The Physiology of Mountain Biking

Article *in* Sports Medicine · January 2007

DOI: 10.2165/00007256-200737010-00005 · Source: PubMed

2 authors:

Franco M Impellizzeri
University of Technology Sydney

Samuele M Marcora
University of Bologna

REVIEW ARTICLE

Sports Med 2007; 37 (1): 59-71
0112-1642/07/0001-0059/$44.95/0

The Physiology of Mountain Biking

Franco M. Impellizzeri[1] and *Samuele M. Marcora*[2]

1 Human Performance Laboratory, MAPEI Sport Research Center, Castellanza (VA), Italy
2 School of Sport, Health and Exercise Sciences, University of Wales, Bangor, UK

Contents

Abstract

Mountain biking is a popular outdoor recreational activity and an Olympic sport. Cross-country circuit races have a winning time of ≈120 minutes and are performed at an average heart rate close to 90% of the maximum, corresponding to 84% of maximum oxygen uptake ($\dot{V}O_{2max}$). More than 80% of race time is spent above the lactate threshold. This very high exercise intensity is related to the fast starting phase of the race; the several climbs, forcing off-road cyclists to expend most of their effort going against gravity; greater rolling resistance; and the isometric contractions of arm and leg muscles necessary for bike handling and stabilisation. Because of the high power output (up to 500W) required during steep climbing and at the start of the race, anaerobic energy metabolism is also likely to be a factor of off-road cycling and deserves further investigation. Mountain bikers' physiological characteristics indicate that aerobic power ($\dot{V}O_{2max}$ >70 mL/kg/min) and the ability to sustain high work rates for prolonged periods of time are prerequisites for competing at a high level in off-road cycling events. The anthropometric characteristics of mountain bikers are similar to climbers and all-terrain road cyclists. Various parameters of aerobic fitness are correlated to cross-country performance, suggesting that these tests are valid for the physiological assessment of competitive mountain bikers, especially when normalised to body mass. Factors other than aerobic power and capacity might influence off-road cycling performance and require further investigation. These include off-road cycling economy, anaerobic power and capacity, technical ability and pre-exercise nutritional strategies.

Modern mountain biking started in the US in the 1970s and is now one of the most popular outdoor recreational activities in the world. Despite some decline in the last 5 years, mountain bikes still represent about one-third of all bicycles sold each year in the US and Europe.[1,2] Official competitions began in the early 1980s, and the Union Cycliste Internationale (UCI) now identifies three types of mountain bike event: cross-country, downhill and stage races.[3] The first World Championship was organised by the UCI in 1990, and the first World Cup series was set the following year.[4] The cross--country circuit race (now named the Olympic cross-country by the UCI) is the most popular mountain biking competitive event and was included as an official Olympic sport in the 1996 Atlanta Summer Olympic Games. During a whole competitive season, there are several competitions other than the World Championship and the World Cup (classified as category CM and WC by the UCI, respectively): continental championships (Cat. CC), stage races (Cat. SHC, S1 and S2) and 1-day races (Cat. HC, C1, C2 and C3). This racing calendar allows mountain bikers to compete once a week for 9 months a year.

In recent years, competitive mountain biking has attracted the interest of sport scientists, and a small but growing number of physiological studies have been published. The aim of this review is to provide a synthesis of this literature and directions for future research. An excellent review on the energy cost of riding bicycles with shock absorption systems has been published recently,[5] so this area of research will not be reviewed here. In the literature, the terms "mountain bikers" and "off-road cyclists" are commonly and interchangeably used, and are employed in this paper to indicate cross-country cyclists unless specified otherwise.

1. The Physiological Demands of Cross-Country Competitions

1.1 Race Characteristics

A cross-country circuit race is a mass-start endurance competition that involves completing several laps of an off-road circuit. According to UCI rules,[3] the course should include forest roads and tracks, fields, and earth or gravel paths, and involve significant amounts of climbing and descending. Typically, the course is between 6km and 9km long, with an average total altitude climb of about 1500m (see an example of a course profile in figure 1). The UCI suggests a differentiated number of laps leading to an optimal competition winning time of 120–135 minutes for men and 105–120 minutes for women. The starting grid is defined according to the UCI point system (during international events) and/or the national point system for national races. This rule allows the best cyclists to start in the front to avoid being slowed down by lower-standard riders. Contrary to road cycling, during the race, off-road cyclists cannot receive any technical assistance. For this reason, mechanical problems can sometimes cause delays that negatively and irremediably influence performance.

1.2 Exercise Intensity Profile

To date, only two studies have described the exercise intensity profile of cross-country circuit competitions. In the first of these studies, we used heart rate (HR) to quantify exercise intensity during four international races (average altitude climbed 1430m and mean competition time of 147 minutes) in a group of high-level cross-country mountain bikers.[6] Exercise intensity was classified in three different zones based on the HR corresponding to two different lactate thresholds (LT) measured during incremental exercise tests in the laboratory. The first was the LT defined as the intensity that elicited a 1 mmol/L increase in blood lactate concentration above the average value measured during exercise between 40% and 60% of maximum oxygen uptake ($\dot{V}O_{2max}$). The second threshold was that corresponding to a blood lactate concentration of 4 mmol/L (the so-called onset of blood lactate accumulation [OBLA]). This analysis (figure 2) revealed that exercise intensity during cross-country competitions is high, with 82% of total race time spent above LT. The average HR during competitions was 90% of the maximum, which corresponds to 84% of $\dot{V}O_{2max}$ measured in the laboratory. Stapelfeldt et al.[7] confirmed and extended our findings by measuring both HR and power output over 15 races. During the races, average HR was 91% of the maximum, and mean power output was 246W or 3.5 W/kg. In addition, Stapelfeldt et al.[7] measured high power output oscillations (69% coefficient of variation), indicating that cross-country events are high-intensity activities characterised by intermittent effort. The authors analysed exercise intensity using the power outputs corresponding to the aerobic threshold (AT) and the individual AT (IAT). The AT was defined as the minimum lactate/$\dot{V}O_2$ ratio, whereas IAT was determined as 1.5 mmol/L above the AT. Using this method, Stapelfeldt et al.[7] found that 39% of total race time was spent at power outputs below AT, 19% between AT and IAT, 20% between IAT and the maximal power output measured during an incremental exercise test, and 22% above this level. In spite of differences in time spent in various intensity zones (probably as a result of the different methods used to quantify the exercise intensity), both studies suggested that cross-country races require high rates of aerobic energy production.

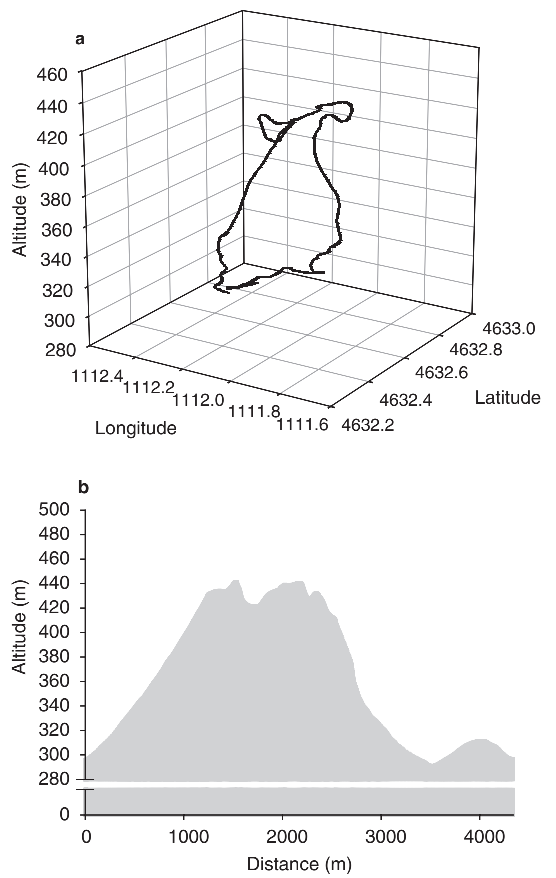

Fig. 1. Example of a course profile for an Olympic cross-country circuit race. (**a**) Shows a 3-dimensional representation and (**b**) a 2-dimensional representation.

1.3 Factors Affecting Exercise Intensity in Mountain Biking

When cross-country races are compared with road cycling competitions,[8-12] it is apparent that exercise intensity, with the exception of well motivated professional road cyclists during time trials,[10] is higher during off-road cycling. This difference could be easily explained by the longer duration of road stage races (4–6 hours) and the cyclists' tactics to cope with this.[13,14] Furthermore, although during road competitions it is possible to reduce energy expenditure by cycling behind other riders,[15] situations in which drafting is useful (high-speed and group cycling) are less frequent during off-road competitions. Other factors might also contribute to the high exercise intensity typical of off-road cycling. For example, the repeated climbs and descents on gravel roads and field trails that characterise cross-country competitions, and the higher mass of mountain bikes may partly account for some of the

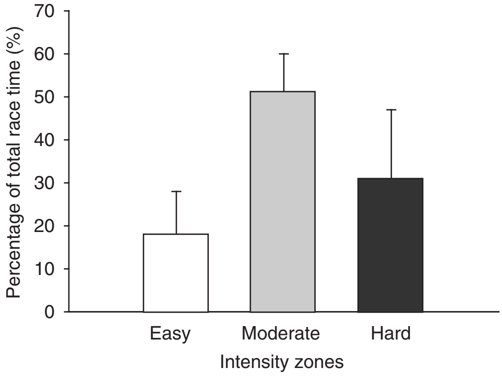

Fig. 2. Percentage of total race time (147 minutes) spent at exercise intensity (heart rate) below lactate threshold (LT) [easy], between LT and onset of blood lactate accumulation (OBLA) [moderate] and above OBLA (high). Based on data from Impellizzeri et al.[6]

difference in exercise intensity compared with on-road cycling.[16] Based on an estimate of the energy cost of cycling on a flat surface, Berry et al.[16] demonstrated a significantly higher $\dot{V}O_2$ (7–20 mL/kg/min) while riding on difficult terrain condition simulated in a laboratory setting by placing a 3.8cm height bump on the treadmill belt. As the difference in rolling resistance as a result of knobbly and larger tyres (1–2 mL/kg/min) was accounted for, the authors suggested that most of the increase in energy cost is caused by the higher rolling resistance associated with the simulated difficult terrain conditions. However, this important finding needs to be confirmed by a properly controlled study.

Higher energy expenditure might also be caused by the intense and repeated isometric muscle contractions of arms and legs required to absorb shock and vibrations caused by difficult terrain conditions, and for handling and stabilising the bike during off-road cycling.[17] Isometric muscle contractions can also increase the HR response to submaximal cycling without any change in energy expenditure[18] and may explain, at least in part, the higher mean HR during off-road cycling compared with on-road cycling. However, the use of front suspension bikes similar to those used by the majority of competitive off-road cyclists reduces average mean HR while cycling on a flat, looped course with fabricated bumps, compared with rigid bikes, although $\dot{V}O_2$ was not different between the two conditions.[19] In addition, the effect of isometric muscle contractions on HR is less evident at the high exercise intensity typical of cross-country races.[18] More studies are necessary to clarify the influence of isometric contractions on the physiological response to off-road cycling and to investigate the potential positive effect of strength training of the arm and leg muscles on performance.

Another factor that may partly explain the high exercise intensity profile of off-road cycling competitions could be the dissociation between HR and power output during the descents. Indeed, Stapelfeldt et al.[7] showed high oscillations in power output during the race while HR remained relative constant. In particular, HR seems to decrease to a lesser extent compared with power output during descents.

1.4 Pacing

Although a uniform pace seems to be the most advantageous for cycling time trials,[20-22] during cross-country competitions a different strategy is commonly used. In fact, both Impellizzeri et al.[6] and Stapelfeldt et al.[7] measured HRs close to maximum soon after the start of the race. This is not surprising, as the initial phase of cross-country competitions, unlike road stage races, is crucial for overall performance. Mountain bikers try from the start to place themselves in the front positions to avoid slowing down when the road narrows into single-track trails and overtaking becomes difficult. After this initial very high intensity phase, HR tends to decrease in parallel with an increase in lap time.[6,23] A decline in exercise intensity during a simulated off-road cycling competition (three 10-mile laps in the heat) has also been demonstrated by Wingo et al.[23] using blood lactate measurements. The authors measured values between 8.1 and 9.1 mmol/L after the first lap, which dropped in the last lap to 5.7–6.0 mmol/L, despite a rest period of 8 minutes between each lap for blood sampling and other measurements. A similar decline in blood lactate concentration was measured in five mountain bikers in the Italian national team during a cross-country race lasting 145 minutes.[24] In that study, blood lactate values were 10–11 mmol/L after the first 45 minutes of the race and 4.0–4.5 mmol/L in the last 20 minutes. A similar blood lactate profile has been reported for cycling time trials with a fast starting strategy.[22]

1.5 Anaerobic Energy Contribution

The above-mentioned blood lactate data not only confirm the decline in exercise intensity measured with HR but also suggest a significant contribution of anaerobic metabolism to the energy requirements of off-road cycling. However, with the exception of these blood lactate measurements during simulated or actual competition, no other studies have investigated the anaerobic energy system during off-road cycling competitions. Further research using other methods is crucial, as this information might be useful for programming aerobic and anaerobic training in mountain bikers. For example, accumulated oxygen deficit is likely to be high, given that direct measures of power output during cross-country races have shown high variations, with values up to 500W during uphill cycling.[7] Furthermore, high power output is required at the start of the race.[7]

2. The Physiological Profile of Mountain Bikers

2.1 Anthropometric Characteristics

The mean height of competitive mountain bikers is between 176cm and 180cm (table I). The average body mass of the first 10 off-road cyclists in the final ranking of the Athens 2004 Summer Olympic Games was 67kg ± 4kg.[25] This value is similar to that reported in recent studies of elite and high-level off-road cyclists (65–69kg)[26,27] [table I]. Lee et al.[27] reported that the average body mass of mountain biking world champions from 1997 to 2000 was ≈60kg. However, data from the 2001–4 world champions revealed an average body mass of 72kg. Furthermore, two of the most successful competitive mountain bikers (at the time of the Athens 2004 Olympic Games), Bart Bretjens and Miguel Martinez, have a body mass of 77kg and 55kg, respectively. These data argue against an important association between body mass *per se* and performance.

What seems more important is body composition. In fact, the average percent body fat has been reported to be <6.4% in high-level off-road cyclists[26,27] and between 8.5% and 14.3% in elite mountain bikers,[23,30,34] suggesting an association between relative body composition and competitive level. This is not surprising, given the advantage of having a low inert body mass for the climbs that are characteristic of cross-country race courses.[36]

Table I. Maximum oxygen uptake ($\dot{V}O_{2max}$) and anthropometric characteristics of male off-road cyclists reported in the literature

Study (year)	Competitive level	n	Height (cm)	Mass (kg)	$\dot{V}O_{2max}$ (mL/kg/min)
Impellizzeri et al. (2005)[26]	Elite, high level	12	176 ± 7	66 ± 6	76.9 ± 5.3
Lee et al. (2002)[27]	High level	7	178 ± 7	65 ± 7	78.3 ± 4.4
Impellizzeri et al. (2005)[28]	Elite	13	177 ± 8	65 ± 6	72.1 ± 7.4
Nishii et al. (2004)[29]	Elite	8	170 ± 6	64 ± 7	67.8 ± 5.8
Stapelfeldt et al. (2004)[7]	Elite	9	180 ± 6	69 ± 5	66.5 ± 2.6
Warner et al. (2002)[30]	Elite	16	178 ± 5	71 ± 5	67.4 ± 4.6
Impellizzeri et al. (2002)[6]	Elite	5	175 ± 3	64 ± 5	75.9 ± 5.0
Baron (2001)[31]	Elite	25	179 ± 5	69 ± 7	68.4 ± 3.8
Wilber et al. (1997)[32]	Elite	10	176 ± 7	72 ± 8	70.0 ± 3.7
Cramp et al. (2004)[33]	Amateur	8	179 ± 6	69 ± 8	60.0 ± 3.7
MacRae et al. (2000)[34]	Amateur	6	180 ± 7	77 ± 4	58.4 ± 2.3
Berry et al. (2000)[35]	Amateur	8 (1 female)	178 ± 7	72 ± 8	56.6 ± 5.2

However, these findings need to be confirmed by studies of elite and sub-elite off-road cyclists using the same method of body composition analysis.

2.2 Maximum Oxygen Uptake

$\dot{V}O_{2max}$ is considered to be a valid indicator of the integrated function of respiratory, cardiovascular and muscular systems during exercise and an important determinant of endurance performance.[37] Therefore, it is not surprising to find in the literature reports of $\dot{V}O_{2max}$ values between 66.5 and 78 mL/kg/min in competitive mountain bikers of various levels (table I). The analysis of these reports suggests an association between $\dot{V}O_{2max}$ and competitive level, with values >70 mL/kg/min a prerequisite for high-level cross-country performance.

Data collected on downhill specialists of the Italian national team[24] showed $\dot{V}O_{2max}$ values of 63.2 mL/kg/min, suggesting that, for downhill, high aerobic power is less important than in cross-country events. To the best of our knowledge, there are no other studies on the physiological characteristics of downhill specialists.

2.3 Ventilatory and Lactate Thresholds

The exercise intensity profile of cross-country circuit races suggests that off-road cyclists should possess the ability to sustain high work rates for a prolonged period of time. This has been confirmed by several studies on the ventilatory threshold and LT. Wilber et al.[32] showed an LT (defined as an exponential increase in lactate above baseline) corresponding to 77% of $\dot{V}O_{2max}$ in cyclists in the national team of the National Off-Road Bicycle Association. Similarly, Impellizzeri et al.[6,28] reported intensities at LT and OBLA corresponding to 75–77% and 85–89% of $\dot{V}O_{2max}$, respectively, in competitive off-road cyclists. In top-level Australian mountain bikers, Lee et al.[27] measured an LT (determined using a modified D-max method[38]) corresponding to 86% of $\dot{V}O_{2max}$. High relative intensity has also been reported for the respiratory compensation point (87% of $\dot{V}O_{2max}$) in high-level mountain bikers. These values are similar to the lactate and ventilatory thresholds reported in professional road cyclists.[13,14] Notwithstanding methodological differences, all these studies demonstrate that off-road cyclists can utilise a high percent of their maximum aerobic power to produce the high and prolonged work rates required for cross-country competitions.

2.4 Anaerobic Power and Capacity

Although anaerobic power and capacity may be important for meeting the physiological demands of off-road cycling competitions, to date, only one study has been published in this area. Baron's[31] investigation compared a group of national- and international-level off-road cyclists with a group of sport science students. As expected, during an incremental test (40W every 4 minutes), mountain bikers had a higher $\dot{V}O_{2max}$, peak power output and power output at OBLA compared with the sport science students. In addition, significant between-group differences in anaerobic power were found (14.9 vs 13.3 W/kg), as measured by a series of 10-second isokinetic cycling tests at different cadences. Unpublished data collected in our laboratory in six national-level mountain bikers revealed a similar peak power output of 14.2 W/kg. These preliminary findings suggest that, once again, anaerobic power should be further investigated, as it may have implications for training and testing of off-road cyclists.

2.5 Comparisons with On-Road Cyclists

Two published studies have directly compared the physiological characteristics of off-road cyclists and road cyclists.[27,32] Wilber et al.[32] reported slightly lower $\dot{V}O_{2max}$, peak power output (25W every 1 minute), and both absolute and relative power output and $\dot{V}O_2$ at the LT in the National Off-Road Bicycle Association team compared with the United States Cycling Federation on-road cycle team. More recently, Lee et al.[27] compared the physiological and anthropometric characteristics of Australian top-level mountain bikers and professional road cyclists and found no significant differences between groups in peak oxygen uptake ($\dot{V}O_{2peak}$), peak power output (50W every 5 minutes), LT and average power output during a

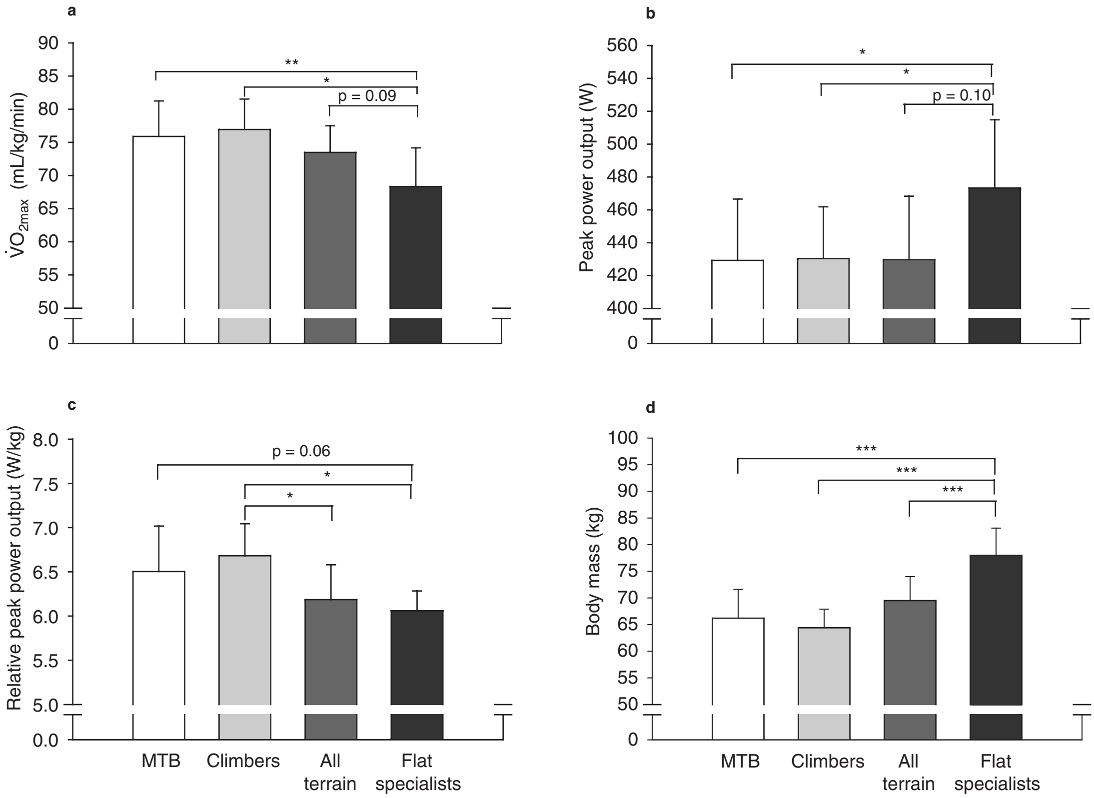

Fig. 3. Comparison of body mass and results from incremental maximal cycling tests between mountain bikers (MTB) [n = 15] and road cyclists divided according to their role in competition (climbers [n = 9], all-terrain riders [n = 15] and flat specialists [n = 10]) using Bonferroni *post hoc* test after one-way ANOVA. $\dot{V}O_{2max}$ = maximum oxygen uptake; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.

30-minute laboratory time trial expressed in absolute values. However, when these parameters were scaled to body mass, significantly higher values were found in off-road compared with on-road cyclists. In addition, mountain bikers were leaner than on-road cyclists.

The normalisation of physiological parameters to body mass better describes cyclists' climbing ability compared with absolute values.[36,39-41] Therefore, the results of Lee et al.[27] suggest that off-road cyclists possess a physiological and anthropometric profile similar to climbers. We recently presented data collected in our laboratory to test this hypothesis (figure 3, unpublished observations),[42] where the physical characteristics of 15 elite off-road cyclists were compared with 34 professional on-road cyclists divided into climbers (n = 9), all-terrain riders (n = 15) and flat specialists (n = 10) according to their role in competitions. All these cyclists were tested with the same protocol, consisting of 25W increments every minute, starting at 100W. Off-road cyclists' body mass, $\dot{V}O_{2max}$ and peak power output expressed both in absolute and relative terms were found to be similar to both climbers and all-terrain road cyclists but significantly different from flat specialists. These findings are in line with the literature. In fact, the body mass of high-level off-road cyclists (65–66kg)[26,27] is between the 68kg reported by Padilla et al.[40] for all-terrain road cyclists and the 62kg and 64kg measured in climbers by Padilla et al.[40] and Lucia et al.,[39] respectively. Furthermore, the $\dot{V}O_{2max}$ values reported in the literature for high-level mountain bikers (table I) are similar to the $\dot{V}O_{2max}$ estimated by Padilla et al.[40] for both climbers and all-terrain road cyclists (80.9 mL/kg/min and 78.9 mL/kg/min, respectively). Therefore, results from our laboratory and the literature suggest that off-road cyclists have physiological characteristics similar to all-terrain cyclists and climbers. This should be taken into consideration when cyclists consider switching from off-road to on-road competitive events (e.g. the cases of off-road cyclists such as Cadel Evans, winner of a World Cup, and Michael Rasmussen, winner of a World Championship) and *vice versa*.

Finally, Warner et al.[30] compared the bone mineral density of 16 mountain bikers and 14 road cyclists. They found a higher bone mineral density normalised for bodyweight in off-road cyclists in all sites measured using dual-energy x-ray absorptiometry (lumbar spine, femoral neck, greater trochanter and Ward's triangle). Warner et al.[30] explained that the higher bone mineral density of off-road cyclists is the result of the higher osteogenic stimulus provided by the loading forces caused by ground surface irregularities. Interestingly, Warner et al.[30] found no difference in muscular strength and power of the lower limbs, as measured on a leg press. However, nobody has investigated the potential differences in trunk and upper limb muscular strength.

2.6 Female Off-Road Cyclists

In the literature, very few physiological data exist on competitive female off-road cyclists. Wilber et al.[32] tested ten females in the United States National Off-Road Cycling Association team (including world champions). The mean age, height and body mass were 30 years, 162cm and 57.5kg, respectively. The female off-road cyclists reached a mean $\dot{V}O_{2max}$ of 57.9 mL/kg/min and a peak power output reached during incremental tests (25W every minute) of 313W, corresponding to 5.4 W/kg. More recently, Stapelfeldt et al.[7] have reported the characteristics of two elite female off-road cyclists in the German national team. They were of age 27 years and 30 years, height 169cm and 170cm, body mass 64kg and 62kg, $\dot{V}O_{2max}$ 58.2 mL/kg/min and 60.6 mL/kg/min, peak power output 320W and 280W (5.0 W/kg and 4.5 W/kg). Unpublished data from our laboratory obtained on ten female off-road cyclists at a national and international level using the same incremental test protocol used by Wilber et al.[32] revealed similar values. We found a similar average $\dot{V}O_{2max}$ of 61.4 ± 3.9 mL/kg/min and a peak power output of 306 ± 31W corresponding to 5.9 ± 0.7 W/kg. The $\dot{V}O_{2max}$ ranged from 57.4 to 70.1 mL/kg/min, with the latter value corresponding to the most successful off-road cyclist within the group, and several placements in the first positions of the most important international cross-country competitions. The mean age, height and body mass of these female off-road cyclists were 26 ± 5 years, 167 ± 5cm and 52.5 ± 3.0kg, respectively. Overall, these data are similar to those reported for elite female road cyclists[43] and demonstrate that females also need high aerobic power and power-to-weight ratio to compete successfully in cross-country events.

3. The Relationship Between Physiological Tests and Off-Road Cycling Performance

Physiological assessment of aerobic fitness is widely used by sport scientists to evaluate endurance athletes, to establish their training intensities, or as a part of the talent identification process. The validity of physiological tests in road cycling has been demonstrated by several studies showing significant relationships between road cycling performance and $\dot{V}O_{2max}$, peak power output and ventilatory threshold or LT.[44-49] However, the relationships between these physiological parameters of aerobic fitness and cross-country off-road performance have been examined only recently in two studies of mountain bikers characterised by heterogeneous or homogeneous performance level.[26,28]

In the first of these studies, we measured peak oxygen uptake, peak power output, LT and OBLA during an incremental test (40W every 4 minutes), and the time to complete an official cross-country circuit race in a group of off-road cyclists with large differences in aerobic fitness (range 60.5–84.7 mL/kg/min) and performance (range 82.4–108.8 minutes). These physiological parameters were all significantly correlated to race time (range from −0.68 to −0.94, $p < 0.05$). The strongest correlations were found when these parameters of aerobic fitness were normalised to body mass. In the second study, we investigated whether similar physiological parameters are good predictors of performance in a more homogeneous group of high-level mountain bikers with high $\dot{V}O_{2max}$ (range 70.8–86.1 mL/kg/min) and narrower range of performance (range 110.8–116.6 minutes). Contrary to the previous study, maximal parameters of aerobic fitness determined using an incremental test of 25W every minute were not significantly correlated to time to complete an official cross-country circuit race. The only physiological tests associated with race time were power output and $\dot{V}O_2$ at respiratory compensation point when normalised to body mass (ranging from −0.61 to 0.66; $p < 0.05$). These two studies confirm that (i) high aerobic power and the ability to utilise a high percentage of it are prerequisites to competing successfully in off-road cross-country races; (ii) these tests are valid for evaluating aerobic fitness in competitive mountain bikers; and (iii) physiological parameters should be normalised to body mass. The significant correlations between lactate and ventilatory thresholds with race time also suggest that highly developed oxidative muscle capacity and/or endogenous buffering capacity are important physiological characteristics of mountain bikers, which need to be further investigated using direct methods.

It is important to draw attention to the fact that in high-level mountain bikers aerobic fitness explains only 40% of the variance in performance, suggesting that other factors need to be considered in the physiological assessment of these athletes.[26] We believe that these other parameters warrant further investigation. The first is off-road cycling economy, which we define as the ability to convert aerobic energy into speed on difficult terrains. This ability may be measured in the laboratory using methods similar to that employed by Berry et al.[16] (bumps placed on the treadmill belt). In road cycling, the ability to convert energy into mechanical power (i.e. mechanical efficiency) seems not to differ between performance levels, although debate about this issue is still ongoing.[50-53] However, in off-road cycling, which is characterised by difficult terrain conditions, factors such as technical ability and trunk and upper body muscle strength and endurance might influence the ability to utilise aerobic energy to generate speed. These factors are likely to vary between riders of different performance levels, making off-road cycling economy a potentially important parameter in the physiological assessment of mountain bikers. Similarly, anaerobic power and capacity may be a useful addition to the battery of physiological tests but need to be validated in mountain bikers.

4. Technical Ability

During cross-country competitions, the different terrain conditions require that mountain bikers have a high degree of technical ability to control and stabilise the bicycle.[17] This is particularly necessary during the several descents performed at high speed. During the race, some riders increase their speed downhill, where riders can gain advantage or decrease time lost in other parts of the course. This strategy decreases the time to react to riding surface irregularities and increases the technical skills required.[54,55] Difference in skill and risk tolerance has been suggested to account for the high inter-individual downhill speed found in a group of 10 amateur mountain bikers by Mastroianni et al.[56] during a simulated off-road circuit. Although the belief that technical ability is an important determinant of off-road cycling performance is widespread between coaches and riders, there are no empirical data to support this hypothesis. Therefore, studies in this area are much needed, as small differences between riders could be crucial for performance among physiologically homogeneous off-road cyclists.

An interesting new concept has been suggested by Damian Grundy, coach of the Australian national cross-country mountain bike team (personal communication, with permission). He suggested that, differently from road cycling, the relationship between power output and speed may change in relation to technical ability. Preliminary data collected at the Australian Institute of Sport surprisingly demonstrated that riders with more time to complete a cross-county circuit track can generate more power output than riders with better performance. This seems to suggest that technical ability can indeed influence how much power output generated by the cyclists is transferred into actual cycling speed. This also agrees with our suggestion of a possible role for off-road cycling economy in cross-country performance.

5. Seasonal Variations in Aerobic Fitness

To date, no studies on the seasonal variations in aerobic fitness of off-road cyclists have been published. However, we recently presented data relative to $\dot{V}O_{2max}$, LT and efficiency measured on a cycle-ergometer in a group of 12 mountain bikers tested before and after the winter pre-season training period and twice during the competitive season until the National Championships (figure 4).[57] Table II shows that both maximal and submaximal parameters of aerobic fitness significantly increase in response to 3 months of pre-season training and they remain stable during the season. The 5% improvement in $\dot{V}O_{2max}$ is similar to that reported by Lucia et al.[58] in professional cyclists. Power output at LT and OBLA increased 7% in the off-road cyclists. This compares well with the 6–8% change in power output at ventilatory thresholds reported by Lucia et al.[58] in road cyclists, but not with the 15% improvement reported by the same authors for LT.

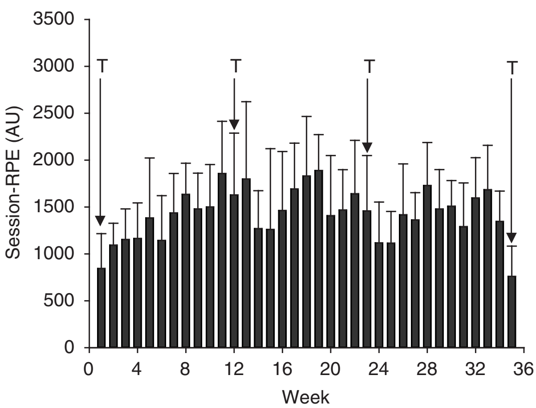

Fig. 4. Time of the four testing sessions (T) during the season. Bars indicate the average weekly training load of the group of mountain bikers calculated using the session rating of perceived exertion (RPE) method, i.e. multiplying the cyclist RPE (using the Category Ratio Scale) referred to the whole training session by session duration in minutes.[59] **AU** = arbitrary units.

In addition to traditional aerobic tests, it has been suggested recently that cycling efficiency should be measured routinely in professional cyclists, in addition to traditional tests.[51,60,61] In his recent case study, Coyle[53] also suggested that the impressive successes achieved by Lance Armstrong could be related to an improvement in cycling efficiency over several years. Therefore, we calculated cycling efficiency in these off-road cyclists using the data measured during the incremental cycling test according to Moseley and Jeukendrup.[62] However, we could not measure any change in gross efficiency or delta efficiency during stationary cycling, even in response to the pre-season training, i.e. when athletes resumed training after 2–3 weeks of rest. However, we cannot exclude that changes in efficiency might occur in mountain bikers over more prolonged periods of time.

6. Nutritional Strategies

The optimisation of performance requires attention to be given to several factors other than physical training. Two recent studies have investigated the effect of pre-exercise nutritional strategies on mountain biking performance.[23,33] These studies are highly relevant for mountain biking, because during off-road cycling competitions feeding and fluid replacement may be difficult because of technically demanding courses.

Cramp et al.[33] investigated the effect of different pre-exercise carbohydrate intake on total energy output during a laboratory simulation of a mountain bike race. After consuming a high-carbohydrate meal (3.0 g/kg) mountain bikers generated 3% more energy compared with those who had consumed a low-carbohydrate meal (1.0 g/kg), although this difference did not reach statistical significance. However, as the effect of this nutritional strategy could be worthwhile in a real competitive setting, further studies with an adequate sample size are warranted.

Table II. Seasonal changes in aerobic fitness and other parameters in a group of competitive mountain bikers (n = 12)

Parameter	November (rest)	February (pre-competition)	April (competition)	July (competition)
Body mass (kg)	66.2 ± 6.9	65.8 ± 6.3	65.6 ± 6.5	65.5 ± 7.1
$\dot{V}O_{2max}$ (mL/kg/min)	64.2 ± 6.2	67.8 ± 6.7[a]	67.2 ± 6.8[a]	68.6 ± 6.7[a]
PPO (W)	346.8 ± 37.1	365.0 ± 37.4[b]	363.8 ± 33.8[b]	374.0 ± 34.3[bc]
LT PO (W)	243.4 ± 37.9	265.3 ± 29.1[b]	272.9 ± 29.6[b]	270.9 ± 30.8[b]
OBLA PO (W)	291.1 ± 45.0	319.3 ± 33.8[b]	326.1 ± 37.2[b]	322.4 ± 35.8[b]
HR max (beats/min)	193.3	187.9 ± 8.0[a]	187.0 ± 7.9[a]	189.3 ± 8.4[a]
HR LT (beats/min)	166.7 ± 10.6	161.4 ± 9.1[a]	162.8 ± 8.6[a]	160.2 ± 8.9[a]
HR OBLA (beats/min)	180.1 ± 9.3	176.7 ± 7.8	177.5 ± 8.3	175.8 ± 8.0
GE (%)	20.1 ± 0.7	19.8 ± 0.9	20.0 ± 0.6	20.4 ± 0.9
DE (%)	25.8 ± 1.4	26.1 ± 1.3	25.9 ± 1.5	26.5 ± 1.1

a $p < 0.05$.

b $p < 0.01$ significant difference from November.

c $p = 0.08$ from April; Bonferroni's tests after one-way repeated measures ANOVA.

DE = delta efficiency; **GE** = gross efficiency; **HR** = heart rate; **LT** = lactate threshold (intensity that elicited a 1 mmol/L increase in blood lactate concentration above the average value measured during exercise between 40% and 60% of maximum oxygen uptake); **OBLA** = onset of blood lactate accumlulation (intensity corresponding to a blood lactate concentration of 4 mmol/L); **PO** = power output; **PPO** = peak power output; $\dot{V}O_{2max}$ = maximum oxygen uptake.

Off-road competitive events are sometimes completed in hot conditions. Because it is not always possible during competitions to replace all the fluid lost, pre-exercise hydration strategies can be very important. In a recent study, Wingo et al.[23] investigated the effects of pre-exercise glycerol hydration and water-only hydration during a field simulation of a mountain biking competition. After glycerol pre-hydration, cyclists showed less dehydration and thirst sensation compared with those who had consumed water only. However, no performance benefit was demonstrated. Again, more studies in this area of research need to be conducted.

7. Conclusions and Future Research Directions

The studies reviewed here demonstrate that cross-country biking is a highly demanding endurance sport during which the aerobic energy system is heavily taxed. Therefore, training and testing of aerobic fitness is of paramount importance. Furthermore, we have shown that off-road riders, as with on-road cyclists, are characterised by high aerobic power and capacity, with a power-to-weight ratio and anthropometric characteristics similar to climbers and all-terrain on-road cyclists. However, the higher exercise intensity and shorter duration of off-road compared with on-road competitive events suggest that different training strategies should be employed. These should include a reduction in training volume and a concomitant increase in intensity through, for example, interval and intermittent aerobic training. Well designed training studies are needed to confirm these indications and to investigate the effects of other types of training, such as sport-specific strength training and technical ability training.

As we have highlighted throughout this review, important gaps in our physiological understanding of mountain biking exist for disciplines other than cross-country circuit races (e.g. marathon cross-country races and downhill competitions). Investigations are also needed on off-road cycling economy, the relevance of high anaerobic power and capacity for cross-country events, the physiological aspects of female off-road cycling, and effective nutritional strategies aimed at optimising mountain biking performance. We hope this review will stimulate further research in all these areas.

Acknowledgements

The authors would like to thank Aldo Sassi (Director of MAPEI Sport Research Center) for his valuable support.

Particular thanks also to Ermanno Rampinini, Massimo Induni, Piero Mognoni, Luca Guercilena, Gianna Meoni and Alessio Nencetti for their help in the collection of our published and unpublished data on off-road cyclists. We are also grateful to David T. Martin, Tammie Ebert and Damian Grundy of the Australian Institute of Sport for their constructive discussions about mountain biking.

The cyclists involved in the unpublished studies have signed an informed consent, and the studies, even if not published, were approved by the Independent Institutional Review Board of MAPEI Sport Research Center. Funding for this research was provided by the MAPEI group. The authors have no conflicts of interest that are directly relevant to the content of this review.

References

1. National Bicycle Dealers Association. 2004-05 NBDA statpak [online]. Available from URL: http://nbda.com/ [Accessed 2006 Apr 14]
2. British Cycling, National Cycling Centre. General information/statistics [online]. Available from URL: http://www.britishcycling.org.uk/membership/general_information.html [Accessed 2006 Apr 14]
3. International Cycling Union. Part IV: mountain bike races. UCI cycling regulations version 03.02.2006 [online]. Available from URL: http://62.50.72.82/modello.asp?.1stLevelID = H&level1 = 0&level2 = 0&idnews = 2676 [Accessed 2006 Apr 14]
4. Union Cycliste Internationale. Mountain bike intro [online]. Available from URL: http://62.50.72.82/modello2.asp?.1stLevelID = C&level1 = 3&level2 = 1&idnews = 1544 [Accessed 2006 Apr 14]
5. Nielens H, Lejeune T. Bicycle shock absorption systems and energy expended by the cyclist. Sports Med 2004; 34 (2): 71-80
6. Impellizzeri F, Sassi A, Rodriguez-Alonso M, et al. Exercise intensity during off-road cycling competitions. Med Sci Sports Exerc 2002; 34 (11): 1808-13
7. Stapelfeldt B, Schwirtz A, Schumacher YO, et al. Workload demands in mountain bike racing. Int J Sports Med 2004; 25 (4): 294-300
8. Padilla S, Mujika I, Orbananos J, et al. Exercise intensity during competition time trials in professional road cycling. Med Sci Sports Exerc 2000; 32 (4): 850-6
9. Padilla S, Mujika I, Orbananos J, et al. Exercise intensity and load during mass-start stage races in professional road cycling. Med Sci Sports Exerc 2001; 33 (5): 796-802
10. Lucia A, Hoyos J, Carvajal A, et al. Heart rate response to professional road cycling: the Tour de France. Int J Sports Med 1999; 20 (3): 167-72
11. Lucia A, Hoyos J, Santalla A, et al. Tour de France versus Vuelta a Espana: which is harder? Med Sci Sports Exerc 2003; 35 (5): 872-8
12. Fernandez-Garcia B, Perez-Landaluce J, Rodriguez-Alonso M, et al. Intensity of exercise during road race pro-cycling competition. Med Sci Sports Exerc 2000; 32 (5): 1002-6
13. Lucia A, Hoyos J, Chicharro JL. Physiology of professional road cycling. Sports Med 2001; 31 (5): 325-37
14. Mujika I, Padilla S. Physiological and performance characteristics of male professional road cyclists. Sports Med 2001; 31 (7): 479-87
15. McCole SD, Claney K, Conte JC, et al. Energy expenditure during bicycling. J Appl Physiol 1990; 68 (2): 748-53
16. Berry MJ, Koves TR, Benedetto JJ. The influence of speed, grade and mass during simulated off road bicycling. Appl Ergon 2000; 31 (5): 531-6
17. Wang EL, Hull ML. A dynamic system model of an off-road cyclist. J Biomech Eng 1997; 119 (3): 248-53
18. Cable NT. Cardiovascular function. In: Eston R, Reilly T, editors. Kinanthropometry and exercise physiology laboratory manual: tests, procedures and data. London: Routledge, 1990: 117-33
19. Seifert JG, Luetkemeier MJ, Spencer MK, et al. The effects of mountain bike suspension systems on energy expenditure, physical exertion, and time trial performance during mountain bicycling. Int J Sports Med 1997; 18 (3): 197-200
20. Atkinson G, Brunskill A. Pacing strategies during a cycling time trial with simulated headwinds and tailwinds. Ergonomics 2000; 43 (10): 1449-60
21. Atkinson G, Davison R, Jeukendrup A, et al. Science and cycling: current knowledge and future directions for research. J Sports Sci 2003; 21 (9): 767-87
22. Mattern CO, Kenefick RW, Kertzer R, et al. Impact of starting strategy on cycling performance. Int J Sports Med 2001; 22 (5): 350-5
23. Wingo JE, Casa DJ, Berger EM, et al. Influence of a pre-exercise glycerol hydration beverage on performance and physiologic function during mountain-bike races in the heat. J Athl Train 2004; 39 (2): 169-75
24. Dal Monte A, Faina M. Valutazione dell'atleta [in Italian]. Torino: UTET, 1999: 372-6
25. The official website of the ATHENS 2004 Olympic Games. Athletes biographies [online]. Available from URL: http://www.athens2004.com/en/ParticipantsAthletes/newParticipants [Accessed 2004 Sep 1]
26. Impellizzeri FM, Marcora SM, Rampinini E, et al. Correlations between physiological variables and performance in high level cross country off road cyclists. Br J Sports Med 2005; 39 (10): 747-51
27. Lee H, Martin DT, Anson JM, et al. Physiological characteristics of successful mountain bikers and professional road cyclists. J Sports Sci 2002; 20 (12): 1001-8
28. Impellizzeri FM, Rampinini E, Sassi A, et al. Physiological correlates to off-road cycling performance. J Sports Sci 2005; 23: 41-7
29. Nishii T, Umemura Y, Kitagawa K. Full suspension mountain bike improves off-road cycling performance. J Sports Med Phys Fitness 2004; 44 (4): 356-60
30. Warner SE, Shaw JM, Dalsky GP. Bone mineral density of competitive male mountain and road cyclists. Bone 2002; 30 (1): 281-6
31. Baron R. Aerobic and anaerobic power characteristics of off-road cyclists. Med Sci Sports Exerc 2001; 33 (8): 1387-93
32. Wilber RL, Zawadzki KM, Kearney JT, et al. Physiological profiles of elite off-road and road cyclists. Med Sci Sports Exerc 1997; 29 (8): 1090-4
33. Cramp T, Broad E, Martin D, et al. Effects of preexercise carbohydrate ingestion on mountain bike performance. Med Sci Sports Exerc 2004; 36 (9): 1602-9

34. MacRae H-H, Hise KJ, Allen PJ. Effects of front and dual suspension mountain bike systems on uphill cycling performance. Med Sci Sports Exerc 2000; 32 (7): 1276-80

35. Berry MJ, Cline CC, Berry CB, et al. A comparison between two forms of aerobic dance and treadmill running. Med Sci Sports Exerc 1992; 24 (8): 946-51

36. Swain DP. The influence of body mass in endurance bicycling. Med Sci Sports Exerc 1994; 26 (1): 58-63

37. Bassett DR, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc 2000; 32 (1): 70-84

38. Bourdon P. Blood lactate transition threshold: concepts and controversies. In: Gore CJ, editor. Physiological tests for elite athletes. Champaign (IL): Human Kinetics, 2000

39. Lucia A, Joyos H, Chicharro JL. Physiological response to professional road cycling: climbers vs. time trialists. Int J Sports Med 2000; 21 (7): 505-12

40. Padilla S, Mujika I, Cuesta G, et al. Level ground and uphill cycling ability in professional road cycling. Med Sci Sports Exerc 1999; 31 (6): 878-85

41. Heil DP. Scaling of submaximal oxygen uptake with body mass and combined mass during uphill treadmill bicycling. J Appl Physiol 1998; 85 (4): 1376-83

42. Impellizzeri FM, Sassi A. Physiology of off-road cycling [abstract no. IS18-1]. 10th Annual Congress of European College of Sport Science; 2005; Belgrade, 28

43. Martin DT, McLean B, Trewin C, et al. Physiological characteristics of nationally competitive female road cyclists and demands of competition. Sports Med 2001; 31 (7): 469-77

44. Hawley JA, Noakes TD. Peak power output predicts maximal oxygen uptake and performance time in trained cyclists. Eur J Appl Physiol Occup Physiol 1992; 65 (1): 79-83

45. Hopkins SR, McKenzie DC. The laboratory assessment of endurance performance in cyclists. Can J Appl Physiol 1994; 19 (3): 266-74

46. Coyle EF. Integration of the physiological factors determining endurance performance ability. Exerc Sport Sci Rev 1995; 23: 25-63

47. Lindsay FH, Hawley JA, Myburgh KH, et al. Improved athletic performance in highly trained cyclists after interval training. Med Sci Sports Exerc 1996; 28 (11): 1427-34

48. Nichols JF, Phares SL, Buono MJ. Relationship between blood lactate response to exercise and endurance performance in competitive female master cyclists. Int J Sports Med 1997; 18 (6): 458-63

49. Bishop D, Jenkins DG, Mackinnon LT. The relationship between plasma lactate parameters, Wpeak and 1-h cycling performance in women. Med Sci Sports Exerc 1998; 30 (8): 1270-5

50. Moseley L, Achten J, Martin JC, et al. No differences in cycling efficiency between world-class and recreational cyclists. Int J Sports Med 2004; 25 (5): 374-9

51. Lucia A, Hoyos J, Perez M, et al. Inverse relationship between $\dot{V}O_{2max}$ and economy/efficiency in world-class cyclists. Med Sci Sports Exerc 2002; 34 (12): 2079-84

52. Martin DT, Quod MJ, Gore CJ, et al. Has Armstrong's cycle efficiency improved? J Appl Physiol 2005; 99 (4): 1628-9

53. Coyle EF. Improved muscular efficiency displayed as Tour de France champion matures. J Appl Physiol 2005; 98 (6): 2191-6

54. Gaulrapp H, Weber A, Rosemeyer B. Injuries in mountain biking. Knee Surg Sports Traumatol Arthrosc 2001; 9 (1): 48-53

55. Kronisch RL, Pfeiffer RP. Mountain biking injuries: an update. Sports Med 2002; 32 (8): 523-37

56. Mastroianni GR, Zupan MF, Chuba DM, et al. Voluntary pacing and energy cost of off-road cycling and running. Appl Ergon 2000; 31 (5): 479-85

57. Impellizzeri FM, Rampinini E, Marcora SM, et al. Seasonal variations in efficiency and physiological parameters of aerobic fitness in off-road cyclists [abstract no. PP15-9]. 10th Annual Congress of European College of Sport Science; 2005; Belgrade, 263

58. Lucia A, Hoyos J, Perez M, et al. Heart rate and performance parameters in elite cyclists: a longitudinal study. Med Sci Sports Exerc 2000; 32 (10): 1777-82

59. Foster C. Monitoring training in athletes with reference to overtraining syndrome. Med Sci Sports Exerc 1998; 30 (7): 1164-8

60. Faria EW, Parker DL, Faria IE. The science of cycling: factors affecting performance: part 2. Sports Med 2005; 35 (4): 313-37

61. Barbeau P, Serresse O, Boulay MR. Using maximal and submaximal aerobic variables to monitor elite cyclists during a season. Med Sci Sports Exerc 1993; 25 (9): 1062-9

62. Moseley L, Jeukendrup AE. The reliability of cycling efficiency. Med Sci Sports Exerc 2001; 33 (4): 621-7

Correspondence and offprints: Dr *Franco M. Impellizzeri*, Human Performance Laboratory, MAPEI Sport Research Center, Via Don Minzoni 34, 21053 Castellanza (VA), Italy.
E-mail: fm.impellizzeri@alice.it