The Road Cyclist's Guide to Training by POWER

by Charles Howe

with contributions from Andrew Coggan, Ph.D.

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Foreword and acknowledgements

The aim of this guide is to provide some basic concepts and techniques of training in general, and with a power-measuring system in particular. It is written for road cyclists who are new to using this type of device, with perhaps no more than a rudimentary understanding of how their body works during exercise, so without being too deeply grounded in the underlying physiological mechanisms of human endurance performance, it is meant to stimulate riders to assess themselves, then help them to develop and administer their own training regime. Now and then, I have strayed into areas only tangentially related to power-based training, such as diet, since they can have a significant effect on power production, but I tried to keep such excursions brief or else merely referential.

To a considerable extent, what I have done here is to gather, review, and set down the principles that have guided me and the training habits I have tried to cultivate in my 20+ years as a 'serious' performance (and occasionally competitive) cyclist, and my purposes in doing so may be somewhat selfish. The larger motive, though, has been to fill a perceived need for a basic guide, made available free of charge, which perhaps will offer some fresh perspectives from those advanced elsewhere.

Initial mention of this idea at an internet forum was met with reservations about the "cookie cutter nature of these books and manuals. Each person needs different training." The purpose of this guide is emphatically *not* to prescribe any sort of pre-fab, one-size-fits-all plan. A sample plan is included, but it is meant to be customized by you, the rider, in order to design a program that fits your capabilities, goals, and schedule, through training principles and guidelines, functional tests, and experimentation as to what works best for you.

Another concern brought up was that "a coach is the best way for an athlete to improve, and . . . a well-educated coach knows how to make adjustments when life intervenes." This is fine – mostly for the elite athlete. The vast majority of riders, however, are self-coached, and I believe it is important to educate them *too*, rather than simply tell them to get a coach (and if they *do* get one, the better informed they are, the better they will understand and carry out any training program). You are capable of coaching yourself, in fact, *you may just be your own best coach.*

That said, I emphasize that no intent exists here to undercut any of the various fine and highly capable individuals who pursue coaching as a profession, only a recognition that most riders are self-coached, since they either cannot afford, or simply do not choose to hire anyone. On the contrary, a basic understanding of power-based training will likely help riders see that the experience, knowledge, and objective viewpoint offered by a coach could benefit them, and a brief directory of coaches who are versed in power-based training is included. Educating riders will allow them to have greater confidence in whatever advice they receive, thus making them more receptive and coachable, and may even spawn new coaches from the more technically inclined.

Admittedly, the self-sufficient approach has its limitations and is not for everyone, as some riders – perhaps many or most of the best – prefer to save time and leave the mental task of their training plan, diagnosis, and prescription to a coach. Indeed, the author's recent request for training information from one of this country's most distinguished competitors brought the response 'I don't know, ask my coach.' For the true professional athlete, who must balance media obligations, demands of travel, and much higher training volume, not to mention competitive pressures, a professional coach may be a necessity. Still, numerous elite athletes are deeply and involved in their training; Greg LeMond once remarked that he didn't do as well in school as he could have because he was often thinking about his training plan. It is for the rider whose interest in race preparation is just beginning to dawn that this guide is written, in the hope of nurturing that nascent fascination.

I wish to thank Dr. Andrew Coggan for his review of this manuscript and numerous contributions, both as noted within the text, and elsewhere without explicit acknowledgment.

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Introduction

Perhaps unique among all endurance athletes, cyclists have the capability of accurately measuring their external work rate, or mechanical power output, while "in the field," i.e., on the road or track, through commercially available power-measuring systems such as the Polar S-710, Power-Tap, and SRM (Schoberer Rad Messtechnik) Training System. These hold great potential as training aids, since power is an objective measure of the stress load, or intensity, being imposed, and as such directly determines physiological and perceptual responses to exercise. They are particularly appropriate for road cycling, where the resistive forces to forward motion vary greatly from one moment to the next in relation to terrain, wind velocity and direction, changes in speed, and road conditions. Indeed, many react with disbelief at how "jumpy" the current power display is when using any of these devices for the first time, and question the readout's reliability. This is a result of having become accustomed to the heart rate monitor (HRM) as a gauge of intensity, and being fooled by its delayed response to changes in intensity into thinking that the energy requirements of cycling are relatively steady, however, the accuracy of the power meter (and hence, the variable, or "stochastic" nature of on-road power expenditure) is verified by checking it against any constant-load indoor trainer.

Cyclists have at times taken their cue from distance runners in adopting pacing guidelines to gauge intensity for flat-terrain workouts. The concept of goal pace and date pace was borrowed from perhaps its most widely known advocate, University of Oregon coach Bill Dellinger. This approach may have some reliability at a given velodrome, so long as temperatures do not vary significantly and the air is calm, but is unlikely to be useful on the road, even under ideal conditions, with the possible exception of a standard (and sufficiently steep) uphill course.

The 'paradigm' for measuring exercise intensity was changed in the mid-1980s, when accurate, reliable, and affordable HRMs the size of a wristwatch began to reach the consumer market. As becomes apparent when correlated with power, however, heart rate is limited not only by its slow response to changes in power, but also since it can vary widely for a given wattage (much moreso during outdoor cycling, as compared to indoors on a constant-load ergometer) due to physiological and environmental factors. Indeed, had power meters preceded HRMs, the latter might have never been marketed and sold as a separate device.

Intensity may also be gauged by "feel," or perceived exertion (PE), either on a 10-point scale, or the original 6-20. PE is subjective in nature, with its precision limited accordingly, and yet, perceptual responses to exercise are an important source of feedback during training, since they actually integrate more physiological information than HR. Still, only occasional reference will be made here other than to power as a measure of intensity.

Finally, power-based training has long been possible with a calibrated bicycle ergometer, but the first power-measuring device for use "on the road" did not appear until 1988, when the SRM system was introduced. It was followed by the Power Pacer (Balboa Instruments) and Look Max One hubs in the early '90s, neither of which was a commercial success. SRM received a significant boost when it was embraced by several national cycling federations, as well as numerous professional and elite riders, including Greg LeMond, but it took the Power Tap (1998, Tune Corp., purchased by Graber Products in late 2000) and Polar S-710 (2001) to bring accurate and reliable power measurement within reach of most any rider. (Ciclosport models are not mentioned here, since they make only a crude estimate of power, based on weight, speed, and gradient.)

BENEFITS OF POWER-BASED TRAINING

1. *It eliminates guesswork from gauging exercise intensity.* Even those with exceptional "feel" are unlikely to judge their wattage any better than to within perhaps 10%, whereas a power meter is accurate to ±2% or less.

2. *It allows fitness to be precisely and accurately quantified and tracked, both daily and over time.* Workouts become carefully controlled, and along with a periodized program, training is less haphazard, making peak performances easier to predict. Carefully planned training may also help prevent overtraining and injury.

3. *Power meters have other uses, such as pacing during interval training, time trials, and even breakaways in mass start races; aerodynamic testing; and possibly as an aid to dieting and weight control.* Previously, wind tunnel testing was necessary to assess air drag, but under carefully controlled conditions, it may be possible to do this in the field.

Still, any advocate of power-based training should have an appreciation of its limitations:

DRAWBACKS TO TRAINING BY POWER

1. *It appeals to the more analytical and technically-oriented.* Not everyone is inclined, whether by background or temperament, to take a quantitative approach to training, furthermore, feedback during a ride or race may only serve as an unwelcome distraction, rather than provide valued information.

2. *It lends itself to a structured program, while demanding discipline and patience.* Use of a power meter and a periodized training plan go hand-in-hand; for many, the planning, structure, analysis, and record-keeping required by such a system are an added hassle in a sport that is time-intensive enough already, and exactly what they seek to escape from through cycling, while its "training by the numbers" aspect seems mechanical, unimaginative, constraining, and slow to yield progress. Practical considerations, like job and family, may make it difficult or impossible to closely follow any plan, however well-conceived.

3. *It is conducive to solitary training.* As Andrew Coggan points out below, the levels in his power-based training schema are referenced to "the athlete's own unique (and current) ability," which usually necessitates training alone, at least during more intense and structured workouts. Again, this is directly contrary to one of the primary reasons why many riders are attracted cycling in the first place, namely, the shared effort and companionship of training together.

4. *Even the most affordable models are expensive.* Cycling is a costly enough sport as it is, and many will simply not be able to justify the added expense of yet another "gadget." Power meters will probably never be priced comparably to HRMs, and like any electronic device, they can malfunction and be unreliable. Still, they are less expensive than many of the latest exotic frames and crazy-light components which seem so ubiquitous, while arguably of much greater benefit.

Energetics of road cycling

Mechanical power output P, expressed as Watts in the international system (SI) of units, is the rate of external work W in Joules, such that $P = W/\Delta t$, where elapsed time Δt is in seconds. Since work is the sum of forces ΣF, in Newtons, resisting the forward motion of the bicycle/rider system through a distance Δx in meters, the previous equation becomes $P = (\Sigma F \cdot \Delta x)/\Delta t$, or simply the product of force and the road speed s of the system in meters per second, i.e., $P = \Sigma F \cdot s$. This is perhaps the best way to think of power: *how fast you can travel against a given resistive load.* Rearranging to solve for speed gives $s = P/\Sigma F$. Thus, two fundamental tasks of the competitive cyclist are to maximize power output through training, diet, and rest, while reducing the sum of forces which resist forward motion, first of all, by minimizing aerodynamic drag, and to a lesser extent, by reducing weight.

An expanded motion equation for cycling is given in the section on aerodynamic testing, and was used to plot the power requirements of cycling (Figs. 1-4), to show how widely and rapidly they can vary, moreso, perhaps, than any other endurance sport, furthermore, this model assumes constant wind speed and direction. Even a rolling 30-second average for a relatively well-paced, flat time trial is surprisingly variable (Fig. 5), let alone 5-second average power for the same race (Fig. 6), or even more so still, for a road race or criterium. It follows that several metabolic pathways, or energy systems, are called upon to meet these demands, with the extent to which each is taxed depending on rider and course characteristics, wind, race type, and pace.

ENERGY SYSTEMS

Muscular contraction represents the conversion of chemical energy to mechanical work, which results from the breaking of a high-energy phosphate bond within a molecule of adenosine triphosphate (ATP), producing ADP (adenosine diphosphate) and inorganic phosphorous (P_i). There are three sources of ATP for the working muscles:

1. *The phosphagen system.* A very limited supply of ATP – enough for less than 10 seconds of maximal effort – is stored directly in the working muscles, while re-phosphorylation of ADP from phosphocreatine (PC) stores provides enough for about 25 seconds total. This system produces the highest power output levels, and thus is used most heavily during any rapid acceleration, such as in sprinting and in the initial "jump" of a hard attack.

2. *Non-aerobic glycolysis*. This is the primary energy pathway used for efforts lasting 45-150 seconds. Type II, or fast-twitch muscle fibers, are the locus for glycolysis, with muscle glycogen (stored glucose) the sole fuel source (substrate). Also called the Emden-Meyerhof Cycle, or the lactic acid system, this pathway is capable of producing large quantities of ATP for a very short time, but is much less efficient in this regard than aerobic metabolism, since it does not utilize oxygen. The byproduct of this is lactic acid, or blood lactate, which if allowed to accumulate faster than it can be metabolized or perfused from the working muscles, can result in fatigue, i.e., a rapid drop-off in power-generating capability, as muscle acidity (pH) must be maintained within an optimal range.

3. *The aerobic system*. Much (19 times!) more efficient than glycolosis, this pathway, known as the Krebs Cycle, provides most of the energy for efforts of 3 minutes or longer. Aerobic metabolism occurs primarily in Type I, or slow-twitch muscle fibers, although there is a continuum within Type II fibers, some of which display characteristics of the former. For fuel, this system relies on fat (which contains more energy than CHO – 9 kcal/gram vs. 4.1 – but is less readily metabolized) at lower intensities, progressing to carbohydrate (CHO) as intensity increases. As exercise duration wears on, there is a gradual shift of fuel source from glycogen stored in the muscles, to blood-borne glucose acquired exogenously via ingested CHO.

The balance of fiber types present (per cent composition) and other muscle physiology characteristics determine the capacity of these systems, and thereby three important functional measures of performance:

Maximal sprinting (anaerobic, or neuromuscular) power. Peak 5-second and average power for an all-out, 25-second effort from a near-standing start. Data should be collected every 5 seconds, preferably less, for this test.

Maximal endurance (aerobic) power. The upper limit or "ceiling" for steady-state power output, this is associated with its physiological determinant, maximal oxygen uptake, or VO_{2max}. No protocol is presented here for a functional equivalent of the familiar incremental ("ramped"), lab-administered test, but the quintessential cycling event suited to a high aerobic capacity (and to a lesser extent, anaerobic capacity) is the individual pursuit. Once considered to have a genetic basis almost entirely, this system's upper limit is now seen as being more responsive to training than previously thought, through intense efforts of short (3-8 minutes) duration.

Threshold endurance (aerobic) power. This is determined by the fraction of maximal endurance power that can be utilized over an extended period (>10 minutes) of time. It correlates highly with the VO_2 reached at lactate threshold (LT), and largely forms the basis for endurance cycling performance. Morphological components which, in turn, associate with VO_2 at LT are the proportion of Type I fibers within the working muscles, the extent of muscle capillarization, and the density of mitochondria present, each being adaptations which occur over years of intense training. The respective relationship between VO_2 and LT may be likened roughly to that of an engine's maximum horsepower to its governor, in that the latter determines what portion of the former can be used. As presented here, threshold power is determined simply by average wattage over a 60 minute time trial, or P_{TT60}. This functional test integrates VO_{2max}, the highest sustainable percentage thereof (VO_2 at lactate threshold), and efficiency, giving a "bottom line" measure of endurance fitness.

Gross mechanical efficiency is the ratio of how much mechanical work is actually accomplished to the amount of energy that is expended metabolically. Since movement in cycling is mechanically constrained almost entirely within the sagittal plane, cycling efficiency is determined predominantly by muscle fiber composition, being directly proportional to the percentage of Type I fibers present, and typically falls within 20-24%, trending upward very slightly as intensity increases, but falling as exercise duration wears on (most of the other 76-80% is lost as heat). Efficiency improves slightly over years of training, as there is a gradual conversion of some Type II fibers to Type I, and does not appear to be related to smoothness of the pedal stroke. Of the three physiological variables mentioned here, efficiency changes the least (and probably most slowly) with training, VO_{2max} is intermediately affected, and LT responds the most, or is the most "elastic."

It follows that a rider with a high proportion of Type I fibers will recruit fewer Type II fibers for a given work load, produce less blood lactate, and have a higher threshold endurance power. How much emphasis to put on training each particular system depends on rider characteristics and condition, as well as the demands of the event being prepared for, and is the subject of the section on formulating an annual training plan.

Training principles

In any program, certain concepts underlie the training prescription, no matter what rider it is being prepared for. As you review the customizable training plan/log provided as a download with this guide, some of the following trends (particularly 1, 2, and 6) will become apparent.

1. *Periodization.* The above referenced training program is divided into and organized by periods of time, each with a specific purpose, leading to a planned peak performance. The aim of periodization is consistency and predictability, i.e., to eliminate highs and lows, while preventing overtraining and injury.

2. *Individualization.* Who are you? How old are you, and how long have you been training seriously and racing? What are your strengths and weaknesses? Where do you live? What is the weather like? What sort of training opportunities does your location afford you? What do your work schedule and other responsibilities allow? What races do you want to do well in, and which do you want to use for training? Since motivation will determine how diligently you will train, which do you *enjoy* the most? Are you on a team, and if so, what is your role? Individualization, in a sense, is specificity applied to *you*.

3. *Progression.* Training plans are often likened to a pyramid, and it is an apt metaphor, since each succeeding week is built on the previous one, up until the peak performance(s). Another analogy is to higher education, where undergraduate courses are the broadest in scope, providing an information basis for more advanced courses, in which general knowledge is applied more narrowly, and in reference to a particular context. Similarly, physical training progresses from general to specific. Meanwhile, training volume – which consists of duration (how long), intensity (the rate of work, sometimes referred to as load), and frequency (how many sessions) – must be increased gradually, consistently, and incrementally.

4. *Overload.* Training adaptation, and hence improved performance, occurs in response to carefully applied, steadily incremental stress loads which challenge the body and *moderately* fatigue it (see Seth Hosmer's fine summary of the workout/recovery cycle for more). In response, and after adequate rest/recuperation, the body's plasticity allows it to "overcompensate" and reach a higher level of fitness. It is in quantifying the imposed stress load, especially at higher intensities, that power-measuring devices are most useful.

5. *Specificity.* It doesn't get much more basic than this: to get better (i.e., induce adaptation) in any one aspect of the sport, you must train (stress) the systems which underlie it in a way that mimics what will be experienced in the event being prepared for. In other words, to get ready for time trials, do long (20 minute) repeats at threshold intensity on a course like the race route (the actual course is best, if possible); to be able to bridge gaps, or prepare for prologue TTs, shorter (3-8 minute) intervals at ~105-120% threshold power are indicated; to improve at climbing, climb hills similar to those you will encounter, etc. Thus, beyond an initial period of general conditioning, intense training needs to be in reference to a particular context.

   A broader concept may be *simulation*, which includes specificity but goes beyond it in attempting to duplicate race conditions, as well as physiological demands, as closely as possible. What is the general lay of the course, and what are the particular characteristics? Where does the road narrow? What are the road conditions? What is the weather forecast? Is it likely to be rainy, hot, cold, sunny, cloudy? Have you prepared in these conditions? What are the prevailing winds, and where are they most likely to be a factor? What time of day do you normally train, and when does the race take place?

6. *Tapering and peaking.* Strategic manipulation of the training cycle to produce peak performance for selected events, this is used to enhance or accentuate overcompensation.

7. *Evaluation and analysis.* Race analysis is not covered here, but periodic testing and careful record keeping of relevant workout and race data are essential to assessing progress.

8 .*Rest, recuperation, and diet.* Progress, i.e., improved fitness, cannot be achieved if there is not sufficient time and rest between workouts, particularly intense sessions. Brief comments on diet will be included later on, since it is such an integral part of both on-bike performance as well as recuperation.

9. *Strength and flexibility* are properly identified as components of fitness, rather than training principles, and although they rate mention here any sort of stretching or resistance training program is beyond the scope of this guide, and will only be touched on.

Power-based training levels

By Andrew Coggan, Ph.D.

In developing the following schema, I have drawn from a number of sources, including Peter Janssen's *Lactate Threshold Training*, *The Cyclist's Training Bible*, by Joe Friel, and the British Cycling Federation's training guidelines (developed by Peter Keen), in addition to my own background in exercise physiology and experience of training and racing with a Power Tap hub since 1999. I would also like to recognize all the people who responded to my initial request for power data, as that has helped me to verify and refine the system. I'll begin by describing the various 'levels' in the system first, followed by a table of the adaptations induced by each, then move to a discussion of some of the details.

INTENSITY	AVG. POWER*	AVG. HR*	PE	DESCRIPTION
Level 1 *Active recuperation*	≤55%	≤68%	<2	"Easy spinning" or "light pedal pressure," i.e., very low level exercise, so as to minimize muscular force requirements; too low in and of itself to induce significant physiological adaptations. Minimal sensation of leg effort/fatigue. Requires no concentration to maintain pace, and continuous conversation possible. Typically used for "active recuperation" after strenuous training days (or races), between interval efforts, or for socializing.
Level 2 *Endurance*	56-75%	69-83%	2-3	"All day" pace, or classic "long slow distance" (LSD) training (note that "slow" is in relation to the very high intensity, interval-centered training programs that were popular at the time the term was coined in the 1970s). Sensation of leg effort/fatigue generally low, but may periodically rise to higher levels (e.g., when climbing). Concentration generally required to maintain effort only at highest end of range and/or during very long rides. Breathing is more regular than at Level 1, but continuous conversation is still possible. Frequent (daily) training sessions of moderate duration (i.e., 2 hours) at Level 2 possible (provided dietary carbohydrate intake is adequate), but complete recuperation from longer workouts may take more than 24 hours.
Level 3 *Tempo*	76-90%	84-94%	3-4	Typical intensity of fartlek workout, 'spirited' group ride, or briskly moving paceline. More frequent/greater sensation of leg effort/fatigue than at Level 2. Requires concentration to maintain alone, especially at upper end of range, to prevent effort from falling back to Level 2. Breathing deeper and more rhythmic than Level 2, such that any conversation must be somewhat or very halting, but not as difficult as at Level 4. Recuperation from Level 3 training sessions more difficult than after Level 2 workouts, but consecutive days of Level 3 training still possible if duration is not excessive and dietary carbohydrate intake is sufficient.
Level 4 *Lactate threshold*	90-105%	95-105%	4-5	Just below to just above TT effort, taking into account duration, current fitness, environmental conditions, etc. Essentially continuous sensation of moderate or even greater leg effort/fatigue. Continuous conversation difficult at best, due to depth and frequency of breathing. Effort sufficiently high that continuous cycling at this level is mentally taxing – therefore typically performed in training as multiple 'repeats,' 'modules,' or 'blocks' of 15-30 minutes duration (totaling 30-60 minutes). Recovery between efforts need be no longer than required for a mental break or to turn around. While consecutive days of training at Level 4 may be possible, such workouts should, in general, be performed only when sufficiently rested/recovered from prior training, so as to be able to maintain intensity.

Level 5 *Maximal aerobic power*	106-120%	>106%	6-7	Longer intervals (3-8 minute, with 2:30-5:00 recovery) meant to raise VO_{2max}. Strong to severe sensations of leg effort/ fatigue, such that completion of more than 30-40 minutes total training time is difficult at best. Conversation not possible due to often 'ragged' breathing. Should be attempted only when adequately recovered from prior training – consecutive days of Level 5 work generally not desirable even if possible.
Level 6 *Anaerobic capacity*	≥121%	n/a	>7	Short (30 seconds – 3 minutes), high-intensity intervals designed to increase anaerobic capacity. Nearly complete recovery in between. Heart rate not useful as guide to intensity due to non-steady-state nature of effort. Severe sensation of leg effort/fatigue, and conversation impossible. Consecutive days of Level 6 training rarely attempted.
Level 7 *Neuromuscular power*	n/a	n/a	**	Very short (<25 seconds), very high intensity efforts (e.g., jumps, standing starts, short sprints) that generally place greater stress on the musculoskeletal rather than metabolic systems. Complete recovery in between efforts. Power useful as guide, but only in reference to prior similar efforts, not TT pace.
*As % of average in a 60 minute time trial. **Maximal				

EXPECTED PHYSIOLOGICAL/ PERFORMANCE ADAPTATIONS	**TRAINING LEVEL**						
	1	**2**	**3**	**4**	**5**	**6**	**7**
Increased plasma volume		✓	✓✓	✓✓✓	✓✓✓✓	✓	
Increased muscle mitochondrial enzymes		✓✓	✓✓✓	✓✓✓✓	✓✓	✓	
Increased lactate threshold		✓✓	✓✓✓	✓✓✓✓	✓✓	✓	
Increased muscle glycogen storage		✓✓	✓✓✓✓	✓✓✓	✓✓	✓	
Hypertrophy of slow twitch muscle fibers		✓	✓✓	✓✓	✓✓✓	✓	
Increased muscle capillarization		✓	✓✓	✓✓	✓✓✓	✓	
Interconversion of fast twitch muscle fibers (type IIb → type IIa)		✓✓	✓✓✓	✓✓✓	✓✓	✓	
Increased stroke volume/maximal cardiac output		✓	✓✓	✓✓✓	✓✓✓✓	✓	
Increased VO_{2max}		✓	✓✓	✓✓✓	✓✓✓✓	✓	
Increased muscle high energy phosphate (ATP/PCr) Stores						✓	✓✓
Increased anaerobic capacity ("lactate tolerance")					✓	✓✓✓	✓
Hypertrophy of fast twitch fibers						✓	✓✓
Increased neuromuscular power						✓	✓✓✓

DISCUSSION

Average power during a 60 minute (40 km) time trial (P_{TT60}) provides a logical basis for training levels since it is roughly the duration of the former standard (and still common) time trial distance of 40 km, and because it correlates very highly with power at lactate threshold (although, if you define LT as a 1 mmol/L increase in blood lactate over the baseline observed during low-intensity exercise, it will be some 10-20% higher), the most important physiological determinant of endurance cycling performance, integrating VO_{2max}, the percentage of it that can be sustained, and cycling efficiency. (Indeed, beyond the first few seconds of exercise the entire power-duration performance curve can be described quite closely using just two mathematical parameters, representing anaerobic capacity and power at lactate threshold, respectively.) While shorter efforts might be more convenient, 1 hour was chosen because it corresponds roughly to the former standard TT distance of 40 km, and because it is only slightly less than that generated during shorter TTs. In theory, one could derive specific correction factors to be used with data during shorter TTs (e.g., power during a ~20 minute TT will be ~1.05 times that of a 40 km) in order to fit such data into the system, but given individual variation in the exact shape of the power-duration curve, day-to-day variability in performance, and the breadth of the specified power levels, this may only convey a false sense of precision. Somewhat along the same lines, one could base a system on laboratory-derived measures, such as lactate threshold itself, but relatively few people have access to such measurements, as opposed to simply going out and measuring their own power during a TT. Conversely, one could dispense with using one single 'anchor' measurement, and simply reference all workouts back to the maximum power that an individual can generate for that duration (i.e., Friel's 'critical power paradigm'), however, such an approach requires much more testing than simply using average TT power, while providing little, if any, advantage in actual practice, in my opinion.

There is about a 3-5% tolerance to each training level, e.g., if your Level 1 recovery rides are up to 58-60% instead of <55%of your "true" threshold (40 km) power, because you have estimated the latter from a shorter test, it really will not make any difference. Any more than 3-5%, though, and things do begin to change significantly, meaning that the percentages used to set the training levels would have to be adjusted, from which arises the question, "what is the shortest TT during which your power will be no more than 3-5% greater than what you could sustain for a 40 km?" The answer will vary somewhat between individuals. For instance, my own power for a ~20 minute TT is only about 4% higher than over 40 km, so my it would work pretty well for me personally, however, my power-duration curve is "flatter" than the vast majority of people out there; one study, for example, found that average power during a 20 km (not 20 minute) TT was 107% of that during a 40 km TT. Consequently, I am leery of basing training levels (using my system, without any adjustments) on the results from anything shorter than a 30 minute effort.

A compromise had to be made between defining more levels, to better reflect the continuum of physiological responses, and fewer, for simplicity. The seven levels specified were considered the minimum needed to adequately describe the different types of training required to meet the demands of competitive cycling. Even with seven levels, though, the range within each is somewhat broad, but this should not be a major disadvantage, for several reasons. First, there is obviously an inverse relationship between power output and the duration that power can be sustained, thus, it is axiomatic that shorter training sessions or efforts will be conducted at the higher end of a given range, whereas longer sessions or efforts will fall towards the middle or lower end of a given range. Second, since power is a more precise indicator of exercise intensity than, for instance, heart rate, workouts should still be adequately controlled despite the seemingly large range in power within each level. Finally, as with all training systems, exercise prescriptions should be individualized, in this case taking into account the power the athlete has generated in previous similar or identical workouts . . . the primary reference, therefore, is not to the system itself, but to the athlete's own unique (and current) ability. In this regard, the present classification scheme should be viewed primarily as an overall framework, not a detailed plan.

The suggested heart rate ranges must be considered as imprecise, because of individual differences in the positive y-intercept of the power-heart rate relationship. That is, even when power is zero, heart rate is not, with differences between individual in this 'zero power' (not resting) heart rate significantly influencing the percentage of average 60 minute TT heart rate corresponding to any given power output. Because of this, I do not believe it is really useful to try to derive power ranges from heart rate ranges (as Friel's initial attempt to do so readily shows). Expressing heart rate as a percentage of the range from that at zero power (derived by backextrapolation of the linear power-heart rate relationship) to that at P_{TT60} – akin to the Karvonen formula for heart rate reserve – corrects for this individual effect and allows you to more precisely specify the levels based on heart rate, however, I rejected this approach as simply being too complex, especially given that this is a power-based system. Nonetheless, I have derived guidelines for heart rate (as well as perceived exertion) from power data, such that can be used along with power to help guide training.

Guideline values given below for perceived exertion are from Borg's 10 point category-ratio scale, not the original 20 point scale that is probably more familiar to most people, since the category-ratio scale explicitly recognizes the non-linear response of many physiological variables (e.g., blood and muscle lactate), and thus provides a better indicator of overall effort.

LEVEL	SENSATION
0	Nothing at all
½	Extremely weak (just noticeable)
1	Very weak
2	Weak (light)
3	Moderate
4	Somewhat strong
5	Strong (heavy)
6	
7	Very strong
8	
9	
10	Extremely strong
**	Maximal

Since perceived exertion increases over time, even at a constant exercise intensity (power), the suggested values or ranges are for relatively early in a training session or series of intervals.

While this system is based on the average power during a workout or interval effort, consideration must also be given to the distribution of power within a ride. For example, average power during mass start races typically falls within the range defined as Level 3 ('tempo'), but races are usually more stressful due to the greater variability (and therefore higher peaks) in power. Similarly, due to soft-pedaling/coasting down hills, the same average power achieved during a hilly (or even mountainous) ride will not reflect the same stress as an equal average power achieved during a completely flat workout. To some extent, the variability in power is taken into account in defining the various levels, especially Levels 2 and 3 (training at the higher levels is likely to be much more structured, thus tending to limit variations in power). Nonetheless, a workout consisting of, say, 30 minutes at Level 1 (as warm-up), 60 minutes at Level 3, and another 30 minutes at Level 1 (as warm down) would best be described as a tempo training session, even though the overall average power might fall within Level 2 ('endurance').

A final caveat: defining various training 'levels' is only the first step in developing a training plan; what matters as well is the distribution of training time or effort devoted to each level. Discussion of such follows shortly, but two points I wish to emphasize are: 1) I believe that training should be highly individualized, to account for each athlete's unique abilities, goals, and state of development (e.g., age, training background), and 2) compared to some, I tend to place more value in training at Levels 2, 3, and 4 – indeed, what many consider to be 'junk training.' In that regard, my philosophy apparently parallels that of Peter Keen, or at least how his ideas are reflected in British Cycling Federation training guidelines.

The annual training plan

"It seemed that all my past life was but a preparation for the hour and trial at hand."

– WINSTON CHURCHILL, 1940

Proof may be lacking from a scientific standpoint, but there is little dispute among those who practice the *art* of coaching that periodized training works, in that it makes performance predictable and helps prevent overtraining, even injury, by budgeting total duration and the distribution of time spent at each training level in a measured, gradually progressive fashion. Every workout is indeed a preparation for just one or a few races, and this approach is not without its drawbacks, since it may create too narrow a focus, and the seeming success or failure of the entire year may judged on a couple performances. Additionally, and as discussed in more detail shortly, there will almost inevitably be disruptions to the training plan at some point.

Time periods in the customizable plan/log provided here are referred to as "phases" (4-16 week periods), "cycles" (3-6 weeks), and "weeks," which seemed less confusing than the more familiar "macrocycles," "mesocycles," and "microcycles," respectively. Daily workouts are derived by breaking down each week's duration according to the time allotted to each intensity level, with some examples of this to follow.

Each phase has a different name and purpose. The off-season ("Maintenance") is for mental relaxation, fun, a break from competition and perhaps even from riding itself. Cycling need not be entirely discontinued, but is usually supplemented through cross-training, i.e., aerobic activities such as running, cross-country skiing, skating, etc., as perhaps strength training. Muscles, tendons, and joints are allowed to recover and rebuild from the racing season through this "active recuperation" process, rather than by total rest. Bicycle fit and medical issues should also be resolved at this time.

Controversy exists as to whether weight training ultimately makes any difference in road cycling performance (as opposed to track cycling); it is likely that similar results can be achieved through 'strength training on the bike,' and Level 7 workouts can be done year round, since no lactic acid is produced. Nonetheless, if a program is undertaken, conventional wisdom generally holds that multi-joint movements, in no more than 20 repetitions, should be used to strengthen cycling-specific muscles without adding mass, with maintenance throughout the year. Weight training is generally not recommended for children under 16, or prior to the closing of the growth plates. For a complete discussion of an annual plan, see Joe Friel's *The Cyclist's Training Bible*.

Phase I ("Preparation") is a 16-week building-up, or "base" period; no time is budgeted in Cycle 1 for Levels 4-6, nor is threshold testing carried out in these first 4 weeks (a loss of 5-10% is fairly typical over the winter, depending on the type and level of activity maintained), which may be neglected depending on the level and type of activity maintained throughout the off-season. Testing is otherwise carried out once a month, usually in the first week of each cycle, although to a large extent, training becomes testing, and testing is training. For consistent and reliable test results, make sure you are rested, neither sick nor recovering from sickness or injury, and avoid extremes of temperature (especially heat) and wind. Flat terrain is recommended, but rolling or even hilly will do if the same course is used each time (average power on a rolling/hilly course, or in windy conditions, is usually somewhat less than for a flat, windless test of similar duration). In your first test, just as in the initial, transitional period of power meter use, you will likely need to use PE and HR guidelines to gauge intensity, while monitoring power, but by the second test, power should guide pace. A useful practice to help gauge intensity may be to adopt a standard set of interval durations for training at each level, e.g., 90 seconds, 3, 5, and 15+ minutes.

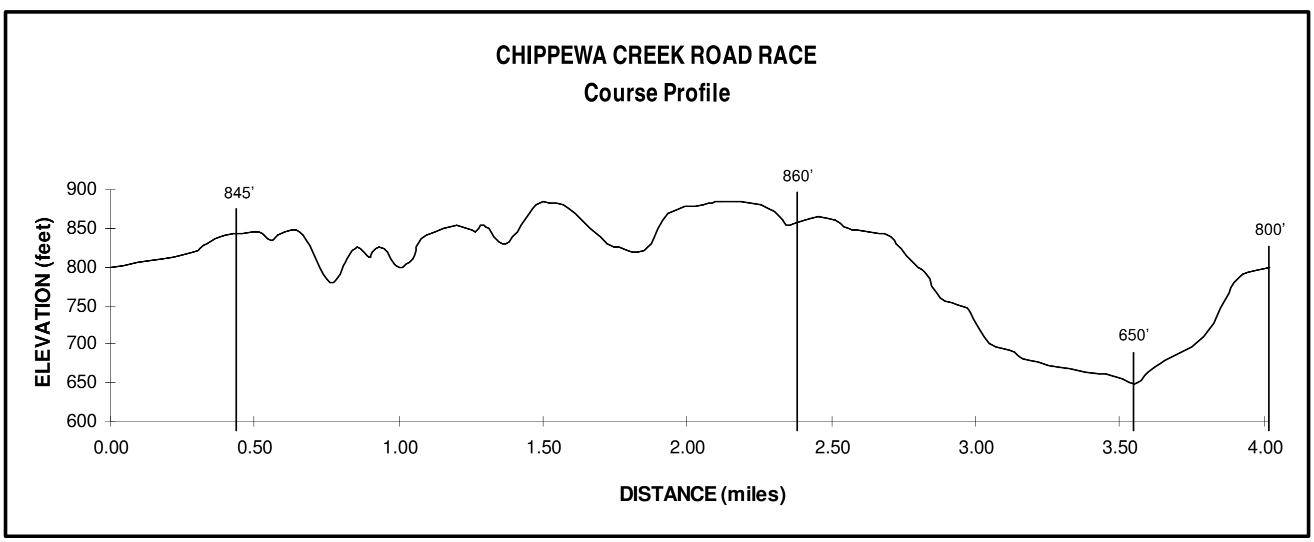
Wattage is raised incrementally each week throughout Phase I, until a target value is reached. For instance, if 300 W was your peak P_{TT60} the previous year, a value of 270 W might be initially assumed or determined by test, and this would be increased by 5 W every other week, until 300 W as reached at the end of 12 weeks. Hill training is generally avoided in the early part of Phase I, and while intervals workouts during this period should be challenging and difficult, it should always be possible to complete them. So a typical week in this Phase I might be broken down something like this:

Week 7 (3rd week in the second of three 4-week cycles) *Total hours in cycle*: 32:00 (8% of 500 yearly hours) *Weekly hours*: 9:16 (29% of cycle)								
DAY OF WEEK	**DURATION (hr:min) AMONG TRAINING LEVELS**							**COMMENT (times in min:sec)**
	2	3	4	5	6	7	RACE	
Monday								Day off
Tuesday	0:30					90 s		Jumps: 3 $\times$ 0:10; sprints: 3 $\times$ 0:25
Wednesday	1:00	0:08		0:20	0:06			3 $\times$ 2:00 (flat) @ 125% P_{TT60} 4 $\times$ 5:00 (flat) @ 115% P_{TT60}
Thursday	1:30							Recuperation ride
Friday	1:00	0:06	0:50					3 $\times$ 16:30 @ 100% P_{TT60}
Saturday								Day off
Sunday	3:00	0:42						Endurance ride, w/ 2 $\times$ 21:00 @ 80% P_{TT60}
TOTALS	7:03	0:56	0:50	0:21	0:06	0:02		
%	75 %	10%	9%	4%	1%	0.5%		

Time spent at Level 1 is not budgeted, but is used as needed for recovery; for Power Tap users, duration there and at Level 2 can be accounted for using HR guidelines and a heart rate monitor (separate from Power Tap), with memory zones set accordingly.

Training becomes more specific in Phase II, tailored to upcoming competition, and can include training races, while each cycle's taper becomes more pronounced. An old bromide runs, 'Train your weaknesses, race your strengths,' and indeed, events you wish to peak for should be chosen to fit your abilities, but your strengths may become less so if you do not train them, too; weaknesses should be trained simply to minimize them as much as possible, not with a goal of rapidly transforming yourself into a different kind of rider.

The most specific way to prepare for any race is to train on the actual course to be used, but this is often impractical or not possible at all. The next best thing is a course map and profile, but if it is unavailable from the race organizer, a way to "remote-view" the route and terrain is with on-line U. S. Geological Survey topographic maps at Topozone.com, or with Topo! interactive software. Here is a profile of a local 36 mile circuit race held annually on the second or third Sunday of May, used by many as one of their "A" races for which they attempt to peak:



The entire course lies within a heavily wooded park. From the base of the climb to the start of the finishing straight, 120' in elevation is gained in 0.3 miles, a grade of 7.6%. The 'backstretch' is technical, with numerous curves and short but steep climbs, the downhill has a few very gradual curves, allowing unbroken descent, and the finishing straight is a 200 meter false flat which heads southwest, into prevailing winds. The remainder of the course is sheltered from the wind. Training in the two weeks prior would ideally be structured so as to reflect these characteristics.

Sprint workouts are neglected and intensity is slightly reduced in the week prior, due to its high volume:

Week 20 (3rd week in the second of three 4-week cycles)
Total hours in cycle: 40:00 (10% of 400 yearly hours)
Weekly hours: 16:30 (33% of cycle)

DAY OF WEEK	**DURATION (hr:min) AMONG TRAINING LEVELS**							**COMMENT (times in min:sec)**
	2	3	4	5	6	7	RACE	
Monday								Day off. Massage and nap, if possible.
Tuesday	1:00	0:08		0:10	0:12			6 × 2:00 (hill) @ ~150% P_{TT60} 2 × 5:00 (rolling/technical) @ 115% P_{TT60}
Wednesday	1:20							Recuperation ride
Thursday	1:00	0:06	1:00					3 × 20:00 (varied terrain) @ 100% P_{TT60}
Friday	1:20							Recuperation ride
Saturday	3:10	0:55						Endurance ride, w/ 2 × 27:00 @ 80% P_{TT60}
Sunday	1:00						1:35	35 mile hilly road race
TOTALS	8:50	1:11	0:16	0:10	0:12	0:00	1:35	
%	67%	9%	7.5%	1.3%	1.5%	0 %	12%	

The week just prior to an event you are peaking for is a 'taper' period of reduced volume. Note that while duration is ~55% of the prior week, frequency is only one day less, and intensity is actually *increased* slightly:

Week 21 (4th week in the second of three 4-week cycles)
Total hours in cycle: 40:00 (10% of 400 yearly hours)
Weekly hours: 7:12 (18% of cycle)

DAY OF WEEK	**DURATION (hr:min) AMONG TRAINING LEVELS**							**COMMENT (times in min:sec)**
	2	3	4	5	6	7	RACE	
Monday								Day off. Massage and nap, if possible.
Tuesday	0:30					125 s		Sprints: 5 × 0:25, on slight uphill grade
Wednesday	0:50							Recuperation ride
Thursday	1:00	0:08			0:12			6 × 2:00 (hill) @ ~155% P_{TT60}
Friday	1:30	0:30						Endurance ride (remainder of Level 2 time), w/ 1 × 30:00 @ 90% P_{TT60}
Saturday								Day off. Massage and nap, if possible.
Sunday	1:00						1:35	35 mile hilly road race
TOTALS	4:45	0:39	0:00	0:00	0:14	0:03	1:35	
%	66%	9%	0%	0%	3%	0.3%	21%	

'WHEN LIFE INTERVENES'

It is the rare exception when any training plan is followed perfectly, as sooner or later, demands of job and family, illness or injury, etc., are sure to intervene. Flexibility and a willingness to adjust or modify the training plan are the keys in responding to any disruptions. Even when 'life' does cooperate, variation in recovery from session-to-session and week-to-week may make it necessary to adjust your training "on the fly."

Usually, when a workout is missed, it is best to simply move on, rather than try to "make it up," since some other training will have to be postponed or skipped later on, such that over a given period (say, the 3 months before an important race), you have still done less of something than you intended. A week off may require no more than an adjustment in the focus of the training plan and a reduction in intensity and duration the first week after resuming, but when two weeks or more are missed, it is necessary to assess fitness at the time training is resumed, choose a new goal, and lay out an amended plan to reach it. Recently, for instance, the author was inactive for 28 days following a 16 week preparation period from March 5 through June 27. Upon resuming, it was time to ask, essentially, 'Where have I been, where am I now, and where do I want to go?' Much condition had been lost, but not all, so there was no need to write the season off entirely. A goal was set of reaching the same level of fitness as before the hiatus, but clearly, another 16 or 12 week period was neither necessary nor practical; as it seemed especially important not to resume too quickly, a 2 week build-up period (4% of yearly duration) was chosen, with no intensity in the first week and little in the second, followed by a 6 week cycle (14% of yearly hours). A 5% loss in P_{TT60} was estimated, since it seemed unwise to begin with a threshold power test.

WEEK ENDING	DURATION (% of cycle)	KEY WORKOUTS
7/28	45%	No intensity, Level 2 only.
8/4	55%	1 × 18:00 @ 94% P_{TT60} (Tue.); 1 × 18:00 @ 95% P_{TT60} (Thu.); 1 hr 50 min @ Level 2 (Sun.)
8/11	14.1%	3 × 4:30 @ 111% P_{TT60} (Tue.); 2 × 15:15 @ 96% P_{TT60} (Thu.); 2:00 @ Level 2/3 (Sun.)
8/18	15.9%	4 × 4:30 @ 113% P_{TT60} (Tue.); 2 × 18:20 @ 100% P_{TT60} (Thu.); 2:30 @ Level 2/3 (Sun.)
8/25	17.6%	4 × 5:00 @ 113% P_{TT60} (Tue.); 2 × 21:00 @ 100% P_{TT60} (Thu.); 3:00 @ Level 2/3 (Sun.)
9/1	19.4%	4 × 5:30 @ 114% P_{TT60} (Tue.); 2 × 22:30 @ 100% P_{TT60} (Thu.); 3:30 @ Level 2/3 (Sun.)*
9/8	21.1%	5 × 5:30 @ 115% P_{TT60} (Tue.); 2 × 23:30 @ 102% P_{TT60} (Thu.)**; 3:50 @ Level 2/3 (Sun.)
9/15	12.0%	2 × 15:30 @ 103% P_{TT60} (Tue.); 25:00 test TT (Sun.)

*Missed workout. **Unable to complete workout due to fatigue. P_{TT60} refers to average 60 minute TT power before the hiatus. Level 2/3 endurance rides included ~25 minutes @ 80-85% P_{TT60} at the end of the ride.

By the end of the period, it was possible to slightly exceed pre-hiatus power levels.

A SIMPLIFIED APPROACH

For the 2003 training year, the author scrapped the plan/log included with this guide in favor of a simplified approach which tracks only duration power for each workout (average with and without 0s, 'normalized' power as defined in the following section on Training Stress Score, or TSS), plus work in kJ, TSS itself, and workout details. I find that TSS has, for the most part, obviated breaking each ride down in to the various training levels, although some accounting of this may still be useful.

As relates to the plan, while it can be a starting point for planning out the year, and give a sense of relative proportion, ebb and flow, etc., I grew skeptical of it because:

1. a 'proportional' approach does not produce reasonable durations for higher overall annual training volumes (>800 hours); too much time will be specified at higher intensities, and reducing the percentages allotted to them means you aren't really taking a proportional approach anyway;
2. it may actually take away from a sense of judgment and proportion; half the time I wouldn't know what my last workout was, or what the next one would be until I checked the plan, due to the constantly-varying nature of each cycle;

3. it is complicated, time-consuming, and somewhat arbitrary to attempt break down races and longer mixed-intensity rides in to the respective intensity levels;

4. especially among the more obsessive-compulsive (hi there), a precisely specified training plan can become an end-in-itself, rather than a means to an end; you become a slave of it, and make your training fit the plan, rather than shaping the plan with reference to the demands of the particular event being prepared for.

So I simply increased interval intensity and overall duration gradually from a chosen baseline, scheduling two intervals workouts during the week, a mixed Level 3 (mostly Level 3, some Level 2 and even some Level 4 and 5) ride of 2-4 hours on the weekend, and a couple Level 1/2 rides in between as recovery.

Finally, as is noted in the training guide, the plan is meant to be customized/adjusted in relation to your goals, schedule, etc., and the values there are meant to be starting points only; it is not a "cookie cutter," one-size-fits-all plan.

Training Stress Score (TSS)

By Andrew Coggan

A STATEMENT OF THE PROBLEM

"A watt is not always a watt" – DAVE HARRIS

"Not all kilojoules are created equal" – ANDY COGGAN

At least in theory, one of the advantages of training and racing with a power meter is that it enables you to more precisely control the overall training load. By continuously recording power output, the exact demands of each workout can be more accurately quantified, and the intensity or duration (or both) of subsequent training sessions can be modified as necessary to avoid either under- or overtraining. Successful application of this approach, however, requires that the athlete or coach be able to quickly make sense out of the huge amounts of data that are amassed when power output (along with other variables) is recorded every second or so during multi-hour training rides. This task is made more difficult by the fact that power is highly variable when cycling outdoors, such that the overall average power may give little insight into the actual stress imposed by a given workout. This is especially true for races, since the fluctuations in power normally resulting from hills, wind, etc., are further exaggerated by tactical considerations, e.g., by the need to maintain one's position in a large field, or by the need to initiate or respond to attacks. The issue, therefore, is how to best summarize or condense power meter data while still adequately capturing or reflecting the actual demands of each race or training session. One solution to the problem is to calculate the frequency distribution of power output, i.e., the percentage of total ride time when power falls within a certain range (e.g., 200-250 W) or training level. Such frequency distribution analyses can be useful, but have two major limitations:

1. A relatively large number of numeric values is still needed to represent a single training session. Such data are therefore best presented graphically (e.g., as a bar chart), and are themselves not readily amenable to further analysis. Furthermore, while large differences in power distribution are readily apparent using this approach, more subtle differences are harder to detect.

2. More importantly, such analyses do not (and in fact readily cannot) take into account how long each "foray" into a given power range or level actually lasts. This has significant implications with respect to physiological responses, as will be discussed below.

Another means of expressing power meter data that is utilized by some is to simply record the total work (in kJ) performed during a race or training session. This can be helpful in understanding the overall energy demands of training and e.g., how this compares to energy intake (useful, for example, if a rider is trying to alter their body composition), however, like keeping track of miles or hours of training, total work only provides a measure of overall training volume, and says nothing about the actual intensity of that training.

The limitations of currently available methods for analyzing power meter data files led me to try to develop an alternative approach.

PROPOSED SOLUTION: TSS AND IF

Dr. Eric Bannister has previously described a way of quantifying training load in terms of a HR-based "training impulse," or TRIMPS, score:

TRIMPS = exercise duration × average HR × an intensity-dependent weighting factor

Since HR is essentially linearly related to oxygen uptake (metabolic rate), the product of the first two factors in the above equation is proportional to the amount of energy expended, or (since efficiency is relatively constant), work performed. The third term then takes into account the intensity of the exercise, since many physiological responses (e.g., glycogen utilization, lactate accumulation) increase non-linearly with increasing intensity.

Reasoning by analogy, it seemed logical that data from a power meter could be used to derive what I have called a "training stress score," or TSS:

TSS = exercise duration × average power × an intensity-dependent weighting factor

Similar to TRIMPS, the product of the first two factors in the above equation is equal to the total work performed, whereas the "intensity factor" (IF) serves to account for the fact that the physiological stress imposed by performing a given amount of work (e.g., 1000 kJ) depends in part on the rate at which that work is performed (the power output itself). IF gives an indication of the intensity, whereas the TSS reflects duration as well. Clearly, for such an approach to have merit, the IF must have some basis in reality, i.e., the relative weight given to higher vs. lower intensity exercise cannot be determined at random, but must be based on the actual physiological "costs." Furthermore, since the physiological responses to exercise at a given power output depend in part on the duration for which that power is maintained, this fact must be recognized as well. The algorithm used to determine the IF is therefore the key to the whole approach, and so this is where developmental effort was focused.

To derive an appropriate algorithm, I relied on blood lactate data collected from a large number of trained cyclists exercising at intensities both below and above their lactate threshold. This choice was made because many physiological responses (muscle glycogen and blood glucose utilization, catecholamine levels, ventilation) tend to parallel changes in blood lactate during exercise; in this context, then, blood lactate levels can be viewed as an overall index of physiological stress. To reduce variability between individuals, the data were normalized by expressing both the power output and the corresponding blood lactate level as a percentage of that measured at LT. The normalized data were then used to derive a best-fit curve. Perhaps not surprisingly, an exponential function provided the best fit, but a power function of the following form proved to be nearly as good:

blood lactate (% of lactate at LT) = power (% of power at LT)$^{3.9}$; $R^2 = 0.806$, n = 76

Based on these data, a 4th-order function was used in the algorithm for determining the IF (the exponent was rounded from 3.9 to 4.0 for simplicity's sake).

The other physiological feature that seemed necessary to incorporate into the algorithm for calculating IF was that responses to changes in exercise intensity are not instantaneous, but follow a characteristic time course. Because of this, exercise in which the intensity alternates every 15 seconds between a high and a low level (e.g., 400 and 0 W) results in physiological, metabolic, and perceptual responses nearly identical to steady-state exercise performed at the average intensity (e.g., 200 W). The specific reasons for this are beyond the scope of this discussion, but the important facts are that the half-lives (50% response time) of many physiological responses are directly or indirectly related to metabolic events in exercising muscle, and such half-lives are typically on the order of 30 seconds. Thus, the decision was made to smooth power data using a 30 second rolling average before applying the 4th order weighting as described above.

Finally, the decision was made to express the IF as a ratio of the "corrected" power obtained by smoothing/ weighting to the individual's power at LT, and to normalize the TSS to the amount of work that could be performed during one hour of cycling at threshold power (= 100 TSS "points"). While these last two steps are not necessary for comparisons within a given individual, they should make it easier for coaches or anyone dealing with multiple athletes to more quickly grasp the significance of a given value.

The steps required to calculate IF and TSS then become:

1. starting at 30 seconds, calculate a 30 second rolling average for power (data point by data point)
2. raise the values obtained in step 1 to the 4th power; these values if plotted as a function of time, should show which parts of e.g., a race were really hard, and which weren't (in fact, since Borg's 10 point PE scale parallels blood lactate, such a plot should look like a continuous record of perceived efforts)
3. take the average of all the values obtained in step 2
4. take the 4th root of the number obtained in step 3; this "adjusted" or "corrected" power is an estimate of the equivalent steady-state power

5. divide the corrected power by the individual's threshold power – this decimal value is the IF
6. multiply the corrected average power for the workout by the duration (in seconds) to obtain the total work performed (in J)
7. multiply the total work by the IF to derive the "raw" TSS
8. divide the "raw" TSS by the amount of work performed in one hour at threshold (threshold power × 3600 seconds) and multiply by 100 to obtain the final TSS

These "quartic root of the mean of the fourth power of the smoothed wattage" calculations (perhaps we can call them something like QRM4, just as root-mean-square is called RMS) are obviously too cumbersome to routinely perform on every power meter file, or part thereof, even when, for instance, using a macro in Excel. Software such as that from Cycling Peaks is available to automate the process.

Originally, average power (uncorrected) for the workout was used in step 6 to obtain total work, but after some thought, this was changed to the corrected average power, since total work needs to be adjusted to account for variations, just like the weighting factor (thus, the final TSS result simplifies to the square of IF multiplied by the ride duration in hours and 100). Here's the reason why: consider two scenarios: a 1 hour TT that is perfectly paced (power absolutely constant), vs. a criterium of equal length in which power is much more variable, but is still the very most the rider can produce. By definition, the IF for the TT would be 1.00. Applying the above algorithm (and assuming it does what it is supposed to do), the IF for the criterium should also be essentially 1.00. Likewise, the TSS score for the TT will, by definition, be equal to 100. However, if you use the uncorrected average power to calculate TSS for the criterium, you'll get a value of less than 100, which shouldn't be, the case since both efforts were equal in intensity and duration. Using the adjusted power to calculate TSS eliminates this discrepancy.

Another way of looking at it is that when power is variable, the arithmetic average will be an underestimate of the true physiological stress. It therefore follows that it is physiologically more stressful to perform a certain amount of work (work = power × time) when power is highly variable (something that I think we all intuitively recognize). Analogous to TRIMPS, I defined TSS as total work performed × an intensity-dependent weighting factor, but only accounted for the variability in deriving the second factor, IF, and not work. [In other words, blame reasoning by analogy to heart rate for my mistake. ;-)]

Somewhat, but not entirely, as an aside: the concepts underlying TSS/IF help to explain some of the apparent discrepancy between indoor and outdoor training. For example, I typically do my recovery rides (Level 1) on my Velodyne at 200 W, and my endurance sessions (Level 2) at 250 W. At first, this seems inconsistent with the training levels I defined, since the former would be in Level 2, and the latter in my Level 3. However, when you consider that power is perfectly constant, then it make sense – the IF values would be 200/300 = 0.67 and 250/300 = 0.833, i.e., directly comparable to outdoor training.

APPLICATIONS

The most obvious application this method (and the original purpose for developing it) is to quantify the overall training load, in terms of the number of TSS points accumulated during a given period of time. For example, by keeping track of the total TSS per week or per month, it may be possible to identify an individual's "breaking point," i.e, the maximum quantity and quality of training that still leads to improvements, rather than overtraining. As well, a very high TSS resulting from a single race or training session may be an indicator that additional recovery on subsequent days is required. Until additional experience is gained with the method, it is difficult to say exactly what a "high" TSS score is, however, the table below gives some rough guidelines:

<100	–	l low (easy to recover by following day)
100-200	–	medium (some residual fatigue may be present the next day, but gone by 2nd day)
200-300	–	high (some residual fatigue may be present even after 2 days)
>300	–	epic (residual fatigue lasting several days likely)

Note that while the TSS score is normalized to an individual's LT, such that comparison across individuals is possible, there could still be differences between athletes in how they respond to a given "dose" of training. Such difference may be due to natural ability, or may be the result of specific training (i.e, the more you do the more you can do). This isn't really a problem, however, since comparison within a given individual is the primary interest.

While the goal at the outset was to develop a method of quantifying the overall training load (duration × intensity) via TSS, the IF score may actually prove to be even more useful. For example, it can be used to compare the intensity of even markedly dissimilar training sessions or races, either within (most valid/relevant) or across (to assess tactical or drafting skill, or just for plain old "bragging rights") individuals:

<0.75	–	level 1 recovery rides
0.75 - 0.85	–	level 2 endurance training sessions
0.85 - 0.95	–	level 3 tempo rides, aerobic and anaerobic interval workouts (work and rest periods combined), longer (>2.5 h) road races
0.95 - 1.05	–	level 4 intervals, shorter (<2.5 h) road races, criteriums, circuit races, 40k TT (by definition)
1.05 - 1.15	–	shorter (e.g., 15 km) TTs, track points race
>1.15	–	prologue TT, track pursuit, track miss-and-out

Perhaps even more importantly, the algorithm used to derive IF makes it possible to estimate steady-state power at LT from highly variable power data. That is, if sustainable power (either constant or non-constant) is essentially "capped" by power at LT, and if the 30-second smoothing/4th order weighting algorithm appropriately corrects the variable power data, then the power estimated at step 4 in the calculation of TSS/IF (see above) provides an estimate of the equivalent steady power that could be produced for the same physiological strain.* Stated another way, the correction algorithm simply provides a means of expressing highly variable power data in physiologically-relevant "language." Consequently, if an individual pushes themselves just as hard in a ~1 hour mass start race (or time trial in very hilly terrain) as they might in a flat time trial, then corrected power provides an estimate (generally to w/in 5-10 W) of their power at LT. This observation reduces, or perhaps even completely eliminates, the need to perform a time trial to determine power at LT. Instead, the results of mass start races can be used for this purpose, for example for beginning power meter users who have never done a time trial using such a tool. Even for riders whose power at LT is well established, the IF score can be used to detect significant changes in fitness – for example, if a rider's IF score for a ~1 h race is greater than 1.05, then their LT power should be reassessed (ideally using the same means used to establish it originally) to determine whether it has truly changed.

*Astute readers will have already picked up on the fact that the IF values given in the table above are the fraction or percentage of power at LT that was equivalently maintained. Indeed, it was suggested to me that the IF should be multiplied by 100 to express it as a percentage, since decimal values less than 1 can be more difficult to immediately grasp. I resisted this quite valid suggestion, however, because I was afraid that scaling IF this way might result in people confusing IF values with TSS scores. As well, expressing IF as a percentage rather than a decimal could result in individuals confusing these values with the percentages limits of the training levels I laid out previously. A really astute reader will realize that they are in fact essentially measures of the same thing, i.e., power output relative to the individual's power at LT – the absolute values differ, however, because deriving the IF score corrects for the effects of variations in power on physiological responses, whereas the training levels have simply been offset to lower power levels to account for this fact (e.g., Level 1, recovery, is defined as an average power of <55% of power at LT, but the IF value of <0.75 corresponds to <75% of power at LT).

Finally, yet another application of the IF algorithm/score is as a teaching tool, as it helps demonstrate why, even when power is highly variable, it is still an individual's "metabolic fitness" (i.e., power at LT) that is important in determining performance. That is, by illustrating (via a 4th order relationship – greater even than the 3rd order relationship between power and wind resistance!) how physiologically "costly" every sustained burst above LT proves to be, the IF algorithm may 1) help less experienced riders understand why it is important to learn how to modulate their effort during mass start races, so that they don't fatigue themselves unnecessarily, and 2) help even experienced riders understand how appropriate training aimed at raising LT can improve performance even in events seemingly much different than a time trial.

LIMITATIONS AND CONCLUDING REMARKS

As mentioned previously, the key to everything I've written about above is the weighting algorithm, and thus the validity and robustness of the TSS and IF scores/values depend entirely on it. I believe that it is based on sound physiological reasoning, and in my experience so far it seems to work quite well (better than I could have hoped, actually). I have not, however, had the chance to evaluate thousands, much less hundreds, of data files, so the possibility of the occasional "outlier" still exists. A greater limitation to the entire concept, though, is that the basic premise – i.e., that you can adequately describe the training load and the stress it imposes on an individual based on just one number (TSS), completely ignoring how that "score" is achieved and other factors (e.g., diet, rest) – is ridiculous on its face. In particular, it must be recognized that just because, for instance, two different training programs produce the same weekly TSS total, doesn't mean that an individual will respond in exactly the same way. Nonetheless, I believe that TSS (and IF) should prove useful to coaches and athletes to evaluate and manage training.

IF/TSS are not meant to replace HR or PE as a tool to guide you *during* training, since, at least at present, such calculations can only be done post-hoc. On the other hand, trying to excessively or artificially constrain the fluctuations in power during certain types of training may be counterproductive, which is why my training levels were specified based on the *average* power for a training session or effort. I think people like Allen Lim and Dean Golich recognize this issue as well, although possibly without explicitly realizing it – that is, the practice of prescribing training sessions in terms of total work ("go accumulate 3000 kJ, then climb this mountain") allows and even encourages a rider to do what they have always done, which is let their power vary depending on the demands at the time. TSS really just allows you to take this practice to a more sophisticated level, by accounting for intensity (via IF) as well. As such, it may prevent riders from overdoing it on any single day, thus enabling them to consistently complete their "benchmark" workouts in style. An exercise prescription using TSS would therefore be "go for a 3 hour ride and accumulate 200 points, but no more!"

Coaches oftentimes tend to micromanage athletes, simply because they can't experience what the rider does when performing a given workout. Because they feel like they are "flying blind," they tend to overcompensate by trying to control every single aspect of a workout, e.g., "ride for 75 minutes at a cadence of 92 while keeping your heart rate between 132 and 145 and your power between 181 and 198 W – and if I don't do what I tell you, you've screwed up." Aside from making things more difficult for both the rider (who now has numerous details to attend to) and especially the coach (who is often dealing with multiple athletes), such ultra-rigid exercise prescriptions are often impractical to implement (due to constraints imposed by terrain, traffic, etc.), and more importantly may not be the best way to prepare for competition (where power is highly variable).

This is not to say that training shouldn't be structured, or that I believe the pendulum should be swung all the way over to the "racing is best training" side of things, but simply that a balance must be achieved between the two extremes. (After all, nothing can be more structured/controlled than doing 100% of your training on an ergometer, yet I can tell you from personal experience that that approach is not optimal.)

So what does this have to do with IF/TSS? I think that by giving coaches a tool that allows them to better quantify and appreciate the demands imposed by a given workout, especially one where power is highly variable, it will make it easier to manage an athlete's overall training load, without having to go to excessive lengths to control every pedal stroke. Again, I think it is this need or pressure to be more "free" that some coaches are responding to when they either simply prescribe training based on total work, or only pay attention to power data after the fact.

For example, suppose that you're coaching (remotely) an athlete who, like many, has the opportunity and wants to take part in your typical mid-week training criterium. They are strong enough that sitting in the field isn't too hard for them, but not strong enough to dictate how hard the race plays out, so they are somewhat at the mercy of who shows up on any given week, getting hammered on some occasions, but not on others. This may affect their ability to complete other "benchmark" workouts the way they should each and every time. Without some means of quantifying the demands of that training crit, it may take some time before the coach and/or athlete pick up on the fact that it was variation in how hard the crit was that explained their varying performance in other workouts. (This would be especially true if, for whatever reason, communication between athlete and coach was a problem.) Using IF/TSS, however, the coach should have a much better appreciation of exactly how demanding that training race was for the athlete, and can then make an informed decision as to how to adjust training as necessary (e.g., have the athlete just sit in, skip the crit entirely, allow for more rest before the next important workout).

Finally, I am releasing this idea in the public domain because I strongly believe that knowledge is to be shared, not hoarded, and I hope that others will benefit from my efforts. To that end, I encourage people to try calculating TSS and IF for some of their own files, and share any interesting observations or questions that arise as a result. To facilitate with its calculation, TSS/IF are included by permission as one of the functions in Cycling Peaks software http://www.cyclingpeakssoftware.com/home.html, Bodil Anderson has created a nice on-line calculator at http://www.virtusphysica.com/forums/upload/htmlspecialedition2003.htm, and James Huntington has posted an Excel macro at http://analyse-it.com/TSSandIF.zip, however, I would be very disappointed if anyone tried to capitalize on these ideas by producing or incorporating them into a commercial program without my permission.

Miscellaneous notes on training

SPRINT AND INTERVAL TRAINING TIPS

Sprinters, goes the conventional wisdom, are born and not made, and indeed, peak sprinting power depends more on genetics (particularly, the percentage of fast-twitch muscle fibers present), and less on training, than any other functional test. It may be useful, however, to distinguish between road race sprinters and criterium sprinters. A good local example of the former is Jeff Braumberger, who clocked 53:16 for a 40 km time trial without aerodynamic equipment in 1986. In a criterium, his sprint often lets him down if he is unable to break away, even against some Cat. 2 riders. On the other hand, he won the 2002 Ohio District Road Race rather easily in a 3-up sprint; he was simply the best sprinter among the climbers that the course had selected for. Additionally, positioning can compensate for lack of sprinting speed, but any discussion of tactics is beyond our purposes here.

Sprint (Level 7) workouts can be done at any time during the year (since ATP is the sole fuel source and lactic acid is not produced, so long as duration is kept under 15 seconds), require complete recovery in between repetitions (since the metabolic stress is limited, and the goal is to maximize the power generated), and should be scheduled early in the training week, prior to interval workouts. As with other intense workouts, try to tailor them to the race you are preparing for. Is the finish uphill or down? Does a tailwind or headwind prevail? (Be sure to note the wind during the race.) Can you identify a landmark which lies at the desired distance from the finish where you want start your sprint (especially important in a point-to-point race)? As Adam Myerson has pointed out at the Wattage Forum at Topica.com, someone with a high maximum wattage should typically go later, i.e., follow wheels, save their burst, and come off a wheel at the last moment, whereas a rider with a lower maximum but a good average wattage needs to go early and try to hold on to the finish.

There are several component parts to a sprint: the initial "jump," when the resistive load is highest (from the change in kinetic energy due to rapid acceleration, or so-called 'inertial' force); the wind-up, or middle portion, when acceleration continues, but at a reduced rate, and speed is brought up nearly to maximum; and the final stage, when cadence and speed are at their highest (each of these phases is analogous to the start/drive, transition, and maintenance phases of 100 and 200 meter sprints in track and field, respectively.) How you structure sprint workouts depends on what type of sprinter you are, and which aspect you are trying to improve. Hard jumps from a low speed (walking pace), in a high gear or on an uphill grade (not too steep) lasting under 10 seconds, are used to improve initial acceleration and maximum power, while 'undergear' efforts (or in a normal gear with a tailwind or downhill), of no more than 25 seconds, will improve pedaling technique (neuromuscular coordination) at high rpm for the final part. Another useful drill is to practice 'jumps' at high speed, coming out of another rider's slipstream, in the latter stages of a 25 second effort.

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Perhaps in no other aspect of quantifying exercise intensity will a power meter have greater impact than on pacing, during both interval training and time trials, especially in the initial stages of each; the delayed response of HR and PE, coupled with the anticipation of intense effort, make it all too easy to start out too hard. Fig. 7 depicts pacing profiles of the author's first two 30 minute time trial tests with a power meter, and the difference is dramatic. Using the average wattage display, ease into intervals and TTs, being especially careful in the first 5 minutes to stay no more than 5 W over the planned average, placing the greatest emphasis on the first minute, then gradually less each minute as PE comes up, and concern about going too hard subsides correspondingly. Don't worry about starting too easily – worry about being consistent in the final stages of the last interval.

As previously noted, first-time power meter users are almost invariably surprised at how "jumpy" the current power display is, with some even concluding it to be in error, and although some of the variability may be due to artifact, the energy demands of road cycling do indeed vary quickly and widely. Thus, a rolling average of 30 seconds is preferable to current wattage during interval sessions. Since the standard Power Tap model lacks this feature, the interval timer feature must be used, but keep in mind that it gives a cumulative average, so as the interval proceeds, this value becomes more and more 'weighted,' that is, based on an increasing number of samples, and is therefore progressively less reflective of changes. For instance, if you have averaged 300 W for 15 minutes, but in 1 minute that drops to 299 W, your average for the 16th minute was just 284 W.

Begin interval workouts with 10-15 minutes easy spinning at Levels 1 and 2, followed by 5-7 minutes in Level 3 and then a brief period to pedal lightly and drink a bit. The week's first interval session should be the shortest and most intense, and if efforts of varying duration/intensity are planned, should progress from the shorter, more intense intervals, to longer ones, which helps to keep intensity up throughout the workout (uphill efforts are performed ~5% higher than those of similar duration on flat terrain). At least 15 minutes of cool-down time at Level 2 should be allotted after each intense workout, usually at no more than P_{TT60}. For a well-modulated, structured set of intervals, there is little need to download workout data if the session's planned goals are met, only to record interval duration, average wattage, cadence, heart rate, and perhaps average speed.

Traditionally, recovery between the "on" portion (work phase) of each interval has been a function of heart rate, but this does little to indicate if you are ready to go again, and sometimes a complete recovery is not desired anyway. A better way of determining recovery is by muscle energetics. For both Level 4 and 5 intervals, all that really counts is what you do during the work phase; you are only trying to keep the intensity up, and not manipulating the work:recovery ratio to alter metabolism. No more than a brief mental break is really necessary for Level 4 intervals, and taking more the minimal amount of rest really serves only to prolong the workout. Use whatever is convenient, such as how long it takes to turn around on an out-and-back course and take a brief drink. With Level 5 efforts, given that the half-life for phosphocreatine resynthesis is about 20-30 seconds, muscle energetics should be completely recovered in 2.5 minutes (~5-6 half-lives). There are, of course, other factors that contribute to fatigue, and it may eventually accumulate, such that stretching recovery to 5 minutes will allow power levels to be maintained in later efforts, but using longer rest periods throughout the entire workout will not allow overall intensity to be raised significantly.

Level 6 sessions are more complex. If the purpose is to work on both musculoskeletal power and anaerobic metabolism simultaneously, or if you are in a peaking phase, then longer recovery periods may be useful, because they will allow you to maintain the highest overall power. What is long enough is a matter of feel, developed through experience, and will vary with the individual, as well as route characteristics (e.g., how long it takes to get back down and turned around during hill repeats.) On the other hand, if you are trying train anaerobic capacity alone, then incomplete recovery may be the way to go, so as to "stack up" the metabolic stress, but with *too* short a recovery, the average power may be too low, and it ends up being a quasi-aerobic effort. So, the test of whether recovery is sufficient is simple . . . if it is very hard, but still possible, to complete the last repetition at the planned intensity, then wattage was correct, and recovery was adequate. If average power falls significantly in the last effort, then either it was too high, or recovery was too short, or perhaps some of both. Lastly, if you can complete the workout too easily, then wattage was probably too low. Thus, pacing *throughout* the full workout (just as within a single effort) is essential, so for instance, if you feel strong in the first interval of a workout, stay at the planned wattage and save a little for later on, trying to finish strongly, rather than fade in the last repetition. An exception may be Level 6 intervals, when intended only to increase anaerobic capacity, which suggests they be done "all out," so that power is very high initially, then is allowed to decline during the interval.

STRUCTURE AND 'STOCHASTICITY'

"Racing is the best form of training," runs an old and oft-repeated maxim, and much has been made of the so-called "stochastic" (randomly variable) nature, not simply of road cycling (as contrasted with an indoor trainer or constant-load ergometer), but of road racing in particular, and criterium racing most outstandingly, which becomes apparent from analyzing power data collected during competition. Focusing excessively on this phenomenon, however, ignores what we already *do* know about the effect, if any, of variations in power, on both acute and chronic adaptations to exercise.

The latter point is key. For example, one possible conclusion that might be reached after carefully analyzing power data files is that the 'stochasticity' of racing is so important that it must be duplicated as closely as possible during training (e.g., by motorpacing), but we know already that conventional training works well as preparation for racing, especially road and stage racing, as opposed to track and criterium racing. That in itself suggests that perhaps variability is not nearly so important, and/or that there is something else going on.

In fact, both are true. First, consider what happens when you start lifting weights: you get stronger very quickly, before any significant hypertrophy can occur. That is evidence of the extent to which performance can be improved through changes in motor control, and how rapidly such adaptations can occur, so it makes sense that just a few weeks of "sharpening," (either specific training, training races, or races used as training) is enough to prepare for highly stochastic racing, even if you have just been plugging away, putting in steady-state miles for weeks on end beforehand. Conversely, though, stochastic training for months on end will not prepare you adequately, for the simple reason that such efforts entail using your muscles the way they "want" to be used, in other words, intermittently, relying on bursts of glycogenolysis for energy, even in Type I (aerobic) fibers.

What that means is that little of an overload condition has been created in terms of metabolism, because you keep giving your muscles a break, during which time they resynthesize some creatine phosphate, refresh O_2 stored locally within the myoglobin, etc. Logically, if you want to induce an increased capacity for aerobic energy production (i.e., an increase in mitochondria), you need to make the muscle fibers work *continuously* for a longer period of time than they are used to, or "want" to, thus forcing them to adapt. This is especially true of the fast-twitch fibers that have a lower inherent aerobic capacity to begin with.

As affects training, this indicates much time spent right around lactate threshold, since that is the point at which fast-twitch fibers are brought into play, and many long, steady miles which fatigue the most aerobic, most easily recruited muscle fibers, requiring use of those further "up the spectrum;" and perhaps using manipulations that further enhance fast-twitch fiber recruitment, such as extended low-cadence/high-force ("overgear") intervals, or the classic approach of going hard at the end of a long (3½+ hour) Level 2 endurance ride. What it *doesn't* mean is a lot of short intervals, motorpacing, or racing, since, while they can be highly effective at increasing muscle power and even VO_{2max}, each is likely to be less effective at increasing the respiratory capacity of the recruited fibers, simply because the "energy crisis" that is the signal to enhance mitochondrial formation is just not sustained long enough, and indeed, this is borne out by several studies in the scientific literature.

Thus, despite the great importance of specificity, racing is not **exclusively** the best training. The 'race twice a week and everything else easy' rule followed by many riders can actually result in a loss of aerobic fitness, and substituting specifically-structured Level 4/5 interval workouts for the regular mid-week training criterium is often better preparation for the upcoming weekend race.

HI-INTENSITY CONFUSION: THE MISUSE OF HEART RATE

It is indeed unfortunate that HRMs preceded power meters to market, since heart rate seems to have become deeply entrenched in the popular mind as the true measure of how hard the body is working, indicative of an often undefined, near-mystical "whole body stress." In fact, metabolic intensity (or physiological strain if you prefer), for a given power output is best assessed, first, by the work load itself, then by perceived exertion, which reflects more physiological responses than HR, and does so more reliably. HR tracks well enough with power at lower intensities, where it provides apparently more "stable" feedback than power, due to the cardiovascular system's slow response to the rapid changes in intensity so characteristic of road cycling (the half-life for an increase in heart rate following a step-change in power is 20-25 seconds, and the effect is accentuated slightly by the smoothing algorithms programmed in to the HRM), so it can be useful for relatively steady-state Level 1/2 training, but as wattage increases, say, beyond ~75% of P_{TT60}, the correlation between HR and power becomes weaker, and HR becomes less and less reliable as an indicator of physiological strain. Factors that are documented to elevate HR include decreased barometric pressure at higher altitudes, environmental heat, dehydration, cardiovascular drift, lack of sleep, time of day, medication, recent illness/infection, diet (e.g., caffeine), variability of terrain, psychogenic factors (e.g., nervousness), and possibly even position on the bicycle, such as when time trialing. On the other hand, it is normal for HR to be depressed by recent heavy training, and by accumulated fatigue/lack of recovery (overreaching). Finally, mere day-to-day variability in HR can be up to 4%, whereas power is normally reproducible to ±2%. Thus, training by HR, while monitoring power, robs any power-measuring system of its most important benefit, namely, to guide training by precisely quantifying and administering the exercise load. The choice of title here is deliberate: we should not simply train *with* power, as though it were a mere adjunct metric, one supplemental gauge of intensity among several others, used to evaluate workouts in relation to HR; rather, it is advocated to train *by* power, i.e., power is the *arbiter supreme* of training prescription, execution, and interpretation.

One prominent coach even goes so far as to advocate using power information purely in a postscriptive fashion:

> *"Watching your wattage during the course of a ride is not very useful. Wattage fluctuates quickly and often; heart rate is a much better gauge of workload during a workout. Power becomes useful when you are sitting in your living room after the workout. I recommend purchasing a power meter that can be downloaded to your home computer. Downloadable power meters help you see how your power output changes with your heart rate, speed, and cadence during the course of a single ride, a few weeks, or several months."*

On he blathers about a world-class triathlete of his who made "astronomical" gains of over 9% in his 20-minute repeats at a given HR. In fact, a 10% increase from off-season lows is not extraordinary for elite riders.

This approach is even worse than a 'train by HR, monitor power' method, since it defeats the purpose of an on-bike power-measuring system entirely, effectively relegating it to a testing device that does nothing to guide training. You might as well just get tested periodically in a lab, and save the cost of the power measuring system and PC, since it will do nothing more than give a nice feeling that your power is better for a given HR, and even that will be with questionable precision, due to the variability of HR at a given power output (indeed, this is likely why the "astronomical" 9% gains were observed.) It is true that power on the road is "stochastic," and because of this, it is more useful to view a cumulative or 30 second rolling average during workouts, rather than the current power display (as is apparently referred to above), but whichever is used, both are more precise and more useful than HR as measures of the stress load being imposed.

Certainly, it is important to have feedback from the body to gauge its response to a given work load, but the point that die-hard HR advocates seem to miss is that our brains are already equipped to integrate information from a variety of sources, not just that provided by instruments which measure power and heart rate. These other sensors have been developed by eons of evolution, and do a pretty good job all by themselves, especially if frequently "calibrated" by reference to an external standard (i.e., a power meter). In fact, that was the whole premise behind Borg's original 6-20 point rating scale for PE: the values are simply the HR expected for the average young untrained person exercising at that intensity, minus the trailing zero. Although useful, this is not quite the best description of how physiology works, since it does not track well with non-linear responses (e.g., blood lactate, a marker of muscle metabolic stress), only linear ones (heart rate). That is why Borg eventually issued a revised 0-10 point scale, and why it was used previously, instead of the original one.

Thus, ignoring HR altogether will likely help develop and refine the sense of PE in relation to power. What matters, though, is the practical difference that it makes in training, and how you respond to "how it feels" for any wattage should be determined mainly from a functional standpoint, that is, whether you can complete the workout as planned (a careful, gradually progressive, periodized program is assumed here). If PE is higher than normal or expected for a given wattage, some say pack it in right there, but the recommendation here is to try to complete the workout, if possible. Whether you "bag it," based on how you feel, even if able to finish the workout, depends on any number of things: how early it is in the workout, your level of motivation, whether you will be able to rest adequately following or have a particularly hard day ahead, where you are in your present training cycle/year, what you have planned for the weekend, etc. Even cutting back slightly (2-4%) on the wattage and making it through the planned duration, if not at the planned intensity, is generally better than just going home, since each workout is (or should be) built on the gains of the last, and you don't get better by not training. Knowing when to quit early is something of an art, but the decision is informed little, if at all, by HR, which will likely just provide comforting confirmation or else confound what power and PE levels have already told you. The proof of whether it was wise to continue or not will come in subsequent workouts.

For instance, in a well-paced, 2×20 minute interval workout at perhaps 100% P_{TT60}, the first repetition is usually strenuous, but not a major challenge to complete. Just as HR drifts upward for a given power output as duration wears on, so too does PE increase, and it usually starts 'getting to me' with about 4-5 minutes to go in the second rep, as I wonder a bit if I can make it to the end, think about how good it will feel to be finished, start counting down the time left and telling myself "2 minutes . . . get through the next minute and the last one will take care of itself," etc. I especially watch average wattage closely as I try not to fade; mentally, it's important to finish strong.

On the other hand, if I do the best I can, but lose a few Watts, as happens occasionally, it likely means I was just a tad below par, since I train in a fairly deliberate, measured fashion, but if I fade in the first rep, then either the wattage was too high, or else there is something wrong physically, especially if this is a workout I have been able to complete in the past. In addition to the foregoing perceived exertion scale, a modified gradation, referenced to responses in the latter stages of interval workouts, may be helpful in evaluating workout duration and intensity:

1 – Workout easily completed. Chosen power or duration were either too low (easy) or too short, respectively, such that average wattage rose (or could have been raised) substantially throughout the interval session, or else wattage/duration were intentionally set low due to lack of condition, recent layoff, illness, etc.

2 – Workout finished with considerable difficulty towards end of last repetition; completion somewhat, but not seriously in doubt. Power/duration about right, as wattage remained steady throughout, and could not have been sustained much or at all beyond where last rep ended.

5 – Extreme difficulty and serious doubts about ability to finish encountered during middle and latter stages of session. Power/duration too high/long, or else recovery inadequate, since wattage either faded during last interval, or workout not was quite completed.

8 – Last interval not completed; workout terminated well short of goal due to illness or accumulated fatigue, or wattage duration not being sustainable (unrealistically high/long).

10 – Workout terminated during early or middle part of session.

Again, the final test of how accurately training has been structured is whether workouts can be consistently completed throughout a gradually progressive, periodized plan. Occasionally failing to finish a workout is not a disaster, especially if due to wattage and duration being chosen too high; after all, in order to find your limits, it is sometimes necessary to exceed them.

So then, to gauge and guide training intensity, the choice here is power, with advice and consent from perceived effort, then heart rate; the last has some uses, but does not merit being elevated to the cult status it seems to have achieved. Old habits die hard, however, and onward it marches still, much like a beast that goes on fighting after having its head cut off, to the extent that its more persistent advocates seem obsessed with it, like true believers in a cult, clinging to a security blanket and projecting meaning on to it beyond anything remotely reasonable. Reasons offered usually run something like "Power is important, but you need heart rate too," (i.e., the "data is good, and more data is better" argument), and "Heart rate tells you how hot your aerobic engine is running for a given power output; training by power alone is like the rev-head who always runs his engine at 800 horsepower and pays no attention to rpm." If HR is substantially different from one workout to another, it is possible that total energy expenditure might be slightly different, even though the amount of useful work done is exactly the same, but it is unlikely that the difference would ever be more than perhaps 5%, and there may not any difference at all (e.g., lack of sleep will elevate submaximal heart rate, but has little if any effect on cycling efficiency.) Even HR did reliably reflect changes in efficiency, it would still be of little use, since its precision in doing so is undetermined.

MANAGING FATIGUE

Fatigue and overreaching are often confused with overtraining, the distinction being that the latter is a *long-term* decrement in performance which requires weeks or even months to recover from, whereas the former is a simply a part of the workout/recovery cycle, as previously discussed. Irritability, disrupted sleep, lack of enthusiasm, and significant changes in HR (whether waking/resting or at a given intensity) are all frequently identified as symptoms of overtraining, but it is *normal* for one or several of these to appear most every week in the course of a season after races and interval sessions, particularly in the next-to-last week of each cycle; it is when such signs persist, accompanied by a protracted downturn in the ability to perform, that they are of concern, and again, power is the final arbiter of diminishing performance and whether added rest is needed.

Overtraining is most effectively prevented by avoiding large, sudden changes in training volume, as well as excessive competition, both of which go without saying in following a periodized, progressive plan. Non-training causes of increased fatigue can include travel, inadequate sleep/rest, and emotional stresses.

Fundamentally, then, minimizing fatigue is a matter of planning and thinking ahead, attention to detail, time management, and decision-making:

- Hydrate and feed before, during, and after all workouts; "Drink before you're thirsty, and eat before you're hungry" is not a cliché, but a sound practice that accurately reflects the body's delayed hormonal stimulus to cravings. ~0.6-0.9 grams carbohydrate (CHO) per kilogram of lean body mass (LBM) should be ingested in a 6-8% solution for every hour of intense exercise, or about 24 oz (710 ml) for a 71 kg rider. On long rides when only water is available, powdered Gatorade carries well in a 2 oz bottle, such as a travel size bottle of shampoo (see Appendix F for a CHO-beverage and other recipes).

  Proof may be lacking that solid foods prolong endurance vs. CHO beverages alone, however, if solid foods are desired, a useful practice on longer (4+ hour) rides/races may be to consume low-glycemic foods early in the ride, perhaps even a sandwich with some thinly sliced meat, then progress to higher-glycemic food sources later on, as well as post-exercise. For an explanation of the Glycemic Index (GI), Glycemic Load (GL), and a listing of these for numerous foods, see http://www.mendosa.com/gi.htm.

  A crucial time is immediately after intense or long workouts and races. No more than 15 minutes post-exercise, ingest ~1-1.5 g of CHO per kg lean body mass plus 0.25-0.4 g/kg protein, perhaps followed by massage, shower (if on the road, take a washcloth and cold water for rinsing), and a nap if possible, then a meal with CHO-protein in the same amount the next hour, with vitamin B, C, and E supplements afterward. Pamper yourself after and in between hard/long workouts!

- Interval workouts should be at least 36 hours apart, and 48 hours before competition, with an intervening 'recuperation ride' of 50-70 minutes, at an easy average wattage, just enough to stimulate recovery – no more than 65% P_{TT60}, and during periods of high heat and humidity, train in the early morning if possible. As a rule of thumb, you should feel fresh and rested two or three times a week, preferably before each intense workout or race. Intensity is usually reduced during high-volume weeks, such as week 3 of a 4 week cycle, but increased in the final (taper) week of each cycle. **Always** include 1-3 days of complete rest per week (no ride).

  Just as with interval workouts, where one rider's specific training objectives rarely match another's, so too do easy days lend themselves to riding alone unless a cooperative partner can be found, but all too often, competitive instincts take over, and a hammerfest ensues. Put another way, it's common to train as if it's a race – and then race as if it's training. Have the discipline to go easy enough on your easy days, so that you can go hard enough on your intense days, and realize the maximum benefit (adaptation) from them.

- Depending on the training volume, total daily food intake should be 16-28 kcal/lb (35-60 kcal/kg) in a CHO-fat-protein *caloric* ratio of 65%-20%-15%; since there are 4 kcal per gram of CHO and protein, and 9 kcal/g of fat, this becomes 5.7-9.8 g/kg CHO, 0.8-1.4 g/kg fat, and 1.3-2.3 g/kg protein, or 216-432 g CHO, 30-60 g fat, and 50-100 g protein for an LBM of 60 kg. This caloric balance may be altered slightly (+5%) in favor of CHO during the 2-3 days prior to competition.

The value provided by the power meter for external work performed (in kilojoules) can be used to approximate internal energy consumption in kcal, however, gross mechanical efficiency (ME) must be determined from a lab-administered VO_{2max} test; where ME = 19%, 1.26 kcal are consumed from 1 kJ of work; for 20%, 1.20 kcal are burned by 1 kJ; at 21%, 1.14 kcal; 22% – 1.09 kcal; 23% – 1.04 kcal. This result can be used to adjust diet according to the caloric requirements of a workout, in addition to basal energy expenditure (BEE), in kcal/day, as obtained from the Harris-Benedict Equation:

$BEE_{♂} = 66.473 + 13.752m + 5.003h - 6.755a$; $BEE_{♀} = 665.096 + 9.563m + 1.85h - 6.755a$

where m = body mass in kg, h = height in cm, and a = age in yr. Alternatively for men, daily calories expended = 960 kcal/s, where body surface area s in $m^2 = 0.007184m^{0.425} \times h^{0.725}$ (the Dubois Equation).

If a weight loss program is attempted, reductions should be no more than 4% each month, but even if protein intake is maintained (or even increased), it is still likely that you will lose at least some lean body mass, which causes a decline in absolute VO_{2max}. Thus, it is overly simplistic to believe that performance can be easily enhanced by losing a few pounds. Without question, losing what is truly excess weight very gradually may improve performance, particularly on extended climbs, but you must titrate things very carefully. Energy balance is a very important determinant of nitrogen balance, and losing only fat is a very difficult thing to do.

INDOOR TRAINING

Most everyone chooses to work out indoors only as a dreaded last resort when weather or schedule preclude an outdoor ride. Training indoors, however, produces some subtle differences and benefits, and may even be preferable alternative (or supplement) to outdoor training.

The most basic (and obvious) difference lies in the nature of the resistive load imposed. Although most trainers have a flywheel, few are heavy enough to accurately simulate the kinetic energy changes of road cycling (or most any form of "free range" activity), nor do most load simulators replicate the almost constant changes in grade and terrain experienced outdoors (a flat road and no wind are practically non-existent). Each of these conditions contribute to the 'stochastic' nature of power output outdoors, even during relatively steady-state efforts. Indoor trainers, on the other hand, even when not set in the "ergo" mode (constant workload), impose a much more even load for a given speed, as becomes quickly apparent if a power meter is used to verify the load.

(Some trainers have an ergometer mode, which maintain a constant workload; that is, when cadence drops, resistive torque increases, and vice-versa, such that the product of the two stays constant. This feature allows the rider to "set and forget" a specific power level, and ensures an unvarying intensity is maintained. What can make the ergo more difficult for some is that load is relentless. You either ride at the set load or you stop; you can't ease off for more than a moment or so. Contrary to occasional claims, neither the Computrainer, nor any type of "erg," keeps power constant *within* a pedal cycle, rather, it keeps power constant *across* a number of pedal cycles, which is what people are not used to, since, when riding outdoors, we get to go hard for a bit, using our fast twitch motor units for a few seconds, go easy, go hard again, etc. This is precisely how our neuromuscular systems are designed to function, i.e., episodically, and why training this way excess may not create the best overload.)

Another difference is the lack of a cooling headwind in the neighborhood of 20-30 mph, causing some to blame any deficit in performance vs. outdoors entirely on thermoregulatory issues, but this is overly simplistic. Depending on the individual, the trainer they use, how adapted they are to it, the terrain/environment they have available for outdoor training, etc., power production and perceived exertion may be either higher or lower indoors. So then, two steps toward raising one's indoor power output are

1. Use a trainer that has a lot of inertia/stores a lot of kinetic energy, i.e., with an adequately massive flywheel, to better simulate outdoor cycling. The Velodyne, among a few others, meets this criteria, and as a result, power output on it is usually as high as, if not slightly higher than, what can be done outdoors (especially if variations in power are accounted for with the normalization algorithm previously presented). On something with a light flywheel, however, like a Minoura mag trainer, it can be disconcertingly difficult to generate the same power indoors as outdoors.

2. Keep cool enough. You should make every attempt possible to minimize thermal stress when training indoors, so that you can maximize the absolute training load, unless you are specifically attempting to prepare for exercise in the heat (which is analogous to the effects of altitude: there is no advantage, and probably significant disadvantage, to training at altitude, and thus compromising absolute intensity, unless preparing specifically for competition at altitude.) This means using a powerful fan, keeping the room cool (at least under 70° F, and ideally below 65°), and staying hydrated. Look for high-velocity "air circulator" models that move at least 2000 cfm, such as those from Holmes, Honeywell, Lakewood, Patton, and Vornado (http://www3.mailordercentral.com/vornado/). Direct the air flow towards your head and upper body, but position the fan to the side, so it does not blow directly in to your eyes.

How you structure indoor workouts will depend on your particular characteristics and abilities, the sort of racing you do, what your outdoor rides are like, and so forth, but it makes sense to balance indoor training with outdoor workouts that are as 'stochastic' as possible. Alternatively, one could attempt to deliberately structure indoor workouts to stress muscle power more, by doing short, high power intervals with compete recovery, or even shorter high power intervals with incomplete recovery (microintervals), the idea being in both cases to induce more of a neuromuscular than a metabolic stress, and having recognized the limitation to monotonic indoor training, some like to throw in frequent out-of-the-saddle "surges" to up the intensity. To best replicate outdoor cycling, however, the variations in power wouldn't be completely random, since you would want them to occur within a certain frequency range. That is, varying the power on even a minute-by-minute basis doesn't really mimic what happens outdoors . . . the changes would have to be more often than that. On the other hand, a sudden doubling of the power requirement in middle of a pedal stroke wouldn't be ideal either, since, unlike cycling outdoors, you don't have as much stored kinetic energy to help carry you through the "dead spot."

To summarize, training outdoors is more specific, whereas training indoors is more controllable. Optimal results therefore may be obtained using some combination of the two approaches.

* * * * * * *

In contrast to outdoors, the relatively constant workload of indoor training makes heart rate a more robust indicator of exercise intensity, so long as cooling is adequate. In particular, being a cardiovascular variable, HR tracks fairly well with cardiovascular fitness, not metabolic fitness, i.e., with VO_{2max} rather than LT (the classic Astrand-Rhyming method for predicting VO_{2max} is based on this very fact). So lower cardiovascular fitness might be reflected in a higher HR at a given submaximal power output, indicating lower VO_{2max}, even with plenty of LT intervals and equivalent sustainable power output.

Such changes are not specific to LT power, but essentially occur across all submaximal power outputs. Interpreting any power/HR value, however, is complicated by the fact that this ratio increases with power output, independent of changes in fitness. One other noteworthy point: the magnitude of the change in submaximal HR is generally greater than the change in VO_{2max}, and it may change even if VO_{2max} does not.

For instance, the author's heart rate during pre-season bi-weekly 2 × 20 minute LT intervals was averaging 149 beats/minute this year, vs. 143 last year, this despite the fact that power is the same as last year, and I don't even really feel like I've started to push myself all that hard just yet. My approach has been basically the same: 3 months of 3 weight training days/week, + 3-4 days per week of steady riding through end of December, after which I dropped the weights and started riding 6-7 days/week with 2 × 20 minute intervals twice per week. What is different is that I was more fit at the beginning of the 3 month "maintenance" phase in Fall 2001 than in Fall 2002 (the result of racing a full calendar in '01, vs. viewing '02 as a write-off), and 2) with different early season goals, I was doing more specific training, namely VO_{2max} type intervals (6 × 5 minutes on/2.5 minutes off) once per week, during my build-up in early 2002, something that I am not doing this year. In other words, and exactly as predicted by the known physiology and training specificity, my HR response seemed to be tracking my (relative lack of) cardiovascular fitness (lower VO_{2max}), and not my metabolic fitness (LT power).

Graphs

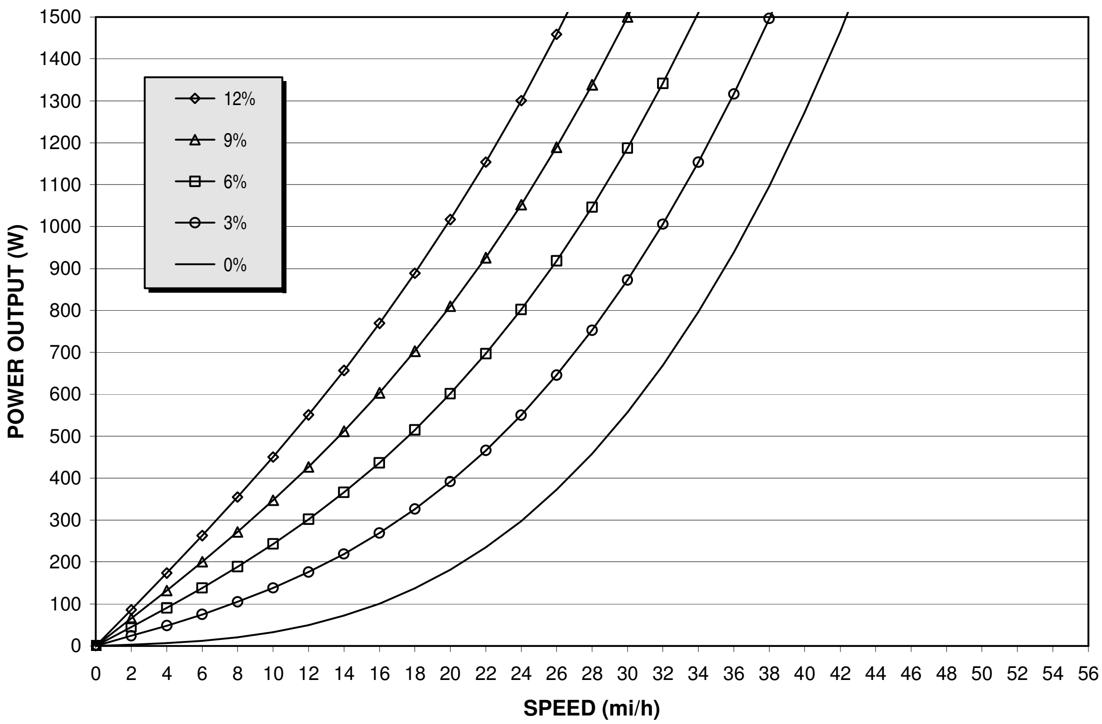

Fig. 1. Power requirements as a function of speed for an 80 kg bicycle/rider over selected grades 0-12%.

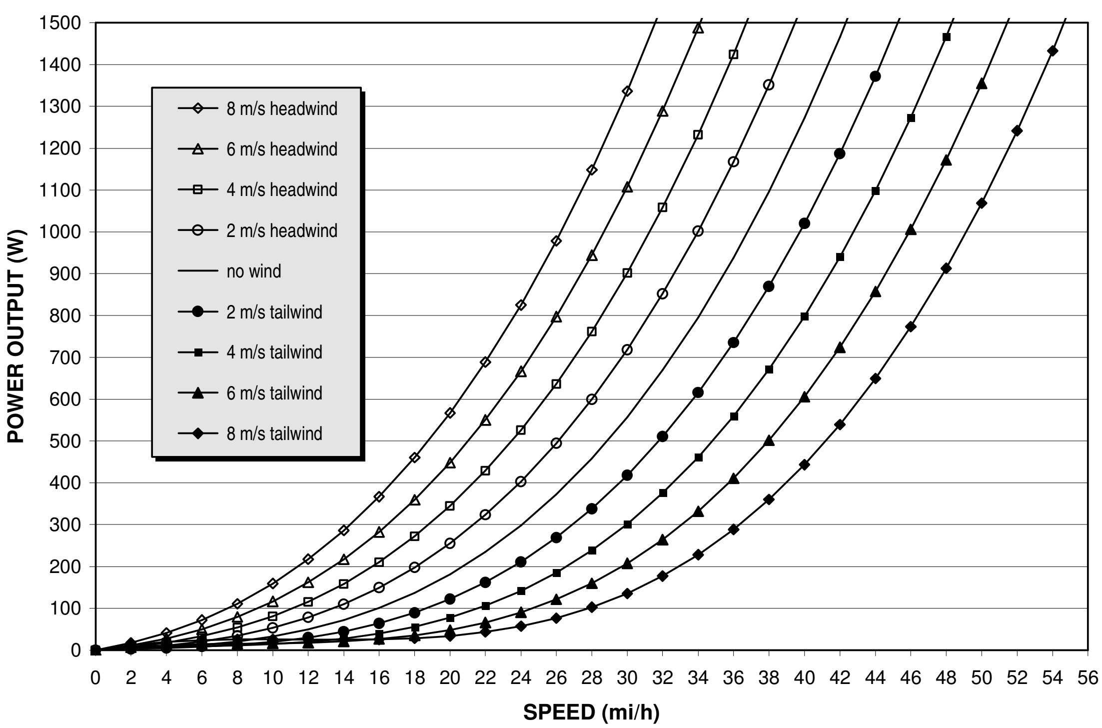

Fig. 2. Effect of wind on power as a function of speed for an 80 kg bicycle/rider over flat terrain.

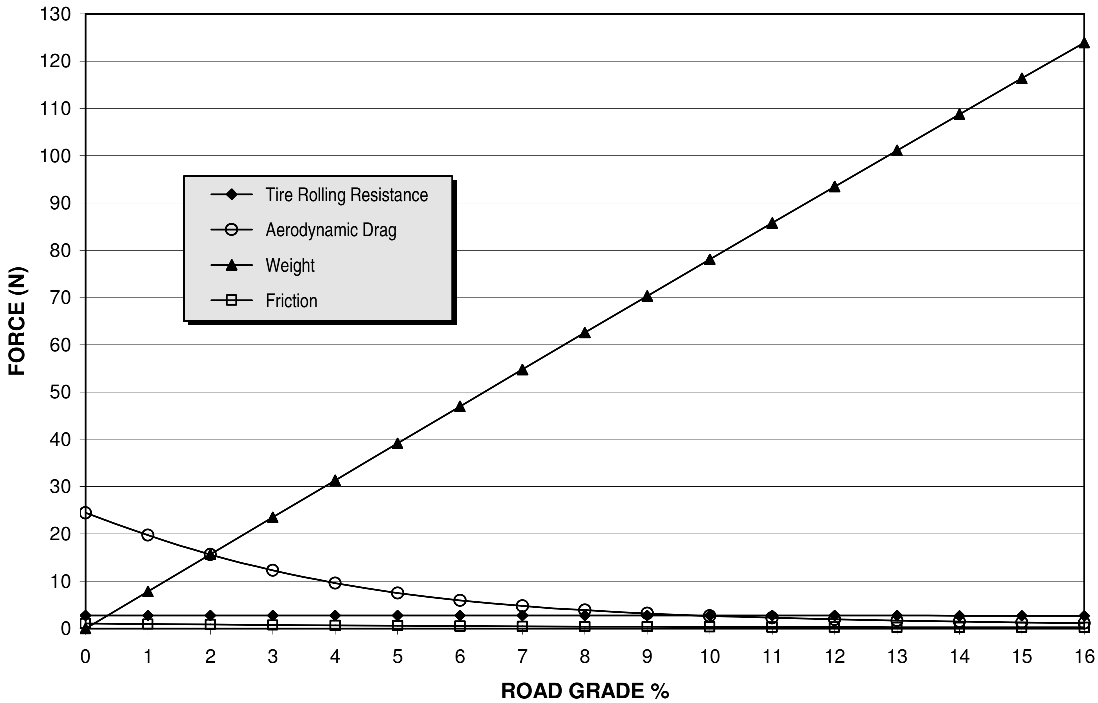

Fig. 3. Magnitude of resistive forces on an 80 kg bicycle/rider at 300 W over varied terrain.

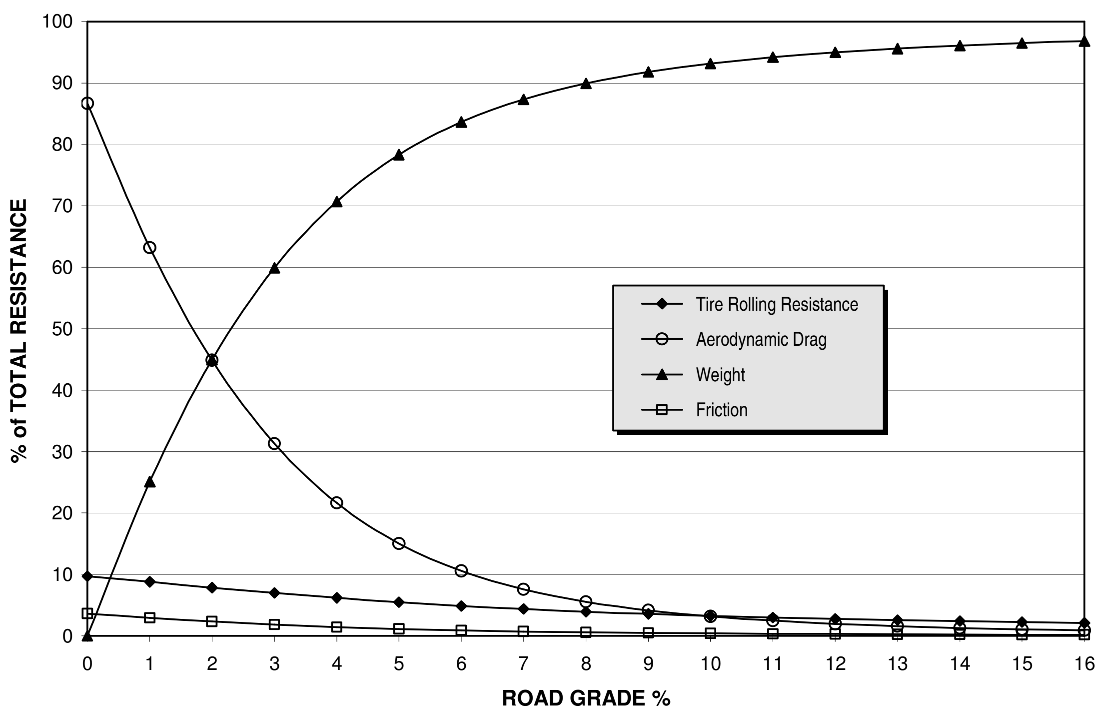

Fig. 4. Relative distribution of resistive forces on an 80 kg bicycle/rider at 300 W over varied terrain.

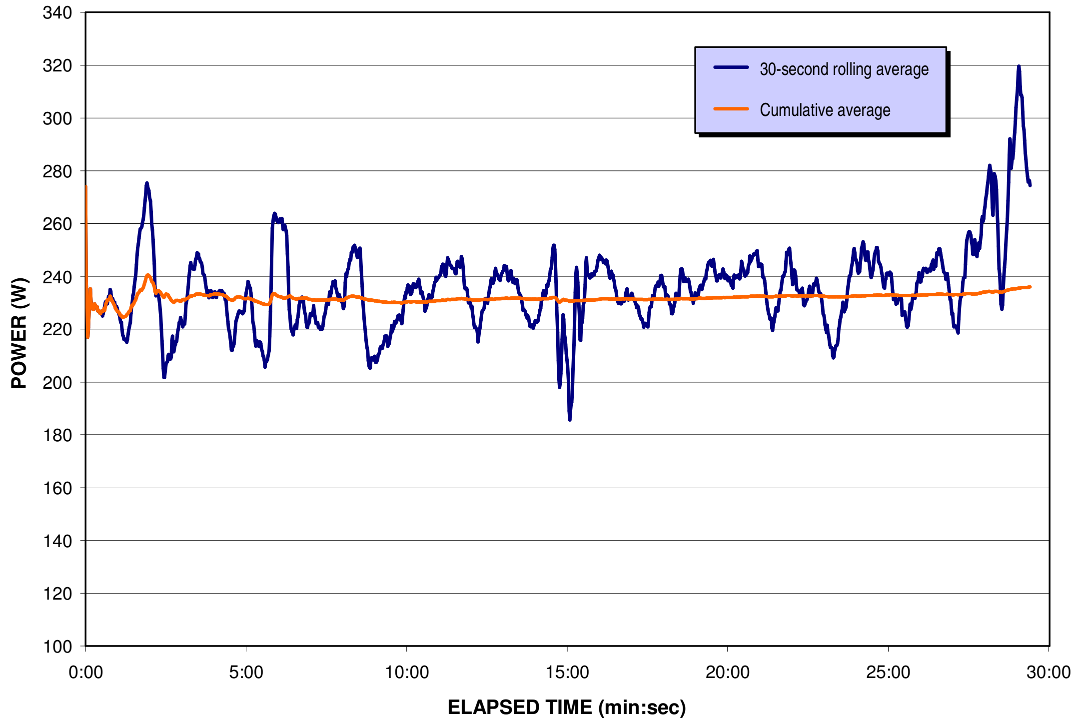

Fig. 5. Cumulative and rolling 30-second average power in a flat-terrain time trial (27 June 2003) .

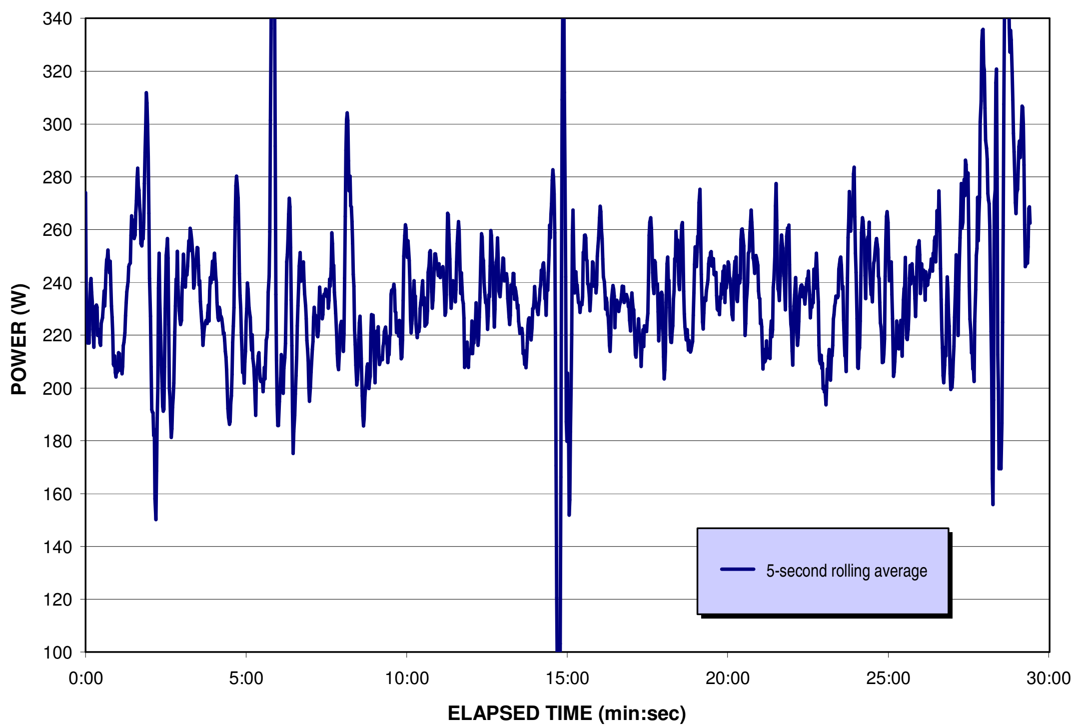

Fig. 6. Rolling 5-second average power in a flat-terrain time trial (27 June 2003).

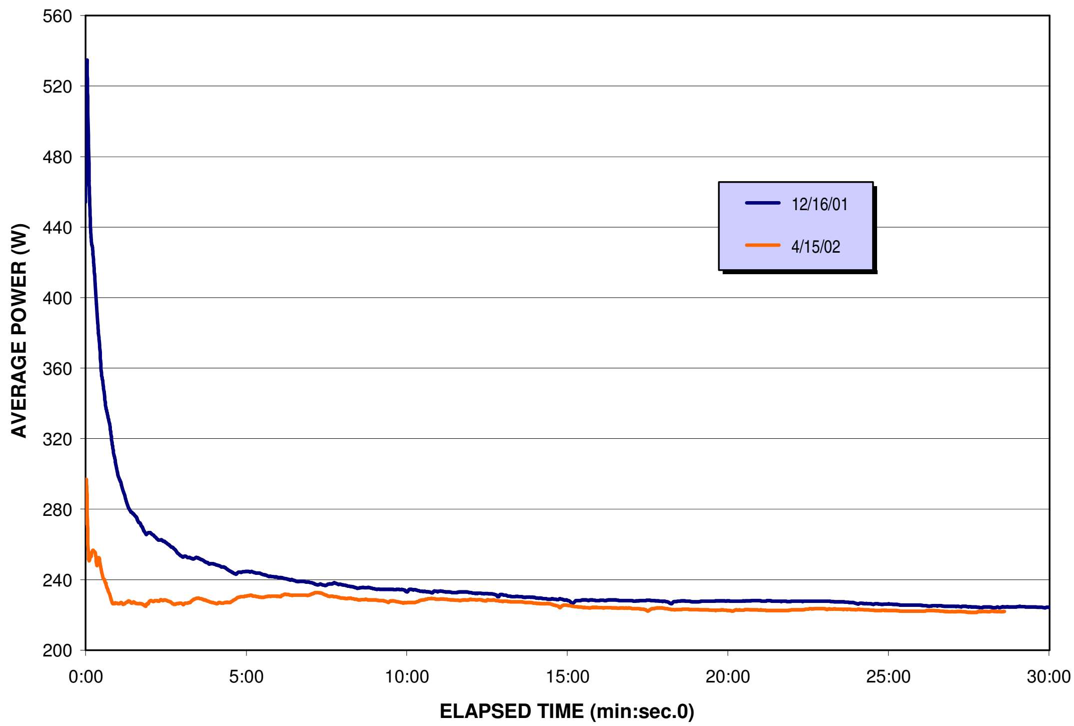

Fig. 7. Cumulative average power in two flat-terrain time trials.

By Andrew Coggan, Ph.D.

THE ISSUE

It is simply human nature to wonder how one compares with others for any measurement, and cycling power output is certainly no exception to this rule. Consequently, there have been numerous calls for, and some attempts at, generating guidelines or benchmarks for power output based on rider category (i.e., Cat. 1, 2, etc.) Aside from satisfying people's natural curiosity, though, such category-based values would seem to have limited practical use – after all, the best measure of a rider's competitive ability relative to that of others is their actual race performance, not their power output. If, however, valid standards were available for power across different durations that represented different physiological characteristics or abilities, then it would be possible to identify a particular individual's relative strengths and weaknesses based on their "power profile." In such an analysis, the primary comparison would therefore be the rider against themselves, and not (directly) against others. Such information could be then used to help plan an appropriate training program, evaluate the effectiveness thereof, and to possibly identify events where an individual might be expected to achieve the greatest success. The goal of this effort was therefore to develop rationale guidelines that could be used for this purpose.

THE APPROACH

In theory, tables of standards for power output for different durations could be generated by simply collecting data on a large number of cyclists of widely varying ability, however, very few (if any) coaches or other individuals are likely to have access to a sufficiently large database for this approach to be very accurate. As an alternative, estimates of power output for riders of differing abilities could be derived from actual performance, e.g., in time trials, but this approach requires making somewhat tenuous assumptions regarding body mass, C_DA, etc., and is particularly complex when applied to shorter duration, non-steady-state events (e.g., the kilometer). The present tables were therefore instead generated using a third approach, which was to "anchor" the upper and lower ends of each range based on the known performance abilities of world champion athletes and untrained persons, respectively. The advantage of this approach is that it enhances the validity of comparisons across event durations, e.g., a "world class" power output should be equivalent regardless of whether the duration over which it is measured is 5 seconds or 20 minutes. The resultant values for intermediate performances were then cross-checked against available data to assure that this approach resulted in valid guidelines.

Since records are not kept for times, only distances, except for the fabled hour, any estimate of what the world "record" holder could maintain must be just that, an estimate. There is also the issue of obtaining accurate data with respect to both power and weight (more to follow). Logically, however, both 20 minute and 60 minute power will be closely related to power at LT, so for estimating the former, I relied on Chris Boardman's 56.6 km World Hour Record in September 1996. Specifically, based on careful measurement of his power-speed relationship in training, Boardman's coach Peter Keen estimated his power to have been 442 W. The question is, how much did Boardman weigh? Keen himself has stated that Boardman must have maintained a VO_2 of 5.6 liters/minute, or 81 milliliters/minute/kilogram during the attempt, which means he must have weighed 69 kg. That makes his power 442 W/69.1 kg = 6.40 W/kg, however, I should mention that Ric Stern has been told by Keen that Boardman was closer to 67 kg at the time of the record, thus contradicting himself.

So what could Boardman have maintained for 20 minutes? Well, using a C_DA value consistent with his 56.6 km/h, 442 W effort, and accounting for stored kinetic energy carried across the finish line, it is estimated that Boardman averaged 543 W (7.86 W/kg) during his 4 minute 11 second world record pursuit. (Note that the steady-state power estimated this way – i.e., 501 W – agrees almost exactly with the power just eliciting 100% of his 6.22 L/min VO_{2max} at his stated efficiency of 22.6%. This is as expected, given that anaerobic capacity is fully utilized during roughly the first 2 minutes of a pursuit, meaning that it is entirely "pay as you go" the rest of the way.) If these values of 6.40 W/kg for 3600 seconds and 7.86 W/kg for 251 seconds are then plugged into a critical power analysis, it is possible to estimate that Boardman could have maintained 7.60 W/kg for 5 minutes, and 6.62 W/kg for 20 minutes. (The same critical power analysis also demonstrates what an unusual talent Boardman was, combining an extremely high aerobic power with a very high anaerobic capacity.)

Based on both wind-tunnel measurements of his aerodynamic drag and lab/trackside measurements of blood lactate, Spanish sports scientists estimate that Miguel Indurain averaged 510 W during his hour record. His stated body mass was 81 kg, which or 6.3 W/kg. I bring this up not to directly compare him to Boardman, but simply to point out the consistency of the power estimates from the two best-documented hour records.

Since performance in flat-terrain time-trialing is best predicted by W/m^2 of effective frontal area (C_DA), and since body mass has minimal effect in such a context, it might seem that absolute power in Watts alone might be a better predictor in such situations, but in fact, since C_DA correlates with body mass, W/kg should still be a better predictor across a wide range of sizes and abilities, even though mass per se has little effect on the flat-terrain. Further, few people know their C_DA, so your choice is either W or W/kg, possibly with the latter scaled allometrically, e.g., W/kg$^{0.67}$.

The argument for W/kg, or better still, W/kg$^{0.67}$, is even stronger when it comes to power profiling because the idea here is to be able to evaluate someone's relative performance ability over a broad time range (i.e., 5 seconds to 20 minutes) which reflects various physiological characteristics. This requires that the normative scales be equivalent, e.g., the 75th percentile on one is equal to 75th percentile on another. This would not be possible if you used only Watts for this purpose, since having additional lean body mass contributes more to short-term power output (when O_2 delivery is not limiting) than to long-term power output. As it stands, road riders already often come off looking as if they lack neuromuscular power, which in fact they do, at least when compared to bigger, more powerful athletes, who typically compete on the track. Most important of all is to remember that the power profiling tables are intended to be used to determine relative strengths/weaknesses, not to predict performance or racing category.

CHOICE OF TARGET DURATIONS

Index efforts of 5 seconds, 1 minute, 5 minutes, and 20 minutes were chosen as those best reflecting neuromuscular power, anaerobic capacity, maximal oxygen uptake (VO_{2max}), and lactate threshold (LT), respectively. This should NOT be taken to imply that, for instance, a 1 minute all-out effort is completely anaerobic (in fact, roughly 40-45% of the energy during such exercise is derived aerobically) or fully utilizes anaerobic capacity (which generally requires 1.5-2.5 minutes to deplete), or that a 5 minute all-out effort entails exercising at precisely 100% of VO_{2max} (most athletes can sustain a power that would elicit 105-110% of their VO_{2max} for this duration). Rather, power output over these target durations would simply be expected to correlate well with more direct measurements of these different physiological abilities. Secondarily, the index efforts were chosen in an attempt to increase reproducibility (e.g., use of 5 vs. 1 second power as an indicator of neuromuscular power), and for convenience (e.g., selection of 20 minute power as an indicator of power at LT).

APPLICATION AND INTERPRETATION

To use the power profiling tables, simply locate and highlight (or circle, if using a printed copy) the peak or maximum power that a rider can generate for 5 seconds, 1 minute, 5 minutes, and 20 minutes, and then connect the values horizontally to derive the rider's "profile." If his or her performance falls between tabled values, which will often be the case, assign them to the nearest ranking. It is critical that the values used in this analysis be truly reflective of the athlete's very best effort over that duration – otherwise, the resultant profile may be distorted, leading to inappropriate conclusions and actions. While each individual is likely to have a somewhat unique pattern that may change slightly over time, some typical patterns and general guidelines for interpretation are given below. In considering the following, however, keep in mind that performance at each duration is being evaluated in comparison to the world best – thus, in comparison to match sprinters, road cyclists will tend to appear relatively weak in 5 seconds and, to a somewhat lesser extent, 1 minute power, whereas non-endurance track racers will likely have relatively low 5 and 20 minute power relative to their abilities at the shorter durations. (The possibility of developing road and track-specific tables was considered but rejected, in part because many riders compete in both disciplines.) Also keep in mind that, based on physiological considerations, an inverse relationship might be expected between the anaerobic (i.e., 5 second and 1 minute) and aerobic (5 and 20 minute) efforts, whereas a positive association might be expected between each pair. (The scientific literature is in fact split on whether there actually is an inverse relationship between short-term and long-term power, however, there is clearly a positive association within each category.)

LEVEL	MEN				WOMEN			
	5 s	1 min	5 min	20 min	5 s	1 min	5 min	20 min
World Record Holder/ World Champion	23.50	11.50	7.60	6.62	19.98	9.78	6.46	5.63
	23.23	11.38	7.49	6.52	19.74	9.67	6.37	5.55
	22.96	11.26	7.38	6.43	19.51	9.57	6.28	5.46
World Class	22.68	11.14	7.28	6.33	19.28	9.47	6.18	5.38
	22.41	11.02	7.17	6.24	19.05	9.37	6.09	5.30
	22.14	10.90	7.06	6.14	18.82	9.27	6.00	5.22
	21.87	10.78	6.95	6.04	18.59	9.16	5.91	5.14
	21.60	10.66	6.84	5.95	18.36	9.06	5.82	5.06
UCI Div. I/II Pro	21.32	10.54	6.74	5.85	18.13	8.96	5.73	4.97
	21.05	10.42	6.63	5.76	17.89	8.86	5.63	4.89
	20.78	10.30	6.52	5.66	17.66	8.76	5.54	4.81
	20.51	10.18	6.41	5.56	17.43	8.65	5.45	4.73
	20.24	10.06	6.30	5.47	17.20	8.55	5.36	4.65
UCI Div. III pro	19.96	9.94	6.20	5.37	16.97	8.45	5.27	4.57
	19.69	9.82	6.09	5.28	16.74	8.35	5.17	4.48
	19.42	9.70	5.98	5.18	16.51	8.25	5.08	4.40
	19.15	9.58	5.87	5.08	16.28	8.14	4.99	4.32
	18.88	9.46	5.76	4.99	16.04	8.04	4.90	4.24
Cat. 1	18.60	9.34	5.66	4.89	15.81	7.94	4.81	4.16
	18.33	9.22	5.55	4.80	15.58	7.84	4.72	4.08
	18.06	9.10	5.44	4.70	15.35	7.74	4.62	4.00
	17.79	8.98	5.33	4.60	15.12	7.63	4.53	3.91
	17.52	8.86	5.22	4.51	14.89	7.53	4.44	3.83
Cat. 2	17.24	8.74	5.12	4.41	14.66	7.43	4.35	3.75
	16.97	8.62	5.01	4.32	14.43	7.33	4.26	3.67
	16.70	8.50	4.90	4.22	14.20	7.23	4.17	3.59
	16.43	8.38	4.79	4.12	13.96	7.12	4.07	3.51
	16.16	8.26	4.68	4.03	13.73	7.02	3.98	3.42
Cat. 3	15.88	8.14	4.58	3.93	13.50	6.92	3.89	3.34
	15.61	8.02	4.47	3.84	13.27	6.82	3.80	3.26
	15.34	7.90	4.36	3.74	13.04	6.72	3.71	3.18
	15.07	7.78	4.25	3.64	12.81	6.61	3.61	3.10
	14.80	7.66	4.14	3.55	12.58	6.51	3.52	3.02
Cat. 4	14.52	7.54	4.04	3.45	12.35	6.41	3.43	2.93
	14.25	7.42	3.93	3.36	12.11	6.31	3.34	2.85
	13.98	7.30	3.82	3.26	11.88	6.21	3.25	2.77
	13.71	7.18	3.71	3.16	11.65	6.10	3.16	2.69
	13.44	7.06	3.60	3.07	11.42	6.00	3.06	2.61
Cat. 5	13.16	6.94	3.50	2.97	11.19	5.90	2.97	2.53
	12.89	6.82	3.39	2.88	10.96	5.80	2.88	2.44
	12.62	6.70	3.28	2.78	10.73	5.70	2.79	2.36
	12.35	6.58	3.17	2.68	10.50	5.59	2.70	2.28
	12.08	6.46	3.06	2.59	10.26	5.49	2.60	2.20
Untrained	11.80	6.34	2.96	2.49	10.03	5.39	2.51	2.12
	11.53	6.22	2.85	2.40	9.80	5.29	2.42	2.04
	11.26	6.10	2.74	2.30	9.57	5.19	2.33	1.96
	10.99	5.98	2.63	2.20	9.34	5.08	2.24	1.87
	10.72	5.86	2.52	2.11	9.11	4.98	2.15	1.79
	10.44	5.74	2.42	2.01	8.88	4.88	2.05	1.71
	10.17	5.62	2.31	1.92	8.65	4.78	1.96	1.63
	9.90	5.50	2.20	1.82	8.42	4.68	1.87	1.55

The shape, or profile of the resulting plot, will fall in to one of several categories:

(–) Generally horizontal plot, i.e., all four values falling at about the same point on their respective range: this pattern is characteristic of the typical "all rounder," i.e., a rider who doesn't necessarily excel at any one thing, but is likely competitive in their category across a broad range of events. Given the fact that only specialists will likely truly excel at the extreme durations (i.e., 5 seconds and 20 minutes), very few individuals will show this pattern and still fall at the upper end of each range. On the other hand, the vast majority of non-elite athletes will likely show a generally horizontal power profile.

(\ ) Distinctly down-sloping plot (especially between 1 minute and 5 minutes): this pattern would be characteristic of an excellent sprinter/"fast twitcher," i.e., an athlete whose naturally abilities are skewed towards success in short duration, high power events. Since aerobic ability is quite trainable, such an individual may be able to turn themselves into more of an "all-rounder" by appropriately-focused training – however, if they have already been training hard for many years, they may always still be better at anaerobic vs. aerobic efforts. If so, focusing on events that favor these abilities (e.g., track racing, criteriums) may result in the most success.

(^) Sharply inverted-V pattern: an athlete characterized by both relatively high anaerobic capacity and aerobic ability, and thus well-suited for events such as the pursuit. Alternatively, a potential "all-rounder" who simply hasn't focused on raising their lactate threshold to its highest possible level.

(/) Distinctly upsloping plot (again, especially between 1 and 5 minutes, but also from 5 to 20 minutes): the classical time-trialist pattern, i.e., weak in neuromuscular power and anaerobic capacity, but with a relatively high aerobic power, and especially a high lactate threshold. While such riders may improve their performance by working on their weaknesses, this may not necessarily be true if it results in a decline in their strength, which is sustainable power.

(V) Sharp V-pattern: an unlikely combination, given the expected inverse relationship between neuromuscular power and lactate threshold, and the positive relationship expected between VO_{2max} and lactate threshold. Should such a pattern be observed, care should be taken to assure that the values being used are truly representative of the athlete's abilities, and to be sure that the pattern isn't simply being misinterpreted (i.e., considering a generally horizontal or "w" pattern to be a "V").

HOW THE CATEGORY VALUES WERE CHOSEN

The upper and lower bounds of each range, of course, were fixed based on known power outputs of world champions/record holders and untrained individuals, respectively, while the values in between were spread equally (i.e., linear relationship assumed), simply because at present there is not enough data to justify doing otherwise. Remember, the purpose of the tables is to compare relative ability across different exercise durations reflecting different physiological characteristics, not to assign categories or describe riders at each level (strip the category guidelines away, and the tables would be just as useful). This is why a normal distribution was not assumed and the values were not spread that way; that might (or might not – no one has the data to say for sure) better reflect reality, but has the disadvantage of squeezing everything together toward the middle, making anyone who isn't well above or well below average appear to be an "all rounder."

The scales tend to be skewed from a road racer's perspective, as they are based on the performance of specialists (match sprinters for 5 second power, kilo riders for 1 minute, etc.) To state it another way: compared to a true sprinter, most people racing on the road *do* have relatively low neuromuscular power, however, I don't think one really can or should try to develop discipline-specific tables. First of all, too many people cross over to different disciplines, thus making it difficult to develop valid standards, especially since the only point of proposing discipline-specific tables would be to improve the category guidelines, which is not the point of the tables. Secondly, discipline-specific tables would deviate from the logic that was used to develop the tables in the first place.

It seems to me that if you assume that there is a big enough population base fighting it out to be "top dog" in each specialty, then that assures that the scales will align properly (the most important part). Logically one would expect that each scale should *not* be linear (thus addressing the point about the extremes), but instead be normally distributed. I could, for example, have assumed that world champion/world record performance is, say, 5 standard deviations above the mean, and the lowest level of the untrained 5 SDs below, or something like that, however, that doesn't alter the comparison across scales, and has the disadvantage of crowding together all values in the middle.

To reiterate: the category guidelines accompanying the scales are just rough approximations, i.e., most riders of a certain category can generate the specified power for the specified duration, however, that doesn't mean that all can, nor does it mean that just because you can generate a certain amount of power that you should be a certain category (although it does indicate that you have that potential).

And again, from a theoretical perspective, the values should really be $W/kg^{0.67}$, not W/kg, however, I think that such allometric scaling might be a little beyond the average person's grasp, at least w/o extensive explanation.

LIMITATIONS AND CAVEATS

There is a paucity of direct data on the power outputs of female cyclists. Thus, as a first approximation the standards for women were simply fixed at 85% of the corresponding standards for men. This correction factor was based on typical male-female differences in VO_{2max}, anaerobic capacity, etc., as reported in the scientific literature (differences that are largely, but not entirely, due to differences in body composition). While relatively crude, the accuracy of values generated using this approach appears to be sufficient, as verified by comparison to available data, e.g., known power outputs of elite Australian road cyclists.

The standards are based on the performance capacities of young adults, and thus do not account for the effects of aging (or development). The possibility of developing age-specific standards was considered but rejected due to the lack of sufficient direct data as well as the complexity of attempting any corrections based on known physiological changes. For example, while VO_{2max} declines by ~0.5 milliliters/minute/kilogram per year (~0.35 ml/min/kg per year in women) starting at around age 30, muscle strength and power are generally well-maintained until around age 50, then begin to decline somewhat more rapidly thereafter. Such observations imply that, for maximum accuracy, different age-based correction factors might need to be applied to the aerobic (i.e., 5 and 20 minutes) and the anaerobic (i.e., 5 seconds and 1 minute) standards. It is unlikely, however, that these differential changes with age are sufficient to significantly alter a rider's "profile," and it is suggested that the tables simply be applied "as is" regardless of a rider's age.

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Appendix C: altitude adjustment (estimating the effect of elevation on power output)

The effects of altitude on VO_2 uptake (and hence power output from the aerobic energy system) are highly individual, so it is impossible to predict how any one person will be affected, although as a general rule it has been shown that elite athletes, as compared to normal individuals, have a greater decline in VO_2max under conditions of reduced ambient pO_2 (partial oxygen pressure). This is caused by their higher cardiac output, which results in a decreased mean transit time for the erythrocytes (red blood cells) within the pulmonary capillary, and thus less time for equilibration between alveolar air and blood in the pulmonary capillary.

The following equations* were generated from 4 groups of highly trained or elite runners, so they are population-specific to that group, but they can be used to estimate aerobic power at a given altitude as a percentage y of what is normally available at sea level, where x = elevation above sea level in km:

For acclimatized athletes (several weeks at altitude): $y = -1.12x^2 - 1.90x + 99.9$ ($R^2 = 0.973$)

Non-acclimatized athletes (1-7 days at altitude): $y = 0.178x^3 - 1.43x^2 - 4.07x + 100$ ($R^2 = 0.974$)

ELEVATION	AVAILABLE AEROBIC POWER	
(feet above sea level)	*acclimatized*	*non-acclimatized*
0	99.9%	100.0%
1,000	99.2%	98.6%
2,000	98.3%	97.0%
3,000	97.2%	95.2%
4,000	95.9%	93.2%
5,000	94.4%	91.1%
6,000	92.7%	88.9%
7,000	90.7%	86.5%
8,000	88.6%	84.2%
9,000	86.3%	81.7%
10,000	83.7%	79.3%
12,000	78.0%	74.7%
13,000	74.8%	72.5%
14,000	71.4%	70.4%

*Bassett, D.R. Jr., C.R. Kyle, L. Passfield, J.P. Broker, and E.R. Burke. Comparing cycling world hour records, 1967-1996: modeling with empirical data. *Medicine and Science in Sports and Exercise* 31:1665-76, 1999.

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Appendix D: a motion equation for cycling

$$P = \Sigma F s = s\,(R_a + R_t + R_f + R_w + R_i)$$

$$= s\,[k_a(s + v_w)^2 + mg(k_t \cos\theta + k_f s + \sin\theta) + ma]$$

where $k_a = ½C_D A\,\rho_0(0.359\,P_B/T)$

and P	=	mechanical power output at rear wheel of bicycle/rider system in Watts		
s	=	road speed of system in meters/second		
ΣF	=	total force resisting forward motion of system in Newtons		
R_a	=	aerodynamic drag of system in Newtons		
R_t	=	tractional (tire) rolling resistance in Newtons $= k_t mg\cos\theta$		
R_f	=	frictional resistance of bicycle mechanism in Newtons $= k_f mgs$		
R_w	=	direct resistance from weight of system in Newtons $= mg\sin\theta$		
m	=	total mass of system in kilograms		
a	=	acceleration of system in meters/second^2		
R_i	=	"inertial" resistance in Newtons $= ma$		
k_t	=	tractional (tire) rolling resistance constant (dimensionless)	=	0.0035
g	=	gravitational acceleration constant in meters/second^2	=	9.806 m/s^2
i	=	incline (grade per cent) of road surface		
θ	=	angle of road surface $= \tan^{-1}(i/100)$	=	
k_f	=	mechanical friction constant of bicycle mechanism in seconds/meter	=	0.00012 s/m
k_a	=	aerodynamic drag constant of system in kilograms/meter		
v_w	=	relative headwind (>0) or tailwind (<0) velocity in meters/second		
C_D	=	aerodynamic drag coefficient of system (dimensionless)		
A	=	frontal area of system in square meters		
ρ_0	=	density of dry air at 760 Torr and 273 K in kilograms/meter^3	=	1.23 kg/m^3
P_B	=	barometric pressure in Torr		
T	=	temperature in Kelvins		

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