical events, which define the chronological time that governs our lives.

Biological activities all vary rhythmically, in a manner that roughly approximates chronological time as well. Body temperature, heart rate, and blood pressure all wax and wane over specific time periods. Some of these *circadian rhythms* have direct bearing on sports performance. Chapter 4 deals with this phenomenon in more depth.

Another way that biological functions relate to the passage of time is the rate over time at which physiological processes take place. Scientists, in their attempts to define the real world as we see it, are accustomed to examining biological structure and function in concrete, three-dimensional terms, measuring things in grams, meters, or liters. However, recognition is growing that time, that impalpable factor of the fourth dimension, plays a critical role in how biological systems function. Most specifically, it is clear that such function must be couched in terms of its duration, or how long it takes to occur.

Functional activities of the body, such as sweating, cellular metabolism, or the rate of blood filtered by the kidney in the production of urine, all occur at a certain level of intensity related to time. Using these same examples, then, we can talk about the number of milliliters of sweat produced in a minute, or metabolic rate in terms of the oxygen used by cells as liters per minute, or urine production in milliliters per hour. In the same way, we can also talk about time defining broader biological processes, such as life span or generation time (time between conception and the age of ability to procreate). We can define the limits of such functions, compare them between different people, and define abnormal functions (as in diseased conditions), all by describing their activities in respect to the time it takes for them to occur.

No surprises yet. But here's the interesting thing. The rates of these functions are not associated with chronological time at all. Somehow they missed the memo from Greenwich. Instead, intriguingly, they relate to body weight, or *mass*. The bigger you are, the slower these processes go in respect to chronological, or clock time, and the longer it takes them (on your watch) to occur. The heart rate per minute of a shrew, which weighs about 2.5 grams, is about 1,000 times in a minute. During the same time period, the heart of an elephant beats only 30 times, and a human being's beats 70 times.

The same thing is true of rate of energy turnover within a mammal's cells when metabolism is expressed relative to the animal's size. That is, the smaller an animal, the more intensely its metabolic fires burn. The daily energy metabolism of a 30-gram mouse approximates 170 kilocalories for each kilogram of its body mass. A 300-kilogram cow uses about one-tenth as much, or 17 kilocalories per kilogram. Everything small animals do happens faster than the actions of big ones. It is not the chronological clock that dictates the speed of physiological function, but rather, body size.[3]

We can express this link between physiological functional time and body mass by a kind of mathematical equation called an *allometric formula*:

$$Y = aM^b$$

Here, Y is a biological process (liters of blood per minute, or times between breaths), M is body mass, a is a proportionality constant, and b (the most important item) is the scaling factor that indicates the extent and direction of the relationship between changes in the variable Y and body mass. A value of 1.0 for b indicates that the rate of the biological function increases in direct proportion to body mass. That would be true for respiratory rate, for example, if an animal weighing 10 kilograms breathed 20 times per minute, while a 40-kilogram animal breathed 80 times per minute. If $b = 0$, body mass would have no relationship to the process Y. Values between zero and 1.0 tell us that the biological process Y is associated with body mass, but Y increases at a faster rate than mass does as an animal's size increases.

What is striking is that when one considers various physiological functions in different groups of animals, there is a rather remarkable frequency of values for the mass scaling exponent b that approximate 0.25. In fact, William Calder was able to find 40 allometric equations in the research literature that related the time duration of different physiological processes in animals with body mass, all of which had a value of b between 0.25 and 0.39. The sidebar illustrates a few examples.

On examining this list, there is another intriguing observation. One cannot help being struck, not only by the consistency of quarter-power scaling exponents (that is, b is about 0.25) on this list, but also by the

Allometric relationships between rate of biological functions and body mass (*M*) of adult mammals (compiled from multiple sources).

Life span, in captivity (years) 11.6 $M^{0.20}$

Reproductive maturity (years) 0.75 $M^{0.29}$

Gestation period (days) 65 $M^{0.25}$

Erythrocyte life span (days) 23 $M^{0.18}$

Plasma albumin half life (days) 5 $M^{0.32}$

Glomerular filtration rate (min.) 6.5 $M^{0.27}$

Blood circulation time (sec.) 21 $M^{0.21}$

Respiratory cycle (sec.) 1.1 $M^{0.26}$

Cardiac cycle (sec.) 0.25 $M^{0.25}$

Metabolic rate per kg (min.) 70 $M^{-0.25}$

wide diversity of the biological functions included. Indeed, at least at first blush, they seem to have no obvious mechanistic connection at all. By what link could one assume, for example, that the rate of urine filtration in the kidney has any commonality with the twitch contraction of the soleus muscle? How about time to reproductive maturity in respect to the relationship to how much one weighs? What do these functions have in common that would give them nearly identical associations with body mass?

Even the duration of life itself fits into this scheme, with a mass exponent of 0.20. From this observation, Calder remarked that "using maximum life span, rather than absolute time, it appears that each life comprises about the same number of physiologic events or actions; in other words, each animal lives its life faster or slower governed by size, but accomplishes just as much biologically, whether large or small."[3]

It's almost as if we were born with a certain bank account of physiological function. The faster we use them up (in this analogy, make withdrawals from the account), the shorter our life expectancy. The average mouse has a 3-year life span, with a heart rate of 600 beats per minute (bpm), while the elephant lives 40 years, with a heart rate of 30 bpm. Yet their total number of heartbeats in a life time is similar. (Fortunately for you and me, human beings are outliers in this relationship. If we were to fit the pattern of other mammals, we would use up our allocated total of heartbeats by the time we reached age 25.)

A consideration of the obvious question of just why body mass is linked to the duration of physiological processes and events begs more time and space than is available here. The bottom line is that no one knows for sure. Attempts have been made to explain the mass scaling exponents for individual functions. But the ubiquitousness of quarter-power values for b, even in processes as seemingly far removed as breathing rate, kidney glomerular filtration rate, and generation time, seem to indicate there is a universal underlying principle involved.

Even if you're thrown by the math, the message should be clear. We can't rely on physiological processes to follow chronological time—they march to a different drummer. And that can be important when studying those functions that influence physical fitness and sport performance.

Before leaving this issue of physiological time, another aspect of biological timekeeping relative to sport performance deserves mentioning. The many factors that combine to determine athletic prowess are extraordinarily complex, but they share one feature in common—during the course of childhood development, they pro-