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The Science of Cycling

Factors Affecting Performance – Part 2

Erik W. Faria,¹ Daryl L. Parker² and Irvin E. Faria²

- 1 Exercise Physiology Laboratories, University of New Mexico, Albuquerque, New Mexico, USA
- 2 Department of Kinesiology and Health Science, California State University, Sacramento, California, USA

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Abstract

This review presents information that is useful to athletes, coaches and exercise scientists in the adoption of exercise protocols, prescription of training regimens and creation of research designs. Part 2 focuses on the factors that affect cycling performance. Among those factors, aerodynamic resistance is the major resistance force the racing cyclist must overcome. This challenge can be dealt with through equipment technological modifications and body position configuration adjustments. To successfully achieve efficient transfer of power from the body to the drive train of the bicycle the major concern is bicycle configuration and cycling body position. Peak power output appears to be highly correlated with cycling success. Likewise, gear ratio and pedalling cadence directly influence cycling economy/efficiency. Knowledge of muscle recruitment throughout the crank cycle has important implications for training and body position adjustments while climbing. A review of pacing models suggests that while there appears to be some evidence in favour of one technique over another, there remains the need for further field research to validate the findings. Nevertheless, performance model-

ling has important implications for the establishment of performance standards and consequent recommendations for training.

When writing this review, we have been aware that advances are being made at an exponential rate in the areas of human biology and exercise biochemistry. Consequently, some of the beliefs that are held today might fail to be supported in the future. However, our goal is to establish a foundation, for the science of cycling, upon which new information can easily be incorporated and applied. This review article attempts to provide an overview of physiological, biomechanical and technological factors that determine cycling performance. A better understanding of the mechanisms and their interactions that underlie the notion of optimisation in the dynamics of cycling will enable more educated approaches to testing, training and research.

1. Aerodynamics

The air resistance component while cycling is proportional to the cube of speed; consequently, it is the primary energy cost factor at high speeds. This aerodynamic resistance represents >90% of the total resistance the cyclist encounters at speeds >30 km/hour.^[1] At speeds >50 km/hour, aerodynamic resistance is the most performance-determining variable.^[1,2] For instance, the drag force at 50 km/hour, computed in a wind tunnel prior to an attempt at the 1-hour cycling world record, was 12g (where g = acceleration of gravity 9.807 m/sec⁻² at sea level).^[3] In an effort to reduce this drag force, the configuration of the bicycle and its components and cyclist's body position have received much attention.

In particular, the aerodynamic effect of the clip-on aero-handlebar was first most effectively demonstrated by Greg Lemond during his spectacular Tour de France win in 1989.^[4] Moreover, aside from equipment, the cyclists riding position has an important consequence for both speed and metabolic cost.^[4-6] The aerodynamic advantage from a reduced frontal area (FA) when the cyclist assumes a forward crouched upper body position is well established.^[7,8] However, when the cyclist's upper body

configuration is changed from the upright to the aero position there is a significant increase in oxygen consumption ($\dot{V}O_2$), heart rate (HR) and respiratory exchange ratio (RER).^[6]

In that regard, riding a bicycle in an extreme aero position increases the metabolic cost of cycling when wind resistance is not taken into account. More specifically, the aero position requires a higher metabolic cost of approximately 37W and decrease in net mechanical efficiency of approximately 3%.^[6,9] Mechanical efficiency is defined as the ratio between power output and energy turnover above resting, expressed in $\dot{V}O_2$.^[6] Nonetheless, there occurs a 20% decrease in air drag when changing from the upright sitting and straight arm position to the hands on the drop bars and another 10–17% decrease from hands on the drop bars to the full crouched aero position.^[7,8,10] Taken in total, a 30–35% reduction in drag occurs when moving from the upright into the aero position.

The FA of the cyclist combined with that of the bicycle play a significant part in the creation of cycling resistance. To estimate the FA, photographs of the cyclist in a specific riding position and of a reference rectangle of known area are taken. The contour of the ensemble cyclist-bicycle and that of the rectangle are then cut out and weighed. The cyclist's FA is then estimated by comparing the masses of the pictures of the ensemble cyclist-bicycle and that of the reference area.^[7,11] Alternatively, the FA may also be measured by planimetry from scaled photographs of the cyclist sitting on the bicycle.^[12] Bassett et al.^[13] describe another method used to estimate a cyclist's FA utilising body surface area (SA) and data from the work of Wright et al.^[14] and Kyle.^[11] Knowledge of the cyclist's FA is especially important since it generally represents ~18% of the cyclist's body SA.^[13] Bassett et al.^[13] present an equation, utilising the cyclist's height and weight that will estimate the cyclist's total FA in terms of

height and mass while in the aero-racing position utilising aero bars:

$$FA = 0.0293H^{0.725} M^{0.425} + 0.0604$$

where: FA = frontal area in m²; H = height in m; M = mass in kg.

While there is little effect of body size on the energy cost of stationary cycling, body size does influence road-racing energy cost. Wind tunnel data and anthropometrical measurements reveal that when expressed relative to body mass, the frontal drag of the small cyclists is considerably greater than that of larger cyclists.^[15] Moreover, the energy expended to overcome air resistance while cycling is proportional to the cyclist's SA.^[15] Accordingly, the larger cyclists have an advantage in terms of relative energy cost of cycling on level ground because smaller cyclists have a ratio of body SA to FA, which is larger, thereby creating a greater relative air resistance.^[7,15] Furthermore, because the bicycle comprises a smaller fraction of the bicycle and cyclist combination for the larger cyclist compared with the smaller cyclist, the total FA (bicycle and cyclist) of the larger cyclist is favoured.^[15]

For example, in a study of large and small cyclists, while larger cyclists had a 22% lower $\dot{V}O_2$ /bodyweight (BW) than small cyclists at speeds of 16, 24 and 32 km/hour the SA/BW ratio of the large cyclists was only 11% lower than that of the small cyclists.^[15] However, in a racing posture, the FA of the large cyclists had a 16% lower FA/BW ratio than the small cyclists.^[15]

Swain^[15] points out that the difference in frontal drag (energy cost) is not compensated for by the advantage to small cyclists in relative $\dot{V}O_{2max}$ (energy supply), since the mass exponent for drag (1/3) is closer to zero than for $\dot{V}O_{2max}$ (2/3). Consequently, the small cyclists would be at a disadvantage in flat time trials where air resistance is the primary force to overcome, which is supported by time trial race data. The question that remains is who is favoured on mountainous ascents? Slowing down while ascending reduces air resistance, therefore, the major force to overcome is gravity. In this instance, the force of gravity is directly proportional to the combined mass of the cyclist and bicycle. Research

reveals that the weight of the larger cyclist's bicycle represents a small proportion of their weight than do the bicycles of smaller cyclists (12% vs 17%, respectively).^[11] That being true, the larger cyclists should once again have a relative advantage in energy cost. However, the smaller cyclists have the advantage in hill climbing because their relative maximum oxygen consumption ($\dot{V}O_{2max}$) is greater compared with larger cyclists than their disadvantage in energy cost, again supported by race results.^[15]

Large cyclists have the advantage during descents since gravity propels them downward with a force that is proportional to the total mass.^[15] Nevertheless, they often find it difficult to make up the time lost in ascending mountainous terrain. Taken together, the smaller cyclists should be favoured in mountainous stage races.

In summary, the FA of the cyclist, ~18% of the cyclist's body SA, and bicycle is responsible for the majority of drag force created while cycling. Energy expended to overcome air resistance is proportional to the cyclist's SA, assuming a full crouched aero position reduces drag by 30–35%. Expressed relative to body SA, the FA of the small cyclist is greater than the large cyclist. In terms of SA/BW, the larger cyclist, on flat roads, has an advantage over the smaller cyclist; however, because of the relative $\dot{V}O_{2max}$ to BW the small cyclist has an advantage in climbing.

2. Drafting

The ability to avoid crashes and efficiently draft appear to be the two most important factors enabling cyclists of the major tours to finish within the same time; however, they are not determinants of a winning performance. Several studies investigated the beneficial effects of the drafting component during cycling and triathlon performance.^[16-19] Drafting was found to reduce air resistance, the primary force opposing cyclists, and reduces energy utilisation by as much as 40%.^[16] Furthermore, it has been demonstrated while drafting a cyclist outdoors at 39.5 km/hour compared with cycling alone results in reductions of ~14% for $\dot{V}O_2$, 7.5% in HR, and ~31% for

expiratory volume (V_E).^[17] In a study of triathletes, it was shown that cycling at 40.9 km/hour continuously behind the lead cyclist lowers the $\dot{V}O_2$ ~16%, HR ~11%, expiratory flow rate ~10% and blood lactate ~44% compared with alternate drafting.^[18] However, alternate drafting, where the cyclist takes the lead every 500m, was not as efficient as continuous drafting.^[18] These data were collected while cycling on an indoor cycling track.

McCole et al.^[19] reported that the metabolic (e.g. $\dot{V}O_2$) benefit of drafting was higher with increasing cycling velocity. In this study, the observed reduction in $\dot{V}O_2$ was independent of the cyclist's position in a line situation, whereas the adoption of a drafting position at the back of the group of eight cyclists has been reported to further reduce $\dot{V}O_2$.^[19] Therefore, there appears to be a great interest for favourite winners of the Tour de France such as Lance Armstrong or Jan Ulrich to use drafting strategically in the middle of the pack to conserve energy for subsequent hard stages (e.g. climbing stages). Toward that end, the air resistance in the middle of the pack is reduced by as much as 40%.^[19]

Briefly, drafting reduces energy cost of cycling by as much as 40%. Likewise, there is a 40% reduction of air resistance when drafting in the middle of the pack. This reduced drag force has the effect of lowering the $\dot{V}O_2$, HR, V_E and lactate values while cycling when compared with remaining on the front. Alternate drafting, taking the lead every 500m, is not as effective as continuous drafting.

3. Rolling Resistance

The third major resistance that must be overcome while cycling is rolling resistance.^[20,21] Rolling resistance is the result of the compression of either the wheel or the ground or both. As the bicycle wheel rolls, the same total area of the tyre and road remain in contact. The greater the area of this 'patch' of the tyre and road that are in contact, the greater the resistance will be, since the contact region will extend further in front of the wheel. Hence, the units of rolling resistance are the pound-force per pound-force, the first unit being the resistance to rolling in pounds of force and the second being the vertical

loading on the wheel. Furthermore, major determinants of the rolling resistance during cycling are wheel diameter, type of tyre, inflation pressure, ground surface and the friction in the machinery of the bicycle.

Rolling resistance can influence power output more than drag at low riding speeds in still air.^[5] Moreover, the rolling resistance is inversely proportional to the radius of the wheel.^[5] Therefore, the small-wheel bicycle will have more resistance to motion than the large wheel under the same conditions. In terms of road surface, there is a 5% difference between the rolling resistance of concrete and blacktop. Tyre pressure can also have an effect on rolling resistance. The higher the operating tyre pressure, the greater the reduction in rolling resistance, which contributes to increased cycling efficiency. The type of tyre (clincher vs sew-ups) influences the power output to speed relationship. For example, at 0.2 horsepower the increase in speed using sew-ups would be almost 6 km/hour faster than clinchers.^[22]

The simplest approach for obtaining air- and rolling-resistance values is the coasting-down method.^[23] It has been demonstrated that this method provides accurate measurements of velocity under conditions similar to those that prevail during cycling.^[12] Candau et al.^[24] developed a simplified deceleration method (coasting-down method) for assessment of resistance forces in cycling. This technique has the practical advantage of allowing testing of both aerodynamic and rolling resistances over real road conditions. Moreover, the method is less time consuming and more affordable compared with wind-tunnel testing. Additionally, it affords opportunities for energy cost evaluation. The subject's personal bicycle is used and is generally equipped with aero-handlebars. Cycling attire includes a classical helmet and racing clothing.

Development of the coast-down test took place in an 80m long indoor hallway (2.5m width and 3.5m height) with linoleum flooring.^[24] Trials were performed at initial velocities ranging from 2.5 to 12.8 m/sec. The cyclist initiated the given speed then ceased to pedal before coasting over three timing

switches located at 1m and 20m. While coasting, the cyclist continued to pedal without transmitting force to the rear wheel. This leg action provided turbulence common during cycling. Newton's second law served as the basis for the equation of motion for a cyclist moving on level ground and for a given effective FA (AC_D , in m^2) and rolling coefficient (C_R , unitless):^[24]

$\Sigma F = M \cdot dv/dt = -C_R \cdot M \cdot g - 1/2 \cdot p \cdot AC_D \cdot v^2$
 where: F = force; d = distance; v = speed (in m/sec);
 t = time (in seconds); p = air density (in kg/m^{-3}); M = mass; g = acceleration due to gravity (in m/sec^2).

The equation assumes that AC_D and C_R are not affected by velocity.^[7,15,20,25] These researchers^[24] found that slight changes in total mass induced significant differences in rolling resistance. From these observations, they predicted that in a 60km competition using racing aero position with the head in the upright position, the time could be improved by 191 seconds through assuming an intermediate head position and by 224 seconds through the head in line with the trunk. Caution is advised that the coast-down test could result in a slight underestimation of rolling resistance and slight overestimation of the aerodynamic drag.^[24]

In summary, the major determinants of the rolling resistance, in terms of pound-force per pound-force, during cycling are wheel diameter, type of tyre, inflation pressure, ground surface and the friction in the machinery of the bicycle. Rolling resistance can influence power output more than drag at low riding speeds in still air. The coasting-down method is a cost-effective means of measuring rolling resistance; however, it may underestimate the resistance.

4. Equipment Configuration

The transfer of power from the human body to the drive train of the bicycle depends upon the crank length^[26-28] longitudinal foot position on the pedal,^[27,29,30] pedal cadence,^[26,29-32] seat height^[26,29,30,33-35] and seat-tube angle (STA).^[26,36-38] Moreover, the cyclist's performance is influenced by the bicycle profile and cyclist's attire.

The STA is measured at the position of the seat relative to the crank axis of the bicycle. Road racing cyclists prefer a STA between 72° and 76° , whereas triathletes prefer a STA between 76° and 78° .^[39,40] The STA can easily be altered for any bicycle frame by sliding the seat forward or backward on the seat's rails. Generally, cyclists move their seat as far backward as possible on its rails. In this regard, road cyclists choose a shallow ($\sim 76^\circ$) STA. Their reason for doing so appears to be because most road races emphasise hill-climbing road stages and not time-trial stages. In contrast, time-trial cyclists using aerobars prefer a steeper ($>76^\circ$) STA.^[39] Optimal STAs range from 78.5° for short cyclists to 73.2° for the tallest cyclists.

Nevertheless, cycling test results regarding the effect of STA on metabolic parameters are conflicting in the literature. Heil et al.^[39] found that mean values of $\dot{V}O_2$, HR and rating of perceived exertion (RPE) for STA at 83° and 90° were significantly lower than for STA of 69° , whereas more recently, Garside and Doran^[40] indicated the lack of significant variations in $\dot{V}O_2$ and HR between STA at 81° and 73° . A STA of 81° was found to improve triathlete 10km running and combined cycling plus running performance,^[40] whereas STAs of 76° , 83° and 90° elicited similar cardiorespiratory responses in cyclists.^[39] Sound scientific rationale for STA preference differences between cyclists and triathletes remain to be determined.

When the STA is shifted from 69° to 90° , a greater flexion at the ankle occurs and there is a change in lower-limb orientation that places the rotation of the legs more directly over the crank axis.^[39] The impact of these changes on power output is not yet known. However, as hip angle is increased with an increase in STA, the length of muscles crossing the hip joint (i.e. biarticulate rectus femoris, hamstring muscles and gluteus maximus) are systematically altered. Applying a forward dynamical musculoskeletal model, Raasch et al.^[41] showed that the gluteus maximus provided 55% of all energy delivered to the crank to overcome the resistive load and hence, to the power production.

Accordingly, it appears that the power phase of pedalling may be dependent upon the hip angle.

Handlebar designs combined with steeper STAs now allow the cyclist to assume a more crouched upper body position resulting in lower wind resistance. Consequently, STA can greatly affect the cyclists' efficiency. Road cyclists try to move the hip joints forward relative to the bottom bracket allowing them to sit more crouched and in so doing reduce wind drag. Steeper STAs will extend the hip, thereby allowing a more forward and more crouched upper body position resulting in a decrease of drag and increase in cycling velocity.^[6,39]

The effect of an aerodynamic frame and wheels on the outcome of a 40km individual time trial (ITT) was modelled by Jeukendrup and Martin.^[42] An aerodynamic frame with the cyclist in an aero position lowered the time by 1:17 minutes for elite-level cyclists, while aerodynamic wheels lowered the time by 1 minute for elite-level cyclists. These findings suggest that at the elite level, cyclists can lower their 40km ITT time by >2 minutes using aero wheels and frame. It should also be noted that improvements in time were larger for lesser trained cyclists since they spend a greater amount of time on the course.^[42]

The importance of cycling equipment configuration and weight is evident in world record attempts. Accordingly, the bicycle used in the 1-hour world record ride weighed 7.280kg. Front and rear disk wheels were made of Kevlar, the diameters being 66cm for the front and 71.2cm for the rear. The front and rear tubeless tyres were 19 and 20mm wide, respectively. A 180mm crank was used. The cyclist wore an aerodynamically designed suit (85% Coolmax, 15% elastane) and a helmet (Rudy Project, Italy).^[3]

In contrast to road bicycles, mountain bikes are typically equipped with either a front suspension or a front and rear (four-bar linkage rear) suspension system. Oxygen cost and HR of the cyclist do not differ when riding uphill on- or off-road utilising front and dual suspension uphill.^[43] However, power output is significantly higher on the dual suspensions system for uphill cycling without concomitant

cardiovascular response differences.^[43] Power output on- and off-road is significantly lower for the front suspension system. These data suggest that the dual suspension bicycle may not be as efficient compared with the front suspension bicycle in cross-country racing where ~70% of the time spent involves uphill riding.^[43]

The use of an eccentric chainring was examined during an all-out 1km laboratory sprint test.^[44] In this study, although no differences between the circular and eccentric chainring were observed for cardiorespiratory variables, performance was significantly improved utilising the eccentric chainring. These authors hypothesise that the improved performance is due to the higher torque during the downstroke resulting from the greater crank length during that cycling phase.^[44] Moreover, the variable crank arm length used with the eccentric chainring may be better adapted for velodrome cycling events. However, at this time, further research with indoor cyclists employing tests in a velodrome is needed to examine the maximal potential of an eccentric chainring.

In summary, the bicycle profile, cyclist's riding position and cycling attire greatly influence performance. An STA between 72° and 76° is preferred by road-racing cyclists, whereas triathletes use an STA range of 76–78°. The change in hip angle with increased STA allows greater power production and a more favourable aerodynamic body position. In cross-country racing, the front suspension bicycle construction appears to be superior to the dual-suspension system. For the moment, the value of the eccentric chainring remains equivocal.

5. Gear Ratios

To meet the requirements of competition in professional racing, i.e. Tour de France, Giro, Vuelta a España, cyclists usually adopt hard gears. During long, flat stages, gears of 53 × 13–14 are employed to reach an average speed of 43.8 km/hour.^[15] Time-trial gears of 54 × 13–14 are used to obtain speeds averaging 47.3 km/hour.^[15] Top performance time-trial cyclists who must perform at an average velocity of ~50 km/hour use pedal rates >90 revolutions

per minute (rpm).^[15] Lower pedal cadences would require use of $58\text{--}60 \times 11$ at 70 rpm in order to achieve winning times. The gear ratio used by the cyclist who set the new 1-hour world record was 59×14 and the average pedal rate was 101 rpm using a 180mm crank length.^[3]

6. Peak Power Output

One of the newest used measuring devices to measure power is the SRM Training Systems (Schoberer Rad Messtechnik SRM, Julich, Germany). The SRM system calculates power output from the torque and the angular velocity. To accomplish this, strain-gauges are located between the crank axle and the chainring, and their deformation is proportional to the torque generated by each pedal revolution. This SRM system, previously validated from a comparison with a motor-driven friction brake^[45] may be used during both laboratory and field-based studies.^[46] The system is able to record power and store the data in its memory. Additionally, it records and stores information regarding speed, distance covered, cadence and HR.

More importantly, to accurately assess power requires an assessment of the relationships between force and velocity. Furthermore, to accurately assess peak and average power output research reveals that the inertial-load method, which uses both frictional resistance and flywheel inertia, and the isokinetic method are valid.^[47-51] When measuring power output, it is recommended that maximal power output, averaged over a complete revolution, is best obtained at ~ 100 rpm and calculated as follows:^[51,52]

$$W_{\max} = W_E + (40w/t \times t_E)$$

where: W_{\max} = maximal power output (W); W_E = power output of last complete stage (W); $40w$ = work-load increment; t = work-load duration (seconds); t_E = duration final stage (seconds).

To determine the maximal power index, the mean of W_{\max} is divided by the mean of highest peak power then multiplied by 100.

Baron^[52] suggests that the power index provides information on the proportion of aerobic to anaerobic energy contribution that is related to specialisa-

tion in competition. Furthermore, it is recommended that cyclists with a power index of $<40\%$ have to improve their aerobic power.^[52] Cyclists with a power index of $>45\%$ have to improve their anaerobic power.^[52] Consequently, the power index appears useful when recommending training protocols.

The importance of the cyclist's ability to produce power is best illustrated by the work of Lucía et al.^[16] who collected data during professional stage races. The mean absolute power output generated during the Giro d'Italia, Tour de France and Vuelta a España stage races has been estimated to be approximately 400W during a 60-minute period.^[16] Data further suggest that a high power output to body mass ratio (≥ 6 W/kg) at maximal or close-to-maximal intensity is a prerequisite for racing cyclists.^[53] In support of this finding, during the 1-hour world record ride, the average power output was 509.53W.^[3] This cyclist had a power/BW ratio of 6.29 W/kg, which lends credence to the concept of a power/BW ratio of 6 W/kg or more as a prerequisite for racing success.

Elite male off-road cyclists, National Off-Road Bicycle Association, have demonstrated maximal power output values of 5.9 to 5.4 W/kg.^[52,54] Peak power output, during a Wingate test, for the United States Cycling Federation road cyclists in categories II, III and IV is reported as 13.9, 13.6 and 12.8 W/kg (load 0.095 kg/BW), respectively.^[55]

In summary, the SRM system calculates power output from the torque and the angular velocity. To accurately assess power requires an assessment of the relationships between force and velocity. When measuring power output, it is recommended that maximal power output, averaged over a complete revolution, is best obtained at ~ 100 rpm. Power output information is useful when establishing training protocols. The cyclist with a power index of $<40\%$ suggests a need to improve aerobic power while an index of $>45\%$ indicates attention be given to anaerobic power training. For road racing success, a power/BW ratio of ≥ 6 W/kg is suggested.

7. Pedalling Cadence

Pedalling rate is widely accepted as an important factor affecting cycling performance, although there does not exist any consensus regarding criteria that determine the selection of cadence. Previous studies have indicated that pedalling rate could influence the neuromuscular fatigue in working muscles.^[56,57] Moreover, pedalling rate may influence the fibre type recruitment pattern.^[58] Fewer fast-twitch (type II) muscle fibres, compared with slow-twitch (type I) muscle fibres, are recruited when pedal cadence is increased from 50 to 100 rpm.^[58] This recruitment is in response to the reduced muscle force required per pedal revolution at the higher cadence. Clearly, the force demands of pedalling, rather than the velocity of contraction, determines the type of muscle fibres recruited.^[58] Consequently, a cadence of 100 rpm is not too high for type I muscle fibres to effectively contribute to cycling velocity. Other than at maximal cycling speed, the cyclist will minimise the recruitment of type II fibres by maintaining a high cadence with low resistance. Moreover, consistent with the metabolic acidosis discussion in part 1 of this review, with less reliance on type II fibres, there is a decreased likelihood for the onset of premature metabolic acidosis.^[59]

Fibre-type recruitment and cycling efficiency appear to be linked with muscle contraction velocity. At 80 rpm, type I muscle fibres of the vastus lateralis are contracting closer to their peak efficiency contraction velocity than type II muscle fibres.^[60] When type I muscle fibres are contracting at a speed of approximately one-third of the maximal speed of shortening in individual muscle fibres they are at their maximised muscular efficiency.^[61] Consequently, the cyclist with a higher percentage of type I compared with type II fibres will be more efficient as reflected by a lower $\dot{V}O_2$ for a given power output. Accordingly, the single best predictor of a 40km time-trial performance is the average amount of power output that can be maintained in 1 hour.^[60] This predictor represents 89% of the variance in time-trial performance.^[15]

Coyle et al.^[60] found a strong relationship ($r = 0.75$; $p < 0.001$) between years of endurance training

and percentage of type I muscle fibres. Nonetheless, the efficiency of muscle contraction is reduced after prolonged cycling and is attributable to both central and peripheral factors but is not influenced by the pedalling rate.^[62,63] The freely chosen cadence appears to be related to the ability of the cyclists to effectively generate force in the quadriceps muscle. Lepers et al.^[63] observed that the decrease in muscle capacities after cycling exercise was independent of pedalling rates.

In this regard, several factors influence the efficiency of pedalling rate. These factors include crank length, body position, linear and angular displacements, velocities and accelerations of body segments and forces in joints and muscles.^[5] Furthermore, cycling experience appears to exert an influence on the metabolic effect of various pedal speeds and on cycling efficiency.^[16] Lucía et al.^[64] examined the effect of pedal cadence of 60, 80 and 100 rpm on the gross efficiency (GE) and other physiological variables (i.e. $\dot{V}O_2$, HR, lactate, pH, V_E , motor unit recruitment estimated by an electromyogram [EMG]) of professional cyclists while generating high power outputs. It was shown that GE averaged 22.4 ± 1.7 , 23.6 ± 1.8 and $24.2 \pm 2.0\%$ at 60, 80 and 100 rpm, respectively. Mean GE at 100 rpm was significantly higher than at 60 rpm. Similarly, mean values of $\dot{V}O_2$, HR, RPE, lactate and normalised root-mean square EMG (rms-EMG) in both vastus lateralis and gluteus maximum muscles decreased at increasing cadences.^[64] These findings confirm that efficiency/economy are very high in professional cyclists and thus corroborate previous findings.^[16] Moreover, these results partly answer the question of which pedal cadence is more efficient/economical in very well trained cyclists and may help understand why the unusually high cadence adopted by Lance Armstrong is so beneficial.

It has been reported that muscle efficiency is highest at velocities that are slightly lower than optimal velocity for peak power output regardless of their fibre type.^[65,66] These authors conclude that there appears to be no relation between fibre type recruitment pattern and neuromuscular fatigue during cycling exercise. However, these findings have

to be viewed with caution as animal models were employed.

Racing cyclists tend to acquire the skill to ride at a cadence >90 rpm, whereas recreational or novice cyclists tend to prefer lower pedal rates.^[67,68] Research has shown that the cadence of trained cyclists during laboratory testing is usually 90–100 rpm.^[53,68] Furthermore, the pedalling cadence adopted with various gear ratios generally varies between 70–100 rpm.

In this respect, there is considerable discrepancy in the literature with reference to preferred cadence.^[27,49,69,70] A popular rationale for the use of higher cadences is that they are more efficient. In general, it appears that the GE, defined as the ratio of work accomplished to energy expended,^[71] during pedalling may be influenced by speed of limb movement. However, Faria et al.^[72] reported that at high power output a decrease in efficiency was not evident when pedal rate was increased while holding power output constant. In this study, at a pedal rate of 130 rpm efficiency remained at 22%. Results from the studies of Sidossis and Horowitz^[61] confirm and extend the findings of Faria et al.^[72] in showing that delta efficiency (DE) increased from 21% to 24.5% as cadence increased from 60 to 100 rpm. Furthermore, both Faria et al.^[72] and Sidossis and Horowitz^[61] employed power outputs that were considerably higher than adopted in previous investigations. Consequently, their efficiency findings appear to be more characteristic of cycling competition. In support of these findings, other investigators report that experienced cyclists are more efficient at higher pedal rates.^[32,73] One factor that may contribute to the higher efficiency at higher pedal rates is that the working muscles are contracting closer to the speed of shortening that maximised their efficiency.

Chavarren and Calbet^[74] demonstrated that regardless of pedalling rate, GE improved with increasing exercise intensity; however, GE decreased as a linear function of power output. In support of this finding, Takaishi et al.^[73] found that trained cyclist's possess a certain pedalling skill regarding the positive utilisation for knee flexors up to high

cadences (105 rpm), which contribute to a decrease in peak pedal force and thereby alleviate muscle activity for the knee extensors.^[75] It appears that a pedalling cadence that decreases muscle stress influences the preferred cadence selection. Furthermore, the preferred higher cadence contributes to the recruitment of type I fibres with fatigue resistance and high mechanical efficiency despite increased $\dot{V}O_2$ caused by increased repetitions of leg movements.^[73] It has been observed that optimal cadence, relative to $\dot{V}O_2$, changes linearly, increasing from >40 rpm at 100W to nearly 80 rpm at 300W.^[76]

While the vast majority of research on pedal rate has been conducted in the laboratory, Lucía et al.^[16] investigated the preferred cycling cadence of professional cyclists during competition. Data obtained during the Giro d'Italia, Tour de France or Vuelta a España stage races reveal that optimal pedalling rate was characterised as that eliciting the lowest $\dot{V}O_2$, lactate and V_E . The means of cadence and speed were significantly lower during high mountain ascents of 7.2% (~70 rpm) than both long, flat stages and ITT (~90 rpm).^[16] The individual value of cadence observed in each flat stage averaged 126 rpm. The larger, more powerful cyclists recorded pedal rates of 80–90 rpm, whereas lighter cyclists adopted faster pedal speeds of 90–100 rpm.^[16] Break-aways during the last kilometres of the stage and sprints resulted in a pedal rate of ~95 rpm.^[16]

Maximum cadence, observed during long, flat stages at average speeds of >40 km/hour, averaged 126 rpm.^[16] The best climbers recorded a pedal rate of ~80 rpm during ascents of <10%. Maximum individual value in each high mountain averaged 92 rpm.^[16] The best time-trial specialist reached a pedal rate of >90 rpm. More to the point, Lucía et al.^[16] found the best time trialist recorded a mean pedal cadence of 96 rpm.

It is well documented that high cadences reduce the force used per pedal stroke,^[53,77] consequently, muscle fatigue is reduced in type II fibres. However, high pedal rates require greater $\dot{V}O_2$ for a given power output because of an increase in internal work for repetitive limb movements.^[31,68,71,76,78-81] Nevertheless, high pedalling rates, which reduce force

demands required per pedal revolution and shorten contraction time, encourage enhanced blood flow to type I muscle fibres, which in turn is associated with greater recruitment of the type I fibres.^[57,58,82] It is interesting to note that the world 1-hour cycling record has been consistently set with average cadence just over 100 rpm.^[3,83]

It is now widely accepted that a pedalling rate exists at which significantly smaller neuromuscular fatigue may be realised. The feelings of strain in the working muscles and joints appear to dictate pedal rate rather than oxygen cost or HR.^[84] However, sensation of muscular effort as measured by RPE, is controversial.^[57] Marsh et al.^[85] reported that RPE may be a critical variable in cadence selection during submaximal power output cycling.

Although higher pedalling cadence demands a greater energy expenditure, it has the advantage of decreasing both actual pedalling force to turn the crank and the ratio of maximal peak tension on the pedal to maximal leg force for dynamic contraction at a given pedal rate.^[75,86] Moreover, it has been reported that the RER ratio for 90 rpm is significantly lower than for 60 rpm.^[87] This finding suggests that many type I muscle fibres, characterised by their high oxidative capacity and adapted for prolonged exercise and mechanical efficiency for contraction, are recruited at higher pedalling rates.^[60,80,82,87] The extent to which these mechanisms are advantageous to the cyclists appear to be related to the cyclist's pedalling skill.^[57,75]

In summary, pedalling cadence, which decreases muscle stress, influences the preferred rate of pedalling. Nonetheless, experienced cyclists do not always select their most economical or efficient cadence relative to $\dot{V}O_2$ for a given power output. Although, terrain and strategy dictate cadence, most professional cyclists select pedalling between 80 and 126 rpm. Increasing pedal cadence, while reducing muscle force, encourages recruitment of type I muscle fibres, thereby minimising type II fibre involvement. Reduced muscle force per pedal revolution during high cadence results in increased circulation and a more effective skeletal muscle pump, thereby enhancement of venous turn. Taken together,

these factors favour the cyclist with a higher percentage of type I muscle fibres. The force demands of the pedal stroke, rather than the velocity of contraction, determines the muscle fibre type recruitment. It is concluded that the optimal pedalling rate is not uniquely specified by the power-velocity relationship of muscle.

8. Cycling Economy

There exist several calculations that relate to cycling economy (CE)/efficiency. The most often used is GE, while work efficiency (WE), net efficiency (NE) and DE are less often addressed in the literature. For baseline, NE and WE have the resting metabolic rate and the energy required by the unloaded cycling, respectively.^[71] Nevertheless, one of the principle determinants of cycling performance is economy/efficiency.

CE is defined as the submaximal $\dot{V}O_2$ per unit of BW required to perform a given task.^[88] Accordingly, enhanced CE is reflected by a decrease in the percentage of $\dot{V}O_{2\max}$ required to sustain a given mechanical work.^[89] It is thought to be the physiological criterion for 'efficient' performance. From both a technical and operational point of view, CE offers a conceptually clear and useful measure for evaluation of cycling performance. Professional cyclists display considerably higher cycling CE and efficiency than amateur cyclists despite similar $\dot{V}O_{2\max}$ values.^[89,90]

Economy is seldom used in cycling, although it has provided valuable information in running.^[91] Research has demonstrated that variations in economy can explain 65.4% of the variation in performance among a group of elite runners similar in $\dot{V}O_{2\max}$.^[92] This same relationship might be true for cyclists since $\dot{V}O_{2\max}$ values, provided a minimum of >65 mL/kg/min is obtained, do not distinguish professional from amateur cyclists.^[89,90] Because of its value to cyclists and coaches, Lucía et al.^[89] recommend that in the future, constant-load exercise protocols, used to measure CE, be included in the 'routine' tests that most competitive cyclists perform several times during the season. CE and GE information made available from constant-load

bouts has applicability complementary to that obtained from other evaluation measures.^[89]

Efficiency is a measure of effective work and is expressed as the percentage of total energy expended that produces external work. Cycling efficiency has been reported to be in the range of 10–25%.^[71] That being the case, then 75–90% of the total energy used to maintain metabolic equilibrium is obtained from adenosine triphosphate hydrolysis and released as heat.^[71]

There is a mounting interest in measures of WE expressed as GE. Toward that end, the formula of Brouwer^[93] is useful. When measures of $\dot{V}CO_2$ and $\dot{V}O_2$ are known, energy expenditure may be determined:

$$\text{Energy expenditure (J/sec)} = ([3.869 \times \dot{V}O_2] + [1.195 \times \dot{V}CO_2]) \times (4.186/60) \times 1000$$

In this instance, GE is calculated as the mean of all data collected in the last 2 minutes of every work rate over and including 95W and until the RER exceeds 1.00.^[94]

$$\text{GE (\%)} = [\text{work rate (J/sec)}] / \text{energy expended (J/sec)} \times 100\%$$

Lucía et al.^[89] found that, in professional world-class cyclists, both CE and GE were inversely correlated to $\dot{V}O_{2\max}$. In this regard, it has been shown that in professional cyclists, the rate of the $\dot{V}O_2$ elicited by gradual increases in exercise workload decreases at moderate to high workloads to the maximum attainable power output. Additionally, mechanical efficiency appears to increase with rising cycling intensity.^[95] Lucía et al.^[89] suggest that a high CE/GE might compensate for a relatively low $\dot{V}O_{2\max}$. GE for the professional cyclists tested was ~24%. CE was calculated as W/L/min, while GE was expressed as the ratio of work accomplished per minute (W converted to kcal/min) to energy expended per minute (in kcal/min). CE of professional cyclists was found to average 85 W/L/min. A two-time world champion cyclist with a $\dot{V}O_{2\max}$ of 70 mL/kg/min recorded a CE >90 W/L/min and a GE of 25%. Factors that may influence GE include pedalling cadence,^[78] diet,^[96] overtraining,^[97] genetics^[98] or fibre-type distribution.^[88]

It is generally agreed that increased GE is an essential determinant of cycling performance. Performance improvement, at least in part, is related to the submaximal variables of GE at the lactate threshold (LT) or at the respiratory compensation point rather than gains in $\dot{V}O_{2\max}$. Moseley and Jeukendrup^[94] found that 35W increments and 3-minute workload stages provided reproducible measures of both GE and CE. It was noted that while DE is suggested to be the most valid estimate of muscle efficiency^[88] it is not the most reliable measure. DE is defined as the ratio of the change in work performed to the change in energy expended.^[71] Moreover, smaller changes in efficiency can be detected in GE compared with DE.

While GE and DE have their limitations, GE is recognised as a poor measure of muscle WE^[71,88,99] but is a better measure of whole-body efficiency;^[71,99,100] consequently, it may serve a more relevant purpose for the cyclist. Until more data are available, it is recommended that both GE and DE be used to assess the cyclist's efficiency.

In summary, enhanced CE is reflected by a decrease in the percentage of $\dot{V}O_{2\max}$ required to sustain a given mechanical work. CE is recommended as part of the 'routine' test series of cyclists throughout the year. World-class cyclists have demonstrated an inverse correlation to $\dot{V}O_{2\max}$ for both CE and GE. In professional cyclists, the rate of the $\dot{V}O_2$ elicited by gradual increases in exercise workload decreases at moderate to high workloads to the maximum attainable power output. Additionally, mechanical efficiency appears to increase with rising cycling intensity. Improvement in cycling performance is best related to submaximal variables of GE at the LT or respiratory compensation point rather than gains in $\dot{V}O_{2\max}$. Both GE and DE are recommended in the assessment of the cyclist's efficiency.

9. Cycling Intensity

Knowledge of the exercise intensity required during cycling competition provides valuable information for the prescription of training regimens. It is interesting to note that at 3 and 5 minutes after

competition of the 1-hour world record, the cyclist's lactate levels were 5.2 and 5.1 mmol/L, respectively,^[3] while the peak HR reached 190 beats/min.^[3] Collectively, the work of Fernández-García et al.^[101] and Padilla et al.^[102] have provided the most comprehensive cycling intensity data collected during the multi-stage road races. Employing laboratory metabolic data collected 2 weeks prior to races, Fernández-García et al.^[101] characterised the cycling intensity utilising HR data recorded every 15 seconds via telemetry. The HR values were then used to establish four heart zones that corresponded to intensities of exercise relative to:

- anaerobic (over the individual anaerobic threshold; around 90% of $\dot{V}O_{2max}$);
- intense aerobic (70–90% of $\dot{V}O_{2max}$);
- moderate aerobic (50–70% of $\dot{V}O_{2max}$);
- recovery (<50% of $\dot{V}O_{2max}$).

Clearly, professional multi-stage cycling races demand long-duration, high-intensity exercise. Fernández-García et al.^[101] observed that cyclists were involved in intense aerobic work of ~75 and ~79 min/day and moderate aerobic work represented ~97 and ~89 min/day during the Vuelta a España and the Tour de France, respectively. During both races, the cyclist spent ~20 min/day over the individual anaerobic threshold. About 93 min/day were spent in flat stages and 123 min/day in mountain stages riding at an intensity >70% of $\dot{V}O_{2max}$ and 18–27 of these minutes were at an intensity >90% of $\dot{V}O_{2max}$. Taken together, ~75% of each stage is spent >50% of $\dot{V}O_{2max}$. In contrast, during ITT, cyclists spend a mean of 20 minutes >90% $\dot{V}O_{2max}$. Lucía et al.^[103] reported that the professional winner of the short road-cycling time trial during the Tour de France sustained 70 minutes at an intensity >90% of $\dot{V}O_{2max}$.

HR data reveal that the HR is related to the course profile rather than being stochastic. In ITT stages, cyclists reached a mean HR of ~171 beats/min and during flat stages a HR mean of ~125 beats/min.^[101] The mean overall HR for the combined tours was observed to be ~134 beats/min for a mean stage time of ~254 minutes.^[101] During flat stage cycling, the combined tour mean HR was ~126

beats/min for a stage time of ~288 minutes.^[101] Interestingly, during the mountain stages, for the combined tours, the mean stage HR was ~132 beats/min for a mean stage time of ~328 minutes.^[101] The low cycling intensity (HR) recorded for the combined tour during mountain stages may be attributable to methodological constraints where the authors were unable to differentiate climbing versus decent HR. Nevertheless, the combined tour mean HR for ITT was ~168 beats/min during a mean time of 45 minutes.^[101]

Two lactate criterion measures of exercise intensity were applied during the tour observations. The LT was identified as the exercise intensity eliciting 1 mmol/L increase in lactate concentration above average baseline lactate values measured when exercising at 40–60% of the maximal aerobic power output.^[104] Based on pre-race laboratory tests, the LT value established for each cyclist was linked to the heart rate (HRLT) and power output (WLT), then termed the LT_{zone}.^[102,105] Secondly, again based on pre-race laboratory tests, the onset of blood lactate accumulation (OBLA = 4 mmol/L)^[102,105] was established for each cyclist then linked to the HR and termed the OBLA_{zone}.^[102] It is noteworthy that the total time spent at and above the OBLA_{zone} during high-mountain stages was similar to that reported for short individual and team time trials (16 minutes). Some cyclists have been observed to spend 80 minutes in the OBLA_{zone}.^[102] High mountain stages accounted for the longest time spent in the LT_{zone}. These data serve a useful purpose for the development of training protocol for stage-racing competition.

Padilla et al.^[102] demonstrated that when exercise intensity recorded during racing is estimated from HR reserve^[106] instead of HR_{max}, values are ~8% lower but close to %W_{max} values. This closeness is good reason to choose the HR reserve method along with individual laboratory HR-power output relationships.^[102] With regard to W_{max} values, approximately 2 weeks prior to each stage race, the cyclists underwent an incremental maximal cycling test. Exercise began with an initial resistance of 100W, with further increments of 35W every 4 minutes, inter-

spersed with 1-minute recovery intervals. A 75 rpm cadence was required.^[102] In this case, W_{\max} was measured as the highest work-load the cyclist can maintain for a complete 4-minute period. When the last work-load cannot be maintained for the complete 4-minute period, W_{\max} is computed as follows:^[107]

$$W_{\max} = W_f + ([t/240] \times 35)$$

where: W_f = value of the last complete work-load; t = time the last uncompleted work-load was maintained (in seconds); 35 = the power output difference between the last two work-loads.

Racing strategy has a significant influence on the HR response. Off-road cross-country cycling competition is shown to demand near maximal effort at the start of the race in order to establish an advantageous starting position. Accordingly, the average HR during such starts has been reported as ~90% of HR_{\max} corresponding to ~84% of $\dot{V}O_{2\max}$.^[108] Moreover, the average exercise intensity of cross-country competitions lasting ~147 minutes is similar to that reported by Padilla et al.^[3] for short road-cycling time trials lasting ~10 and ~39 minutes ($89 \pm 3\%$ and $85 \pm 5\%$ of HR_{\max} , respectively). When the intensity profile is expressed as a percentage of LT, cross-country cyclists have been observed to spend longer time periods at and above LT than road stage-racing cyclists.^[108]

The higher intensity and longer duration at high intensity by off-road cyclists may be partially explained by the demand placed on the cyclist for bicycle control and stabilisation on very rough terrain. Repeated isometric muscle contractions of the arms and legs may influence HR values during off-road racing. However, there is evidence that use of front suspension cycles serve to minimise such a response.^[43]

In summary, professional multi-stage races and off-road cross-country races demand long-duration, high-intensity exercise. In stage races, approximately 75% of each stage is spent at >50% $\dot{V}O_{2\max}$. ITT cyclists spend 20 minutes at >90% $\dot{V}O_{2\max}$, while the winner of the Tour de France sustained 70 minutes at >90% $\dot{V}O_{2\max}$. Mean HR for the combined tours is ~134 beats/min for a mean stage time of

~254 minutes. Total time spent at and above OBLA during high mountain stages is 16 minutes, while some cyclists remain at OBLA for 80 minutes. Off-road cross-country racing demands a starting HR of ~90% HR_{\max} or 84% $\dot{V}O_{2\max}$. The mean intensity of off-road cross-country racing is similar to road-racing time trials and a longer time is spent above LT than road stage-racing cyclists.

10. Muscle Recruitment

Road and off-road bicycle racing call for hill-climbing ability. High mountain stages require uphill cycling during several periods lasting 30–60 minutes. While climbing, the cyclist is confronted with and must overcome the force of gravity and gravity-induced resistance of the body mass.^[109] In response to increased resistance, cyclists frequently switch from the conventional sitting position to a less economical standing posture. Consequently, the cyclist can then exert more force on the pedals but is it economical to do so? Accordingly, Millet et al.^[110] demonstrated that the technical features of standing versus seated position may affect metabolic responses. Toward that end, these investigators discovered that level-seated, uphill-seated, or standing-cycling positions exhibit similar external efficiency and economy in trained cyclists at a submaximal intensity.^[110] In contrast, HR and V_E were found to be higher in a standing as opposed to a seated position. In addition, during a maximal 30-second sprint, the power output was reported to be 25–30% greater in a standing position than when seated.^[110] In the standing position, a higher power output would be expected since the cyclist's BW can contribute to a greater force on the pedal per pedal revolution. Furthermore, pedalling cadence was ~60 rpm, for both seated and standing while climbing, compared with ~90 rpm in level cycling. This study was limited to a single gradient, short duration and different pedal cadences, therefore, the combination of speed, hill gradient and duration that would favour climbing in the seated or standing position remains to be investigated.

The cyclist can generate a high climbing speed of 20 km/hour by using light gears (39×23 – 25) and

high cadences (≥ 90 rpm); however, that is generally not the case. Rather, most cyclists elect to rise off the saddle and push harder gears (39×17 – 21) at relatively low cadences while others remain on the saddle and push hard gears. Standing on the pedals, however, changes the range of motion of the hip joint substantially during the crank revolution. More importantly, the centre of body mass is modified by standing on the pedals.^[111,112] Consequently, standing and seated postures produce different pedal force, crank torque and joint movement profiles.^[111,112] A change in cycling posture suggests that there will be modifications in the patterns of muscle activity. Additionally, alteration of grade accompanied by a change in cycling posture will result in changes in the direction of the force applied to the pedal.^[111]

When climbing, the magnitude and activity of the gluteus maximus, whose function is hip extension, is higher in the standing position than when seated on the saddle. Its activity begins just before the top dead centre of crank position and continues well into the later part of the downstroke, which is not different from the saddle position.^[5] However, the gluteus maximus does not appear to increase extensor moment but rather serves to enhance pelvis stabilisation.^[113] The vastus lateralis, a powerful knee extensor, is observed to be activated earlier in the upward recovery phase and is active longer into the subsequent downward power phase when moving from sitting on the saddle to standing during a climb. During the down-stroke of seated cycling, extensor moments are needed at all three lower extremity joints, except for the knee joint moment that changes from extensor to flexor in the middle of the down stroke.^[114,115]

With a change from the seated to standing position, a distinct alteration in the pelvic angle occurs accompanied by a dramatic increase in muscle activity of the gluteus maximus.^[113] The more forward position of the hip joint in relation to the crank spindle, in the standing posture, reduces the horizontal distance between the hip joint and the point of force application on the pedal. Consequently, this position reduces the moment arm of the vertical

pedal reaction force in relation to the hip joint axis. Calwell et al.^[111] observed this vertical force to be the major component of the pedal reaction force while standing. The vastus lateralis, a one-joint knee extensor, and the rectus femoris, a biarticular extensor, increase their duration of activity with a change to the standing posture. It appears that the single-joint plantar flexor soleus increases ankle plantar flexor moment when standing on the pedals. The rectus femoris, a knee extensor and hip flexor, becomes active for a longer duration in the standing versus seated posture.^[111,112] It is interesting to note that three muscles, the biceps femoris, gastrocnemius and tibialis anterior, appear to display similar activity for both saddle and standing positions.^[114,115]

The activity patterns of mono- and bi-articular muscles have been shown to have different activity patterns with respect to seated and standing uphill conditions.^[113,116] This variance is believed to be due to the possibility that monoarticular muscles contribute to positive work, whereas biarticular muscles control the direction of force applied to the pedal.^[117] The involvement of the biceps femoris appears to be related to the specific pedalling technique of the cyclist. The use of a fixed rather than flexing ankle joint throughout the crank cycle results in different muscle recruitment and coordination.^[117] It should be noted that a limitation of this type of research, if performed in a laboratory where the bicycle ergometer is fixed in place, is the absence of the confounding factor of lateral sway of the bicycle, which occurs in standing while climbing and is commonly observed among cyclists when ascending and sprinting. This sway action could introduce modified muscle activity patterns.

In summary, shifting from a seated to standing posture while cycling changes the magnitude and activity of several key muscle groups whose function is to provide maximum force to the pedals. When standing, the magnitude and activity of the gluteus maximus is higher. Activation of the vastus lateralis is earlier and its duration of activity is longer. Likewise, the rectus femoris increases its duration of activity and the soleus increases ankle

plantar flexion. However, similar activity is observed for the biceps femoris, gastrocnemius and tibialis anterior for the saddle and standing position. Nonetheless, in well trained cyclists and within the limitations of current investigations, economy and gross-external efficiency in seated uphill cycling are not different than in uphill standing cycling. Further research is needed in order to expand our knowledge of those variables that affect uphill cycling performance.

11. Pacing Strategy

Whether racing against the clock or other competitors, finishing in the absolute quickest time possible is the cyclist's goal. Similarly, the objective of time trialing is to maintain the highest sustainable speed for the period. Toward that end, knowledge of the effects of systematic variations in pacing strategy on performance allows the athlete and coach to plan optimal strategy for energy expenditure. Palmer et al.^[118] suggested that varying power may impede time trial performance. Moreover, Foster et al.^[119] reported that the best performance in simulated 2km time trials was attained when the cyclist maintained an even pacing strategy for the duration of the ride. Despite this finding, there were no systematic differences in serial $\dot{V}O_2$, accumulated oxygen deficit, or post-exercise lactate that could account for the even pacing advantage.

Starting strategy may also play an important role for the racing cyclist. Bishop et al.^[120] reported that an all-out start strategy for 10 seconds followed by a transition to even pacing resulted in a significantly greater 2-minute, all-out kayak ergometer performance when compared with an even pacing strategy. These authors found that the average power was significantly greater during the first half of the test using the all-out start strategy, and significantly lower in the second half of the tests when compared with the even strategy. The all-out start strategy resulted in significantly greater $\dot{V}O_2$ at 30 and 45 seconds and a significantly greater total $\dot{V}O_2$.

A small body of research tends to support the strategy of even pacing albeit with a slightly faster steady speed employed during the second half of the

race, which results in a 'negative split'.^[121] In contrast, maintenance of a variable pace throughout a race means that a cyclist will be accelerating and decelerating. This mode of pacing is common among road and off-road racing cyclists. Variable pacing, however, is said to lead to excessive glycogen depletion and premature onset of fatigue. Compared with a variable pace during a 20km time-trial, steady pace riding was shown to be 6% better.^[118] Subsequently, these authors found that time-trial performance was similar when well trained subjects performed prolonged variable interval exercise or constant-load exercise of the same average intensity. Only small differences were observed in skeletal muscle carbohydrate metabolism and muscle recruitment and such differences did not affect the performance of a subsequent bout of high-intensity cycling.^[53] It was concluded that type I muscle fibres were more depleted by constant rather than variable pacing while type II muscle fibres were more depleted of glycogen by variable pacing. Faria et al.^[122] examined the use of HR as variable for pacing strategy. Pacing with HR did not produce significant decreases in time to completion of a given amount of work compared with no pacing.

A basic question raised concerning pacing strategy is whether the lower power output during the downhill/downwind race section will allow sufficient recovery for the cyclist to successfully accomplish a variable power strategy. Swain^[123] demonstrated that modestly increasing power output during uphill/up-wind sections (by as little as 5%) and decreasing power during downhill/downwind sections resulted in faster times as compared with those during a constant power effort. In his computer model, Swain^[123] confirmed that the fastest time when riding in winds or on hills should occur when the cyclist varies power to counter the conditions. This variable power strategy resulted in significant time savings, even when the magnitude of variation was only 5% above and below mean power.

In support of this finding, Liedl et al.^[121] found, using a pacing strategy that deviated $\pm 5\%$ every 5 minutes from the cyclist's mean power output during a 1-hour time trial, imposed no additional physi-

ological stress compared with constant power output. Moreover, Atkinson and Brunskill^[124] tested Swain's computer model with a computer-generated 16.1km course in which the cyclists encounter a headwind on the first half of the course and a tailwind in the second half of the course. These authors^[124] found a significant decrease in time to complete the course when paced by power output. They further found a small but non-significant increase in performance when varying power by +5% into the headwind and -5% in the tailwind. These data suggest that a small variance in pacing will significantly increase ITT performance.^[124]

Counter to intuitive practice, it appears wise to speed up slightly when the cyclist begins to feel heavy legs, rather than to slow down. In this instance, type II muscle fibres begin to work while giving type I muscle fibres a chance to provide more pyruvate to the mitochondria. This practice is followed by Kenyan runners who are the best endurance runners in the world. Along this same line of thinking, Billat et al.^[125] suggest that it is normal for athletes to vary their pace. However, to produce the best possible time it is suggested that the pace should not vary >5% for either the slow or fast side.^[123]

The majority of time-trialing studies have been conducted in the laboratory; however, in reality cycling time trialists must consider which form of pacing might best fit the environment and terrain. Consequently, future field studies are required to confirm the best time-trial protocol.

In summary, common among racing cyclists is a variable pace strategy throughout the race. However, steady pace riding compared with variable pacing has been shown to be 6% better for 20km time trialing. Yet, time-trial performance was shown to be similar when well trained cyclists performed prolonged variable interval exercise or constant-load exercise of the same average intensity. Research suggests that varying power by +5% into the headwind and -5% in the tailwind may be the most effective race pace strategy. In close agreement, other findings suggest that to produce the best possi-

ble race time may it may be best not to vary >5% for either the slow or fast portion of the race.

12. Altitude Acclimatisation

Competitive cycling events are often staged at moderate altitude (1500–2500m). If not given special adaptation consideration, for the lowland native cyclist, altitude may be the nemesis. Consequently, a considerable amount of research has been conducted on short- and long-term altitude acclimatisation and its effects on the performance of endurance athletes at altitude and sea level; however, the weight of scientific evidence remains equivocal.

The positive effects of living and/or training in an environment with decreased partial pressure of oxygen appear to be mediated primarily through increases in haemoglobin concentration, buffering capacity and adaptations in skeletal muscle.^[126] Theoretically, these changes should result in an improvement in endurance exercise performance at both sea level and altitude. Nonetheless, it is apparent from a review of the literature, that methodological technicalities have often been responsible for the lack of consistent evidence in favour of altitude residence for performance at sea level.^[127] Research has been limited by small sample sizes, insufficient or varying durations of altitude exposure, varying altitudes, different types of exposure (hypobaric vs normobaric), unequal training status and lack of adequate controls.^[128,129] Furthermore, past altitude research has been confounded by the use of training as a variable, which elicits similar physiological changes to acclimatisation alone.^[130]

Sea-level endurance athletes that are acutely exposed to even moderate altitudes, 900m^[131] and 580m^[132] have demonstrated significant drops in $\dot{V}O_{2\max}$ and performance. The decline in $\dot{V}O_{2\max}$ has been documented in athletes^[132] and trained subjects^[133] to begin as low as ~600m. For every 1000m increase above 1050m, Robergs and Roberts^[133] reported an 8.7% decrement in $\dot{V}O_{2\max}$. A decrement in aerobic exercise performance at an altitude of 2240m above sea level may approach 7%.^[134] Furthermore, this decrement is increased to 12% at 2286m.^[135] In trained subjects, the reduction

in oxygen saturation (SaO_2) with increasing hypoxia accounts for around 86% of the variance in the decrement in $\dot{V}\text{O}_{2\text{max}}$.^[136] It is interesting to note that athletes with a $\text{SaO}_2 < 90\%$ during maximal sea-level exercise display a significant decline in $\dot{V}\text{O}_{2\text{max}}$ during acute exposure to a mild altitude of $\sim 1000\text{m}$.^[137] However, trained athletes who maintain a $\text{SaO}_2 > 92\%$ during maximal sea-level exercise do not display a significant reduction in $\dot{V}\text{O}_{2\text{max}}$ at 1000m .^[138] Trained cyclists residing at moderate altitude ($1800\text{--}1900\text{m}$) have been shown to have an $\text{SaO}_{2\text{max}}$ significantly higher by 5% during hyperoxia versus normoxia.^[138] Furthermore, moderate altitude-acclimatised athletes appear to preserve oxyhaemoglobin saturation at sea level.^[138]

Consequently, to meet the challenge of racing above sea level, cyclists have used various novel approaches and regimens for altitude training. The method called 'live high/train low' has recently received much attention. Toward that end, a 2- to 4-week stay at moderate altitude has afforded acclimatisation resulting in a decreased production or increased clearance of lactate and moderate improvement of muscle buffering capacity.^[130] Furthermore, it appears that acclimatisation to moderate altitude does not include increased red cell production sufficiently to increase red cell volume and haemoglobin mass.^[130] Nevertheless, hypoxia does increase serum erythropoietin levels but only weak evidence exists of an increase in young red blood cells (reticulocytes).^[130] Living and training at moderate altitude does not appear to improve sea-level performance of highly trained athletes. Living at altitude and training near sea level may be effective for some cyclists; however, more research is required to confirm its efficacy.

With acute exposure to altitude, subjects demonstrate increased ventilation and increased diuresis. Both of these responses increase fluid losses and subsequently decrease plasma volume. The more prolonged the exposure, the greater the decrement in fluids and presumably the greater the decrement in performance. This response has lead Daniels^[139] to suggest that lowland athletes stay low for as long as

possible prior to competing at altitude to minimise the drop in $\dot{V}\text{O}_{2\text{max}}$ at altitude.

The other option presented by Daniels^[139] was to ascend to the competition site early to undergo acclimatisation to the altitude. Indeed, Fulco et al.^[140] have pooled submaximal and maximal data and shown significant increases in submaximal performance following acclimatisation, with very little change in $\dot{V}\text{O}_{2\text{max}}$ following acclimatisation. However, full acclimatisation can take several weeks and is therefore not practical for most athletes. Although it is often more inconvenient, many athletes sleep at a low altitude until the morning of the event and then are transported to the competition site early in the morning. This practice may not be necessary and may be unwise.

Weston et al.^[141] examined performance after arrival at 1700m following 6, 18 and 47 hours of exposure. These authors reported that the greatest drop in performance was following 6 hours with improvement in performance following 18 hours and no further improvement following 47 hours. These data suggest that an overnight stay at the altitude competition venue may be of value rather than detriment. Similarly, in an unpublished observation, Parker et al. examined changes in $\dot{V}\text{O}_{2\text{max}}$ following an overnight stay in a hypobaric chamber decompressed to 440 Torr ($\sim 4300\text{m}$). Following a 13-hour exposure, these authors reported no significant changes in $\dot{V}\text{O}_{2\text{max}}$ and arterial oxygen saturation. Parker et al. did report significant decreases in BW, leg muscle cross-sectional area and plasma volume due to increased diuresis. Despite the decrement in plasma volume, $\dot{V}\text{O}_{2\text{max}}$ was retained. Robergs et al.^[142] previously found that maintaining arterial oxygen saturation and decreasing leg muscle size would minimise the drop in $\dot{V}\text{O}_{2\text{max}}$ at altitude and may serve as an explanation for how the acute responses of hyperventilation and increased diuresis observed by Parker et al. maintained $\dot{V}\text{O}_{2\text{max}}$ (unpublished observation). The increased diuresis and hyperventilation as a result of altitude exposure that Daniels^[139] was trying to avoid may in fact be advantageous rather than compromising to performance at altitude. The decline in fluid volume at

altitude decreases muscle volume, thus diffusion distance in the muscle to help maintain oxygen delivery. Furthermore, the hyperventilation observed at altitude has the advantage of shifting the oxyhaemoglobin curve to the left and protecting SaO_2 during intense exercise.^[143] Therefore, it appears that the more appropriate recommendation for cyclists that are going to compete at altitude is ascend to the competition the day before to undergo partial acclimatisation.

Past literature on altitude acclimatisation reveals that following ≥ 10 days of exposure to moderate altitude, a significant improvement is seen in physical work capacity at altitude^[144] and a reduction in plasma lactate occurs when subjects exercise at the same power output.^[145] More importantly, these changes occur without a significant change in $\dot{V}\text{O}_{2\text{max}}$.

Cycling at altitude has special circumstances in relation to effects on performance. For example, there has been a definite drop in $\dot{V}\text{O}_{2\text{max}}$ demonstrated at altitude, but performance at altitude may actually improve despite this drop in $\dot{V}\text{O}_{2\text{max}}$. Since the primary source of resistance in cycling is air moving over the body of the cyclists, the lower barometric pressure at altitude leads to a decrease in air resistance. Using the equations of motion of Di Prampero et al.^[20] for a theoretical drop in $\dot{V}\text{O}_{2\text{max}}$ of 5% at an altitude of $\sim 1500\text{m}$ would actually lead to an increase in speed of 4%. This response, however, is only true for level ground cycling, the oxygen cost of hill climbing stays very close to the same at altitude. These equations suggest that cycling performance at moderate altitude is improved on flat terrain despite drops in $\dot{V}\text{O}_{2\text{max}}$, while hilly terrain performance will drop proportionately with the drop in $\dot{V}\text{O}_{2\text{max}}$. Moreover, during most aerobic competitive cycling events, athletes perform at intensities below that which elicits $\dot{V}\text{O}_{2\text{max}}$. Fulco et al.^[140] have commented that submaximal exercise performance decrements are difficult to predict based on the decline in $\dot{V}\text{O}_{2\text{max}}$, since the measurement of $\dot{V}\text{O}_{2\text{max}}$ represents only the maximal aerobic contribution, whereas differing proportions of aerobic and anaerobic processes are involved in exercise of various intensities and durations.

In summary, adaptations to altitude are mediated primarily through increases in haemoglobin concentration, buffering capacity and adaptations in skeletal muscle. For every 1000m increase above 1050m there is an 8.7% decrease in $\dot{V}\text{O}_{2\text{max}}$. Reduction in SaO_2 with increasing altitude accounts for around 86% variance in $\dot{V}\text{O}_{2\text{max}}$ decrement. However, $\dot{V}\text{O}_{2\text{max}}$ alone is not valid indicator of submaximal exercise performance. Nonetheless, trained athletes who maintain a $\text{SaO}_2 > 92\%$ during maximal sea-level exercise do not display a significant reduction in $\dot{V}\text{O}_{2\text{max}}$ at 1000m. Because full acclimatisation to altitude can take several weeks, it is not practical for most athletes. It appears that cyclists who are going to compete at altitude, but who are limited in altitude acclimatisation resources, should ascend to the competition the day before to undergo partial acclimatisation.

13. Performance Modelling

Performance modelling is employed to estimate the power required to perform individual and team pursuits under a variety of cycling conditions. Additionally, the power required to cycle at a certain speed can be estimated by adjusting the model for important factors affecting cycling performance.

While recent development of the SRM bicycle crank dynamometer has made it possible to accurately measure cycling power output, theoretical modelling serves as an alternative method. As such, modelling remains useful to athletes, coaches and researchers who might want to estimate the power required to establish new cycling records under various conditions. Since 1876, the distance for the prestigious 1-hour cycling record has been doubled. Mathematical models have been used to predict the power requirements needed to better the 1-hour record, 4000m team and individual pursuit races, and other competitive events. Physiological, aerodynamic and equipment-related modelling has proven to be a valuable guide for the prediction of successful performance.^[13] Since 1967, $\sim 60\%$ of the improvement in the 1-hour record has come from aerodynamic advances and $\sim 40\%$ for higher power outputs.^[13] The world 1-hour record of 56.375km set by

Chris Boardman in 1996 was accomplished employing a power output of 442W.^[13]

Factors such as body mass, height, saddle position of the cyclist, type and aerodynamic characteristics of the bicycle and cyclist's apparel, rolling resistance of the surface, wind, temperature, air density, humidity and many more have proven valuable in the prediction of performance.^[13] More importantly, modelling is useful to further improve training protocol and testing for potential racing success. Practically, theoretical calculations applied during pre-competition allow for effective strategy modification.

The validation of various models is generally accomplished utilising metabolic data, power output variables and practical testing.^[146] Models enable an estimate of performance impact of changes in physiological, biophysical, biomechanical, anthropometric and environmental parameters. Numerous researchers have demonstrated reasonable accuracy of performance modelling.^[7,13,114,146-152] Moreover, modelling software predicts that, for a trained cyclist (riding an average of 300W over 40km), a 1% improvement in efficiency will result in a 63-second improvement in a 40km time-trial time.^[94]

Pursuit and time-trial racing requires high aerobic and anaerobic power and special aerodynamic characteristics. Modelling affords the opportunity to evaluate in advance the cyclist's potential for top performance. Toward that end, the work of several investigators has provided important basics for the modelling of cycling performance.^[146-150] For instance, the energy cost factor for the interchange of front cyclist in the 4000m team pursuit, when exposed unshielded from team-mates (one-fifth of a lap) has been estimated to be 0.7697.^[147] Research evidence reveals that power (W) at increasing speed is dependant on the track characteristics and rolling resistance (K) and A_f of the cyclist.^[147] Taking into consideration these dependent variables, a theoretical model was designed to predict individual and team pursuit times by utilising either direct field or laboratory power measurements or by estimating power from actual individual pursuit performances.^[147] The following equation yields an expres-

sion for the average team pursuit power as a function of velocity:^[147]

$$P = 0.7697 K(0.00953 M_t V + 0.0075V^2 + K_1 (A_f) 0.007551V^3)$$

where: P = power (W); K = constant describing track characteristics and rolling resistance; M_t = mass of cyclist and bike (kg); V = speed (km/hour); K_1 = constant describing aerodynamic factors; A_f = frontal area of the cyclist, calculated as $A_f = 0.0293 \times \text{height}^{0.725} \times \text{weight}^{0.425} + 0.0604$; and 0.7697 = correction factor for team pursuit.

The constant K, which is usually around 1, quantifies the influence of aerodynamic factors and is calculated as follows:

$$K_1 = K_d \times K_{p0} \times K_b \times K_c \times K_h$$

where: K_d = density ratio (1 at sea level, 0.78 at 2500m altitude); K_{p0} = position of the cyclist on the cycle (1.08–1.18 for standard position, 1 for standard aero position); K_b = bicycle-related factor (1 for standard cycle, 0.93 for aerodynamically optimised track cycle); K_c = clothing (1 for aerodynamic skin suit, 1.09 for long sleeve jersey); K_h = helmet (1 for aero time-trial helmet, 1.025 for conventional cycle helmet).

Related factors include bicycle weight, disk wheels, front and rear wheel diameter, tyre construction, inflation pressure, gear ratio and rpm.

Padilla et al.^[3] have demonstrated the validity of mathematical models that integrate the main cycling performance-determining variables that predict velodrome cycling performance. It is interesting to note that the FA value of 1-hour cycling record holders represent ~18.1% of their BSA. Consequently, some may find it useful to apply this FA to BSA relationship when selecting potential 1-hour record competitors.

A model of cycling performance based on equating two expressions for the total amount of work performed was designed by Olds et al.^[150] One expression was deduced from biomechanical principles deriving energy requirements from total resistance. The other models the energy available from aerobic and anaerobic energy systems, including the effect of $\dot{V}O_2$ kinetics at the onset of exercise. Like other models, the equation can then be solved for

any of the variables. Empirically derived field and laboratory data were used to assess the accuracy of the model.^[150] Model estimates of 4000m individual pursuit performance times showed a correlation of 0.803 ($p \leq 0.0001$) with times measured in 18 high-performance track cyclists, with a mean difference (predicted-measured) of 4.6 seconds (1.3% of mean performance time).^[150] This model enables estimates of the performance impact of alterations in physiological, biomechanical, anthropometric and environmental parameters. Additionally, Olds et al.^[151] presented a cycling efficiency model for road-cycling time-trial performance. It includes corrections for the effect of winds, tyre pressure and wheel radius, altitude, relative humidity, rotational kinetic energy, drafting and changed drag. Relevant physiological, biophysical and environmental variables were measured in 41 experienced cyclists completing a 26km road time trial. The model yielded 95% confidence limits for the predicted times and suggested that the main physiological factors contributing to road-cycling performance are $\dot{V}O_{2\max}$, fractional utilisation of $\dot{V}O_{2\max}$, mechanical efficiency and projected FA. The model was applied to some of the following practical problems in road cycling:

- the effect of drafting;
- the advantage of using smaller front wheels;
- the effects of added mass;
- the importance of rotational kinetic energy;
- the effect of changes in drag as a result of changes in bicycle configuration;
- the normalisation of performances under different conditions;
- the limits of human performance.

This model predicted a 3% improvement in 26km time-trial time with a 1 standard deviation improvement in GE.

Van Soest and Casius^[153] present a modelling/simulation approach to pedalling rate in sprint cycling in which the movement is calculated from the neural input to muscles. Furthermore, others^[154] have reported that maximal power output has been found to be sustainable for only approximately 5 seconds at a pedalling rate of 120–130 rpm. Van Soest and Casius^[153] identify three factors as having

an impact on the optimal pedal rate. First, from the perspective of the power-velocity relationship, optimal pedalling rate is one that allows as many muscles as possible to actively contract close to the velocity at which power production is maximal.^[76,153] A second factor that influences optimal pedalling rate is the process of calcium release and reuptake from the sarcoplasmic reticulum.^[153] The third factor is pedal forces that are so high that the upper body loses contact with the saddle, resulting in a change of the mechanical system.^[152] Accordingly, the authors elected to fix the pelvis to the saddle to circumvent this issue. These investigators discovered that activation dynamics was a major determinant of the pedalling rate that maximises mechanical power output of the model during sprint cycling.^[153] The results of the study showed that activation dynamics is a major determinant of the pedalling rate that maximises mechanical power output of the model used during sprint cycling. The authors comment that this study presents a strong case, in that both model structure and parameter values were taken from previous work on vertical jumping.^[155] The model structure and parameter values used in this study provide a description of the musculoskeletal system involved in the task of sprint cycling. Moreover, it was shown that the muscle spends a large fraction of total metabolic work on pumping calcium ions back into the sarcoplasmic reticulum. Accordingly, fast sarcoplasmic reticulum calcium is a prerequisite for high mechanical power output.^[153] It was concluded that the optimal pedalling rate is not uniquely specified by the power-velocity relationship of muscle.

Heil^[156] developed a generalised allometric model (GMA) of endurance time-trialing cycling performance:

$$S_{\max} = (R_{\text{NET}}) \times (W_{S(\max)})$$

where: $W_{S(\max)}$ = maximal metabolic steady-state power supply capable of directly resisting R_{NET} during a time-trial performance; R_{NET} = net resistance to forward motion (N) and the sum of aerodynamic drag (R_D , N) and gravitational (R_G , N) resistance.

The GMA predicted that larger cyclists are favoured to win endurance time-trial races when the road incline is downhill, flat or slightly uphill (grade 1.5°), while lighter cyclists were favoured during steep uphill races (grades $>2^\circ$).^[156] These findings are compatible with the work of Capelli et al.^[7] and Swain.^[15] At slight incline, however, the GAM predicted that cycling time-trial performance would be independent of body mass. The author^[156] comments that the GMA is useful to coaches, athletes and sport sciences in evaluation of the optimal body mass for the 1-hour record and for development of laboratory protocol that accurately mimics the physiological demands of uphill time-trial cycling. Furthermore, it could be useful in creating tests specifically for youth talent identification.

In summary, theoretical models are designed to predict individual and team performance by utilising either direct field or laboratory measurements. Performance modelling focuses on numerous dependent variables, which are critical for the cyclist's potential optimal performance. Among those variables are the musculoskeletal determinants of the optimal pedalling rate in sprint cycling. It was concluded that the optimal pedalling rate is not uniquely specified by the power-velocity relationship of muscle.

14. Conclusion

This review has taken a macroscopic approach, which characterises cycling performance as a global phenomenon dependent on the interrelationship between various metabolic, biomechanical and technological factors. Each of these factors may play an important role in the potential to optimise cycling performance. Future cycling research should continue to be heavily influenced by emerging technology. There are many challenges facing cycling scientists who must harness the new technologies and take an aggressive stance in bringing new information to the sport of cycling. By harnessing other disciplines, i.e. tapping fields of human biology, biomechanics and engineering, interdisciplinary basic and applied research will then contribute new knowledge to the science of cycling.

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Correspondence and offprints: Dr *Irvin E. Faria*, 3731 Dell Road, Carmichael, CA 95608, USA.
E-mail: irvfaria@saclink.csus.edu