Jean-Benoit Morin
Pierre Samozino *Editors*

Biomechanics of Training and Testing

Innovative Concepts and Simple Field Methods

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Finally, we would like to thank our families for their constant support, patience and love.

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Part III Running

Chapter 1
Introduction

Jean-Benoit Morin and Pierre Samozino

> Everything should be made as simple as possible, but not simpler.
>
> Albert Einstein (1879–1955)

Although it is a "young" scientific discipline, locomotion and sport biomechanics has taken an important place in the daily routine of many practitioners of sports training, medicine and rehabilitation. It allows both a better understanding of human locomotion and performance and a better design of sports training and injury prevention programs. In these processes, the testing of athletes is crucial, and the quality and quantity of variables analysed will directly influence the effectiveness of coaches, physiotherapists and other practitioners' interventions.

This book presents a state of the art of innovative methods, and for most of them, gives direct and practical insights into how practitioners may benefit from using them in their everyday practice. It also details how to interpret the data measured, and the underlying neuromuscular and biomechanical factors related to sport performances.

Written and edited by the same researchers who proposed and validated these methods and concepts, the aim of this book is to both present innovative methods and concepts for an effective and accurate training and testing process (most of them being based on very simple technology and data processing methods), and discuss the associated underlying knowledge. Before presenting in details the theoretical basis and practical applications of these methods and concepts in the

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following chapters, this introduction section will focus on the specificities of the overall approach the authors of this book used as sport scientists to bring some new insights in human performances.

1.1 Optimizing Sport Performance Is like Cooking

A good dish is the result of the optimal combination of different ingredients. A head cooking chief chooses the best ingredients and mixes them in the optimal way. Similar processes happen in sports. Performance is a complex integration of different qualities, abilities and skills. The head cooking chief is the coach, or the strength and conditioning coach if we focus on physical qualities. He has the genius of training to mix at best the different ingredients required to reach high levels of performance. To improve athlete's performance, one needs to know the different ingredients well, and how they can interact, to achieve the best mix possible. Both of the latter can come from empirical experience, but also, from evidence and data brought by sport sciences. Sport scientists do not aim to propose take-away recipes to sport practitioners, but only to bring some insights about ingredients, effects of their combinations and how to accurately taste/test them. This book presents some of these "ingredients" related to running, jumping, throwing and cycling performance, notably innovative methods and concepts to test and quantify some of these ingredients for each athlete, most of these methods being easily usable out of laboratories.

In the same way that only one ingredient cannot be not responsible of the success of a delicious dish, the performance in sport does not depend on only one or two factors. However, to better understand the effect of one specific physical, technical, psychological or tactical quality on the final performance, the sport scientist is forced to isolate each of them and to study their effect on only one part of the performance. This does not mean that he neglects the other factors also contributing to performance, but increasing the knowledge about a specific factor necessary goes by playing with this factor and considering the others as stable (*ceteris paribus*). For instance, explosive movements and sprint accelerations are key factors in soccer. While a good sprinter would not be necessarily a good soccer player since many other specific qualities and skills are needed, a soccer player who jumps higher, accelerates more and runs faster than his opponent, all other qualities being equal, will take a certain advantage in the game. So, increasing the understanding and evaluation of individual capabilities determining explosive performances is of great interest, yet not sufficient, to optimize soccer performance. In a delicious dish, each ingredient is indispensable, even not enough to explain the final flavor. This book will present theoretical and practical insights about biomechanical factors determining the ability to run or pedal faster, to jump higher or to throw further, which can be interesting to improve performance in some sports, keeping in mind that they are only some ingredients of the success. Sport practitioners should be aware about these factors and how to evaluate and train them, but they have to integrate and associate them at best with the other ingredients involved in the targeted performance. Coaches are and remain the head cooking chiefs and sport sciences an indispensable tool.

1.2 See the Big Picture First

> You can’t see the forest for the tree

When aiming at understanding and contributing to improve sport performance, a scientific approach going from macroscopic to microscopic levels is of great interest. It consists in starting the analyses from the performance itself, its different integrative biomechanical factors (when focusing on physical qualities) to then study the biological or neurophysiological underlying mechanisms. This allows a clear understanding, in a logical order, of the relationships between performance, the mechanical requirements of the underlying tasks and the associated mechanical outputs, the various athlete’s individual intrinsic qualities involved and in fine, the corresponding biological features. In the field of applied sport sciences, this implies to use a back-and-forth approach between fields of practice and laboratory. Most of time, the initial basic questions come from sport practitioners on the field regarding what they need to better know to improve performance. Some of these interrogations require laboratory approaches using standardized experimental protocols, biomechanical or physiological models, mathematics, physics, and statistics. This inevitably puts some distance between research and the actual performance on the field, but this makes possible to find some answers which have then direct practical applications for performance optimization and training. This book will thus present some theoretical approaches, mainly based on biomechanical models, which bring some new insights contributing, at least in part, to answer practical issues for sport practitioners. These theoretical answers are associated to validation by comparison to experimental data and practical applications supporting their relevance and interest in training and testing.

1.3 Simple Models, Simple Methods

> The simpler the model, the clearer it is which of its characteristics are essential to the observed effect
>
> Alexander (2003)

The originality of the biomechanical models presented in this book and associated to the above-mentioned macroscopic approaches, is to correctly explain human performance from the fewest variables possible. This philosophy of such models is well illustrated by the words of Robert McNeill Alexander in an interview presented in the “Questions and Answers” section of Current Biology journal in

2006 (Alexander 2006): "*Use simple mathematical models for clarifying arguments and generating hypotheses. Don't try to make your model as complex as the animal it represents: you will never succeed, and the effort may be counterproductive because it is often not apparent which features of a complex model are responsible for the effects it shows. On the other hand, if a model is simple enough, you can tell what caused the effect. I have found optimization models particularly useful — models that seek the best possible structure or behaviour. For example, if a model tells me that a particular pattern of behaviour is the best possible in given circumstances, and if real animals do something quite different, that suggests that I may have failed to understand the issues at stake*". Such biomechanical models do not aim at representing all the biological structures forming human body, but rather at characterizing in the simplest way possible[1] the actual mechanical behavior of the different part of the body acting in sport performance. These models allow sport scientists and practitioners to better identify and understand the different integrative biomechanical factors affecting human performances (dynamics approach). When using these models in the opposite way, i.e. the model's input is the performance and the outputs are the underlying mechanical properties (inverse dynamics approach), they can be used to develop simple methods to evaluate some individual mechanical properties without any specific dynamometers or other laboratory devices. This book will present both ways to use such biomechanical models. First, it will present some models that led to some original concepts to better understand the biomechanical factors affecting sport performances. Second, this book will present simple methods to assess, easily and out of labs, mechanical properties of an athlete's neuromuscular system or biomechanical features of human locomotion. Theoretical background, validation against "gold standard" methods and practical applications in training will be detailed in the following chapters.

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Alexander RM (2006) R. McNeill Alexander. Curr Biol 16(14):R519–R520

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[1] The simplest as possible in respect of the initial question at which the model is used to answer.

Part I

Cycling

Chapter 2
Maximal Force-Velocity and Power-Velocity Characteristics in Cycling: Assessment and Relevance

Sylvain Dorel

Abstract Cycling is a “common” task considered relatively intuitive and hence easy to perform by everybody. Although pedaling represents a typical multi-joint movement characterized by several degrees of freedom, in contrast with running it can be regarded as less complex since the fixed trajectory of the pedals and the mechanical coupling between both legs constrain lower-extremity movements to a higher degree. In this chapter we will define a macroscopic model to measure maximal cycling power output and typical measurements involved in stationary ergometer conditions and also on the field in Sect. 2.5. We will give some reference data and discuss how best to interpret the force, power and velocity indexes obtained from this testing procedure. Force-velocity and power-velocity relationships allow reliable assessment of maximal power capabilities and its two force and velocity components in cycling. Provided that the proper methodology and advice presented in this chapter are used, the different indexes extracted from these relationships give very useful information on (i) evaluating lower-limb muscle function, (ii) monitoring specific and general strength training effects and (iii) interpreting and characterizing muscle involvement in the efforts performed on the field within the training or competition context. Use of a stationary ergometer is now straightforward and particularly suited for each individuals and hence remains the reference method to use, yet portable power meters are now accessible and will become more and more suitable.

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2.1 Introduction

Cycling is a “common” task considered relatively intuitive and hence easy to perform by everybody. After the French engineers Michaux and Lallement added the pedals, the pedaling machine (i.e., the first “bicycle”) appeared at the beginning of the 20th century with approximately the same general design as today’s bicycle. Currently, it is more and more widely used in daily life (e.g., to go to work) as well as for recreational, fitness, sport or rehabilitation activity. From a biomechanical point of view, cycling consists in propelling (or “driving”) a system (cyclist and its bicycle or an inertia flywheel) using alternative actions of both legs on a crank system in rotation. Although pedaling represents a typical multi-joint movement characterized by several degrees of freedom, in contrast with running it can be regarded as less complex since the fixed trajectory of the pedals and the mechanical coupling between both legs constrain lower- extremity movements to a greater extent.

Historically, the maximal power produced during sprint cycling has been considered an indirect measurement of “maximal anaerobic power”; that is, ability related to the rate of energy turnover from anaerobic metabolism (specially related to the phosphagen pathway). The last three decades have shown it is now well established that this ability is more representative of the global muscle function of the lower limbs and mechanical muscle properties. Hence explosive cycling movement is greatly determined by the maximal force and power capabilities of the muscles involved which directly depend on the well-known force-velocity relationship (Hill 1938). As a consequence, at the macroscopic level, it is well established that the total maximal power produced during cycling is similarly very well characterized by both force-velocity and a power-velocity relationships. Although these relationships reflect a range of other neuro-mechanical properties (see Chap. 3), they allow the determination of useful indexes of global power, force and velocity abilities that provide interesting simple tools to evaluate athletes and at the same time monitor specific and general strength training effects.

In this chapter we will define a macroscopic model to measure maximal cycling power output and typical measurements found under stationary ergometer conditions and also on the field in Sect. 2.5. We will provide some reference data and discuss the best way to interpret the force, power and velocity indexes obtained from this testing procedure. Additionally, we make a special attempt to provide the main practical tips to ensure validity and precision in the determinations of the different indexes in order to encourage a good interpretation of the results in the context of training and sport performance.

2.2 Measurement of Mechanical Output (Force, Velocity and Power) During Sprint Pedaling

The system involved in riding an ergometer is generally represented by a crankset and the associated wheel in rotation on which external forces are applied. Then the “external power” produced by the subject can be considered part of the power output used to overcome external resistances (i.e., different frictions and the weight or inertia of the system) or linked to the changes in total mechanical energy of this system (i.e., kinetic energy in this case). This external power (*Ps*) is therefore directly related to the torque generated at the level of the crank axis (T_{Feff}, which only depends on the perpendicular component of the total force F_{eff} produced on the pedals) and the crank angular velocity (ω, in rad·s^{-1}, Eq. 2.1). In practice, *Ps* can also be calculated considering the effective force (F_{eff}, in N, by dividing torque by the crank length in m) and velocity (*V*, in m·s $^{-1}$) at the pedal level (Eq. 2.2).

$$Ps = T_{F\mathrm{eff}} \cdot \omega \tag{2.1}$$

$$Ps = F_{\mathrm{eff}} \cdot V \tag{2.2}$$

Many methods have been developed in the last 30 years to calculate the two components of *Ps* (Driss and Vandewalle 2013) and two main modalities were used: isokinetic (i.e., control of pedaling rate and direct measurement of force with sensors in the crank or pedal; Mc Cartney et al. 1983b; Sargeant et al. 1981) and the more common isoinertial condition (i.e., control of the external resistance and inertia parameters of the flywheel and measurement of its velocity and acceleration; Dorel et al. 2005; Hautier et al. 1996; Martin et al. 1997; Vandewalle et al. 1987). All these methodologies use the same general equations of movement for measuring the torque produced by the subject (T_{Feff}, Eq. 2.3) and then the power (*Ps*, Eq. 2.4):

$$T_{F\mathrm{eff}} = I \cdot \alpha + T_{\mathrm{Fric}} \tag{2.3}$$

$$Ps = I \cdot \alpha \cdot \omega + T_{\mathrm{Fric}} \cdot \omega \tag{2.4}$$

where T_{Fric} represents the sum of the resistive torques applied on the system in rotation (friction or magnetic resistance in most cases); *I* is the moment of inertia of this system (in kg.m^2); and α is its angular acceleration (in rad·s^{-2}). Historically this equation has been used on friction-loaded cycle ergometers (e.g., Monark) and then considered the flywheel as the system in rotation. Instead of the torque and angular velocity at the crank, the values are in this case expressed referring to the flywheel axis. Ultimately, in studies using the Monark ergometer (Hautier et al. 1996; Morin and Belli 2004; Vandewalle et al. 1987), force and velocity are expressed in components corresponding to the forces applied at the periphery of the flywheel (in N or kg equivalent) and the velocity of the point of application of these forces (*v*, in m·s^{-1}). So Eq. 2.4 becomes:

$$\mathrm{Ps} = \mathrm{I}/\mathrm{R}^2 \cdot \mathrm{a} \cdot \mathrm{v} + \mathrm{F}_{\mathrm{Fric}} \cdot \mathrm{v} \tag{2.5}$$

where R represents the radius of the flywheel (in m), a the tangential acceleration (in $\mathrm{m{\cdot}s^{-2}}$) and $\mathrm{F_{fric}}$ the friction force applied by the belt (generally measured by a strain gauge) or the magnetic resistance (in N). Note that this last processing methodology is reliable and convenient depending on the equipment resources. However, taking into account the variability of the ergometer's characteristics (radius of the flywheel, gear ratio…), it is not really useful to compare values of force between the studies and the ergometers (e.g., the maximal force index, see below). On the same issue, it is important to keep in mind that a slight but non-negligible difference is observed between the power measured at the flywheel level and that measured directly by strain gauges at the crank or at the shoe-pedal interface, depending on the losses induced by frictions in the chain, sprockets and the different rotation axis (Driss and Vandewalle 2013).

During a sprint exercise, it is possible to monitor the force and then power output produced provided that (i) the friction force applied and the velocity and acceleration of the flywheel (or the crank) are precisely measured and that (ii) the moment of inertia of this flywheel is known. The time course of force, velocity and power during a single sprint of few seconds can be tracked, depending on the sampling rate. Finally, the mean value on each pedal stroke or each complete cycle allows to plot the crank velocity-time and power-time relationships (Fig. 2.1a–b), and also the evolution of force and power in function of the velocity (generally expressed as pedaling rate, Fig. 2.1c). These typical relationships are detailed in the next part.

This methodology was largely applied in the last twenty years and remains very useful when using friction-inertial-loaded (Arsac et al. 1996; Dorel et al. 2003) or only inertial-loaded (Martin et al. 1997) cycle ergometers. However other methods were historically proposed and can still be used (see the two detailed reviews for more information, (Cross et al. 2017; Driss and Vandewalle 2013)). Indeed, the first approach to assess the force-velocity in cycling was based on simplification by considering only the second part of the Eq. 2.5 (i.e. the power required to overcome the braking force) omitting the power required to accelerate the flywheel inertia (Vandewalle et al. 1987). The power estimated by this methodology is valid only when the acceleration is equal to zero, which is solely the case when the peak velocity is reached during sprint performed in isoinertial condition. Then a single couple of force-velocity (i.e. braking force-peak velocity) can be assessed per sprint. It is necessary to repeat a series of six to ten sprints against progressively increasing braking forces, to record different peak velocities and finally plot a force-velocity relationship as well (Fig. 2.1c). Theoretically this approach remains reliable to assess the maximal force- and power-velocity relationships and you can see on Fig. 2.1c the good agreement between the F-V relationship resulted from "peak velocity" method and the relationship resulted from the "reference" method (i.e. Eq. 2.5). The advantage was that the material is very simple: the braking forces are predetermined by known weights and only the peak flywheel velocity should be measured. However, the repetition of the 8–10 sprints can induce a significant

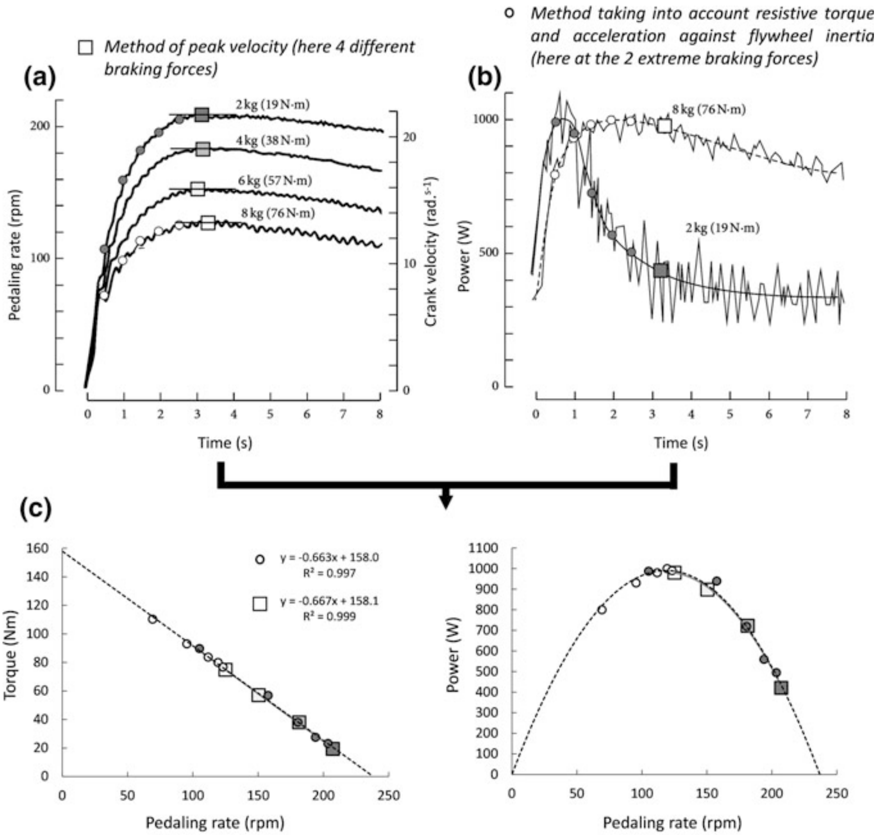


Fig. 2.1 **a** Typical example of the time-course of the pedaling rate (or crank velocity) during a force-velocity test on a Monark cycle ergometer: 4 short sprints against 4 braking forces (in kg at the circumference of the flywheel and equivalent resistive torque in Nm at the crank axis). Squares correspond to the peak values and circles to the mean values on each complete cycle before. **b** Time-power curves for the two extreme loads with the raw and filtered data (grey lines) and the same representation of the mean values on the five first complete crank cycles and at the peak velocities. **c** Mean value of torque, pedaling rate and power on these complete cycles (first 3 s of each sprint) can be used to plot torque- and power-velocity relationships. Note the good match in this example between the shape of these relationships for the two methods: one that considers only the peak velocity values of the 4 distinct sprints of panel a (squares: power corresponds to the product of peak velocity and braking force) and the other that considers all the cycles of the 2 sprints of panel b (circle: power measurement also takes into account the force to accelerate the flywheel inertia during the first phase of the sprint). Adapted from Driss and Vandewalle (2013)

fatigue throughout the test session and the protocol assumes an absence of fatigue at the time of the peak velocity occurrence which can be questionable in some cases (see the next parts). Note that although there are still few people which propose to use this methodology (i.e. only the power against the braking force) to estimate power also during the acceleration phase, this approach should be logically ruled out due to its invalidity (Morin and Belli 2004).

Finally, with the development of a new generation of commercialized electronic cycle ergometers (e.g., SRM^{TM}, Lode Excalibur Sport^{TM}), especially from the last fifteen years, they are increasingly used. With these devices, the estimation of the resistive torque (braking or magnetic) is no longer required because of the direct measurement by strain gauges of the force at the crank or the pedal level (Buttelli et al. 1996; Capmal and Vandewalle 1997; Dorel et al. 2010). Moreover, the setting of these ergometers has been particularly improved to be better adapted to the size and muscle capacities of all athletes (Dorel et al. 2012; Gardner et al. 2007). For this reason, the next parts of the chapter presenting in detail the methodology and interpretation of force- and power-velocity capabilities will often use data recorded with this type of ergometry.

As for all biomechanical models aiming at simplifying the complex multi-joint movement to facilitate its interpretation, this macroscopic model of external power output measurement in cycling implies several assumptions:

- From a mechanical standpoint cycling remains a double task: (i) moving the leg segments in such a way that the foot moves on a circular trajectory; (ii) producing torque at the crank levels. The work produced by the muscles is then transformed into mechanical work at the crank level but also used to move the leg segments (Driss and Vandewalle 2013; Kautz and Hull 1993). Therefore, it is important to keep in mind that pedal force measured at the shoe-pedal interface can be decomposed into a muscular component due directly to the intersegmental net joint torques and a non-muscular component due to gravitational and inertial effects of the segments.
- This cyclic movement of the lower extremity requires a specific coordination of several lower-limb muscles with a lot of co-activation between synergists as well as antagonist muscles (see next chapter, Dorel et al. 2012; Hug and Dorel 2009). In this line, despite a maximal involvement, the maximal activation level is not verified for all the muscles and the cyclic characteristics of the task induce that mechanical output is also governed by excitation-relaxation kinetics (Neptune and Kautz 2001).
- This movement is classically considered by the scientific and coaching communities as a useful evaluation of the human dynamic muscle function of the lower limb extensor muscles in a "concentric" mode. However, some muscles could theoretically act in different modalities of contraction (particularly the bi-articular muscles), and also operate in different range of their force-length relationship.

Note that all of these points will be further examined and discussed in the next chapter (see Chap. 3 for more information).

2.3 Maximal Force- and Power-Velocity Relationships in Cycling

2.3.1 Testing and Processing

Sprint exercise on cycle ergometer is widely used to evaluate force and power characteristics of the lower limbs. These muscle capacities can be accurately measured on a cycle ergometer, using the well-known “force-velocity” test that consists of performing 3 brief all-out exercises of 5-s duration against difference resistances. The corresponding resistive torques generally applied are 0, 0.5–0.8, and 1–1.8 Nm.kg^{-1} body mass depending on the body mass and level of expertise. Actually, these values of resistance are indicative and may be adapted in line with the general principle of allowing subjects to attain a large range of pedaling rates over the cumulative three bouts. Classically the value of force, velocity and power are averaged on a period corresponding to a full crank cycle (or a half cycle, i.e. one downstroke) and then 4 to 10–12 couples of force and velocity values are obtained from each sprint, allowing modeling the relationships with a large number of points (Fig. 2.2).

Whatever the approach to measure the mechanical data, the velocity is preferentially expressed in pedaling rate at the crank level (in rpm). Then force-velocity relationship obtained during pedaling is classically presented as a maximal torque (or effective force)-pedaling rate relationship which is very well fitted by a linear regression model (Dorel et al. 2003, 2005; Driss and Vandewalle 2013; Driss et al. 2002; Hautier et al. 1996; Hintzy et al. 1999; Vandewalle et al. 1987). The linear relationship obtained (Eq. 2.6) enables assessment of $V_{\max}$ and $F_{\max}$, which have the dimensions of maximal pedaling rate at the zero force axis and the effective force corresponding to a zero pedaling rate, respectively (Fig. 2.2; Eq. 2.7).

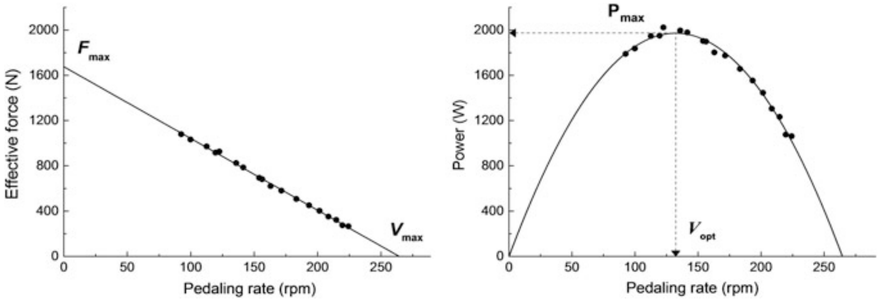


Fig. 2.2 Typical force-velocity (left) and power-velocity (right) relationships of an elite track cyclist, fitted using linear and quadratic regressions, respectively and considering mean crank cycle values obtained from three sprints of 4-s duration. Determination of maximal power ($P_{\max}$), optimal pedaling rate (V_{opt}), maximal pedaling rate ($V_{\max}$), and maximal effective force ($F_{\max}$)

$$F = \alpha V + F_{max} \tag{2.6}$$

$$V_{max} = -F_{max} \cdot \alpha^{-1} \tag{2.7}$$

Maximal power generation is described by a polynomial (2nd order,) power-velocity relationship (Eq. 2.8) with a maximum value (P_{max}) reached at an optimal cycling rate (V_{opt}) and hence at an optimal force (F_{opt}).

$$P = aV^2 + bV + c \tag{2.8}$$

P_{max} can be determined directly basing on the F-V relationship with the following equations:

$$P_{max} = V_{opt}.F_{opt}, \quad P_{max} = 0.5V_{max}.0.5F_{max}, \quad P_{max} = 0.25.V_{max}.F_{max} \tag{2.9a–c}$$

where V_{opt} and F_{opt} are expressed in official unit (rad·s^{-1} and Nm at the crank axis or m·s^{-1} and N at the pedal, respectively).

V_{opt} and P_{max} can be determined based on Eq. 2.8 (P-V relationship) with the following equation:

$$V_{opt} = \frac{-b}{2a} \tag{2.10}$$

$$P_{max} = \mathrm{a} \cdot \left(\frac{-b}{2a}\right)^2 + b \cdot \left(\frac{-b}{2a}\right) + c \tag{2.11}$$

Practically, the relation between the power and velocity is fundamental because it means that (i) an athlete can reach the actual maximal value of power (P_{max}) only at an optimal trade-off between force and velocity (Eq. 2.9a–c), and (ii) the maximal power-generating capacity dramatically decreases when velocity significantly moves away below or above this V_{opt} value (Fig. 2.2). Interestingly, the more the target power is below P_{max} value (i.e. submaximal values under the curve), the more the possibilities to produce this power on a large range of different pedaling rates (and hence force) exist. On the training and testing viewpoint, the power-velocity relationship implies that P_{max} can be reached around to the small range of pedaling rates corresponded to almost V_{opt} value. It means that the higher V_{opt} the more the athletes should pedal at a high cadence to be able to reach their maximal power (Fig. 2.3). Then even if two athletes with different V_{opt} have a large difference in their absolute P_{max} (e.g, 12 rpm and ~200 W in the example of Fig. 2.3), this discrepancy in power production could be very lower or even disappear on the field if the effort is performed at specific pedaling rate advantageous for the athlete with the higher V_{opt} (e.g., at almost 180 rpm on Fig. 2.3).

However, it is important to keep in mind that due the mechanical fundamental laws, even if the mechanical constraints (e.g., effects of gravity, rolling resistance,

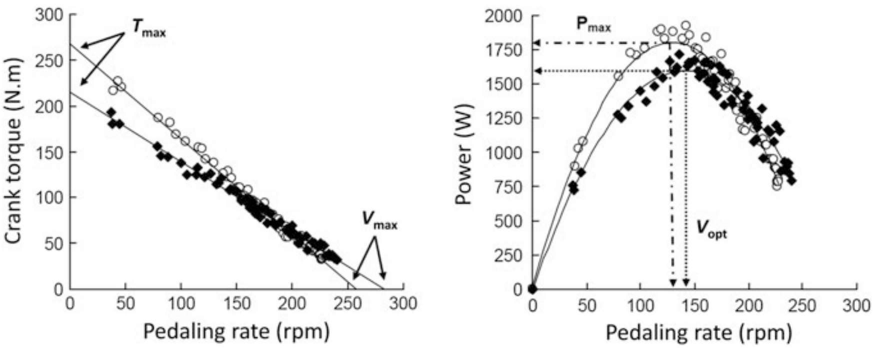


Fig. 2.3 Determination of the torque- and power-velocity relationships of two typical elite sprinters in cycling with large differences in torque and velocity capabilities: one (white circle) with very high value of maximal torque (T_{max}: ~270 Nm) giving him a higher value of maximal power (P_{max}: 1800 W), the other (black diamond) with extremely high value of maximal pedaling rate (V_{max}: 285 rpm) giving him a high P_{max} also (despite lower: 1650 W). Observe the greater discrepancy between power capabilities of both athletes at the pedaling lower than V_{opt} (60–70 to 130 rpm) and the lower discrepancy at higher pedaling rates and even an absence of difference at pedaling rates around 180–200 rpm

air friction, moment of inertia of the system) can directly influence the speed of the system on the field (i.e. the cyclist + bicycle), they do not directly act on the capacity to reach maximal power output per se if the pedaling rate can be adjusted. Indeed, contrary to running for example, it is easier to change the ratio between speed and pedaling rate by using a gear ratio system on the field. Consequently, the athlete by changing the gear ratio can adjust his pedaling rate to be close to V_{opt} conditions and then to be able to reach his maximal power output in very different mechanical situations (speed, external resistances…etc…).

2.3.2 *Meaning of the Indexes Extracted from the Relationships*

The force- and power-velocity relationships allow the determination of several useful parameters (i.e. indexes) for normative evaluation as well as training monitoring. One often tries to link these indexes with performance factors in different explosives disciplines requiring power of the lower limbs (Dorel et al. 2005; Morin et al. 2002) and to describe the alteration of these indexes with training or with age to better understand the loss of power capacity and functional performance in elderly population (Bonnefoy et al. 1998; Martin et al. 2000). Then, it is important to state on the interpretation of the different parameters and how each can account to the lower limb muscle function.

Optimal and maximal pedaling rate. Due to the linear model, both indexes correspond to the same global velocity capability (i.e. $V_{\mathrm{opt}} = 0.5\ V_{\mathrm{max}}$). The pedaling rate being directly linked to the pedal speed it influences indirectly the angular velocity of the main joints (especially the hip and the knee) and hence is considered to influence also the muscle shortening velocity. Therefore, V_{opt} is often considered as the condition where the majority of the muscles involved are shortening near their optimal velocity (Sargeant 1994; Zatsiorsky 2008). In this line it is interesting to note that V_{opt} values reported in subjects specialists in "explosive" performances (and hence presumably characterized by a higher percentage of fast twitch muscle fibers) are classically higher than those reported in endurance athletes (Buttelli et al. 1996; Davies et al. 1984; Dorel et al. 2003, 2005; Gardner et al. 2007; Hintzy et al. 1999; Sargeant et al. 1981; Vandewalle et al. 1987). The optimal pedaling rate range between almost 90–100 rpm for extremely low values up to 140–145 rpm for extremely high values. Interestingly, this link between the proportion of fast twitch fibers and V_{opt} was experimentally demonstrated in two subjects (McCartney et al. 1983a) and ten healthy specifically trained subjects (Hautier et al. 1996) confirming that this high proportion of type II fibers, at least on the knee extensor muscle, may be one factor associated with a high pedaling rate for maximal power. As depicted on Fig. 2.4, the fact that V_{opt} is gradually impaired with advancing aging (Bonnefoy et al. 1998; Martin et al. 2000) can be confidently related to the well-known deterioration of the maximal unloaded shortening velocity of muscle fibers with aging (Power et al. 2016) and further suggest that fiber type distribution influences, at least partly, the V_{opt} ability.

Nevertheless due to the characteristics of the movement, other factors clearly influence the maximal pedaling rate. Among them, we can point specifically the muscle coordination and the activation dynamics (see next chapter for more details). As cycle frequency increases, the capacity of nervous system to activate and deactivate the muscles increase in importance, and then have a significant

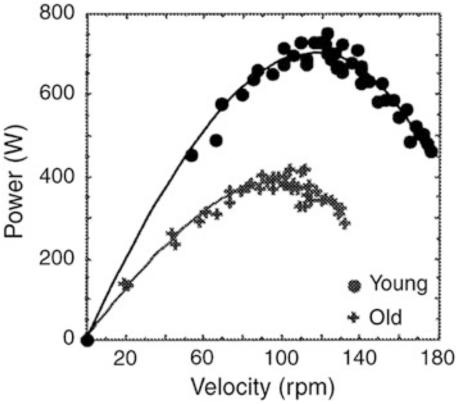


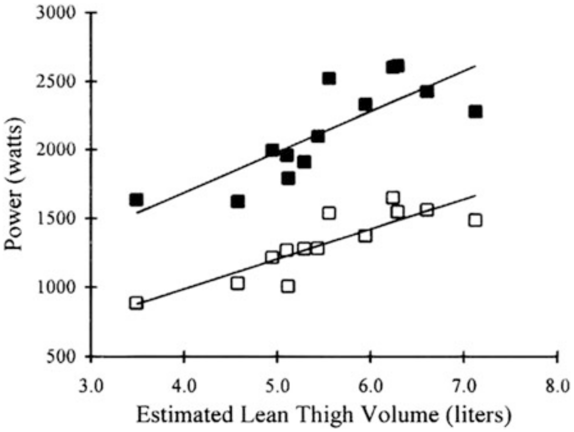
Fig. 2.4 Typical power-velocity of an young and an old individual illustrating the great difference in maximal power due to both a decrease in maximal force and velocity capabilities (note the decrease in optimal velocity, Bonnefoy et al. (1998))

influence on force production additionally to the intrinsic force- and power-velocity characteristics of the muscles (Bobbert et al. 2015; Caiozzo and Baldwin 1997; Neptune and Kautz 2001; van Soest and Casius 2000). Moreover, the coordination between the muscles seems to have a significant impact on the capacity to continue to produce a high force at pedaling rate higher than V_{opt} (Samozino et al. 2007) and is even more critical at extreme pedaling rate (Dorel et al. 2014).

Optimal and maximal effective force (or crank torque). Due to the linear model, both indexes corresponds the same global qualities of force (i.e. $F_{\mathrm{opt}} = 0.5\ F_{\mathrm{max}}$). F_{max} is the theoretical maximal "isometric" force produced on the pedals by both legs. This data is not frequently reported in the literature compared to P_{max} and often expressed in different units (braking force at the flywheel, crank torque or effective force applied on the pedals) making difficult to compare the values. By referring to data directly observed or basing on the P_{max} and V_{opt} values we can state that F_{max} values expressed in torque range between almost 115–120 Nm for extremely low values (unpublished data: recreational or endurance road cyclists or triathletes) up to 300–320 Nm for extremely higher values (unpublished data: world-class BMX and track sprint male cyclists). This index is clearly considered as reflecting the maximal force ability of the main lower limb extensor muscles and then as a good indicator of maximal strength. In this line, significant relationships have been demonstrated between F_{max} and different indexes of specific maximal isometric or isokinetic peak torque (i.e. between 0 and 240° s^{-1}) of the knee extensors on single-joint ergometer when data were expressed in absolute units or normalized to the quadriceps mass (Driss et al. 2002). Moreover, F_{opt} and F_{max} were significantly related to thigh muscle area or volume determined from tomodensitometry (Linossier et al. 1996; McCartney et al. 1983a). Finally, a similar link was also reported with the lean leg volume (estimated by anthropometry using Jones and Pearson's technique Jones and Pearson 1969) in a relative homogeneous population of elite track sprint cyclists ($r = 0.77$, $p < 0.01$, Dorel et al. 2005).

Maximal power. Theoretically maximal power depends on both force and velocity capabilities. P_{max} values measured in very different populations range between 500–600 W/10 W·kg^{-1} and 2100 W/22 W·kg^{-1} (Arsac et al. 1996; Dorel et al. 2005; Driss and Vandewalle 2013; Gardner et al. 2007; Hintzy et al. 1999; Martin et al. 1997; Vandewalle et al. 1987) up to almost extremely high values of 2400–2500 W and 25–26 W·kg^{-1} (unpublished data on world-class BMX and track sprint male cyclists). These extreme values are logically recorded on subjects exhibiting low (almost 100 rpm) and high V_{opt} (almost 135–140 rpm) respectively (in relation with the proportion of fast twitch fibers). In this line it has been reported significant relationship between P_{max} and V_{opt} in quite heterogeneous population (Arsac et al. 1996; Hintzy et al. 1999). However, the $\sim$40% difference in "velocity" capability is dramatically lower compared to the $\sim$300% difference in P_{max}. It should therefore keep in mind that despite importance of velocity, force capability is definitively the main key factor that explains such great differences in P_{max} between subjects. In this line, no relationship was reported between P_{max} and V_{opt} in homogeneous elite track cycling sprinters while a strong relationship ($r = 0.92$, $p < 0.001$) was observed with F_{max} (Dorel et al. 2005). In the same way, a lot of

Fig. 2.5 The relationship between maximal power measured during a force-velocity test and the estimated lean thigh volume (n = 13): peak power obtained during the cycle in black, mean power produced over the complete cycle in white, Martin et al. (1997)



studies highlighted direct correlation (Fig. 2.5) between P_{max} and indices of muscle mass or lean leg of thigh volume (Linossier et al. 1996; Martin et al. 1997; Pearson et al. 2006) and interestingly some of them reported the same statistical significance for the relationship between strength indexes of knee extensors and P_{max} than that obtained with F_{max} ability (Driss et al. 2002).

What about the improvement possibilities by training? Based on the aforementioned literature and a longitudinal follow-up of elite track cyclists in the last 15 years with the French Federation of Cycling, it is reasonable to think that strength capacities are the best candidate for improvement power at both short and long terms. It is in agreement with the impressive increase of muscle mass and the maximal force measured in strength and conditioning movements (e.g., squat exercise) observed on the athletes throughout their career. Moreover, it is also corroborated by the concomitant alteration classically observed in maximal force and power in cycling and the muscle mass and force indexes of the athletes in periods of detraining or reprise of training. In the same time, the alteration of V_{opt} or V_{max} are note really noticeable (between these periods or throughout the career). The question is: does it means that velocity capabilities are not important and cannot be improved? Three arguments suggest that the question is not so obvious and the answer is likely no. First, the extremely highly powerful athletes are also those that exhibit the highest V_{opt} values (e.g. between 135 up to 145 rpm for the best 4–5 elite sprint track and BMX cyclists performing all at the highest international level; unpublished personal data). Basically, compared to an athlete A with P_{max} = 2000 W and V_{opt} = 130 rpm an athlete B with the same maximal force but with a V_{opt} = 140 rpm directly benefits from almost additional 150 W at P_{max}. Second, even rarely, new young adult athletes can sometimes show non negligible increase of V_{opt} ($\sim$10 rpm) in early years of training; perhaps linked to an improvement of muscle coordination. Thirdly, although the gain of V_{opt} are limited (certainly mainly due to the influence of heredity on the muscle typology), we know that possible change in a range of 5–8 rpm can appear over the time (as a result of a velocity-specific training block or related to a period of very high level of expertise during the career). For all these reasons, it appears that velocity capabilities are non-negligible and that testing $V_{\max}$ remains interesting and should still be considered for talent identification and development (Tofari et al. 2016).

2.4 Methodological Consideration and Practical Advices

2.4.1 Period of Averaging to Draw F-V or P-V Relationships and Duration of the Sprint

Mean cycle versus peak instantaneous values. As previously described, the phase/period for averaging values on cycle ergometer classically corresponds to a full crank cycle because matching with the period of the cyclic movement (i.e. during which each muscles are activated on one phase and deactivate on another). As movement is done by both legs in antiphase it is also often proposed to average the data only on one half cycle which corresponds to only one pedal stroke (i.e. the downstroke of one leg + upstroke of the contralateral leg) while a full cycle corresponds to two pedal strokes (i.e. downstroke and upstroke of each legs in antiphase). Note that if the different measurement sensors and the acquisition system allow to record quasi instantaneous values it is then possible to describe the torque profile inside each pedal cycle (see the next chapter). As a consequence, in rare cases (specially in former studies) the peak "instantaneous" values of force and power reach in each pedaling cycle are reported (Beelen and Sargeant 1991; McCartney et al. 1983a; Sargeant et al. 1981), these values being clearly not comparable with the classical mean values on cycle (i.e. almost 50% higher).

Sprint duration and influence of the occurrence of early fatigue. Practically, the choice of the period of time (or number of cycles) to be included for each bout is an important question to draw fatigue-free force- and power-velocity relationships. During a maximal sprint performed at a constant pedaling rate (to avoid the effect of the pedaling rate confounding factor, Gardner et al. 2009; Tomas et al. 2010) the power output can be maintained during a very short period of almost 4–5 s depending on velocity (higher pedaling rate inducing a higher decrease) and certainly the athletes' individual profile (endurance vs. sprint athletes) (Beelen and Sargeant 1991; Dorel et al. 2003; McCartney et al. 1983a). It is therefore important to remove frome the analysis all the values for which fatigue potentially already occurs at the end of the sprint: after 3–4 s for low pedaling rates (50–120 rpm) and maximally after 3 s for high pedaling rates (120–250 rpm). On the other hand, it is possible to include more data (4–5 or 5–6 s) keeping in mind that the $P_{\max}$ and associated $V_{\max}$ resulted from the relationships would then represent a slight different capability (e.g., 5–8%) also already accounting a fatigue resistance ability (Fig. 2.6).

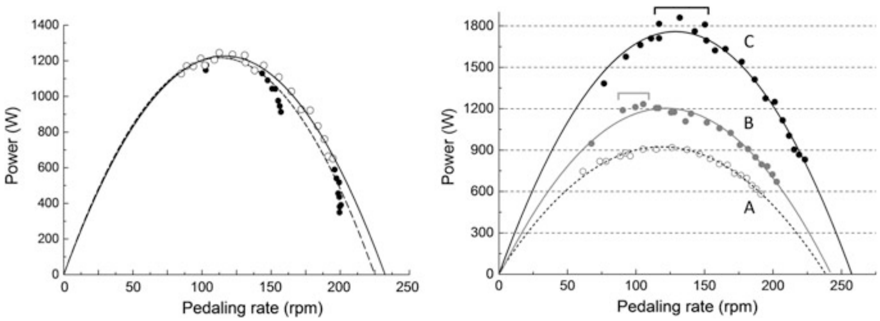


Fig. 2.6 **Left**: Effects of taking into account the power values produced during the first 3 s (white) versus the first 5 s (white + black) of the three sprints performed during F-V testing session. Despite an absence of a great influence on the maximal power estimation, black points illustrate an effect of early fatigue for this individual leading to a significant underestimation of the maximal velocity and the power at the high pedaling rates (and likely an overestimation of the maximal force, not illustrated here). **Right**: typical example of P-V relationships for 3 subjects illustrating the importance of visual inspection of data in addition to the coefficient of determination of the model (R^2). Maximal power (P_{max}), optimal velocity (V_{opt}) extracted from the model, and mean of the three higher power values (P_{Peak}, bracket) and the associated velocity (V_{Ppeak}) for each subject are as follows: (A) $P_{\text{max}} = 912$ W, $V_{\text{opt}} = 119$ rpm; $R^2 = 0.977$; $P_{\text{peak}} = 900$ W at $V_{\text{Ppeak}} = 121$ rpm; (B) $P_{\text{max}} = 1182$ W, $V_{\text{opt}} = 120$ rpm; $R^2 = 0.968$; $P_{\text{peak}} = 1195$ W at $V_{\text{Ppeak}} = 105$ rpm; (C) $P_{\text{max}} = 1760$ W, $V_{\text{opt}} = 129$ rpm; $R^2 = 0.982$; $P_{\text{peak}} = 1828$ W at $V_{\text{Ppeak}} = 133$ rpm. See details of interpretation in the text

2.4.2 Quality of the F-V and P-V Models: "Calculated" Versus "True" Data

As a whole, the reliability of the force-velocity test is well established (Jaafar et al. 2015) and we can be even more confident for data obtained on athletes. Nevertheless, to go a step further in the use of the indexes, some advices can be serve. The power of the linear and quadratic models to estimate useful values of P_{max} and V_{opt} and others indexes logically depends on the number of points, the capacity to obtain points on a large range of pedaling rates below and above V_{opt} and the coefficient of determination (R^2). One can consider that the latter should be at least equal to 0.80–0.85 but it might be better to obtain a coefficient higher than 0.9–0.95 to enable valid assessments. Figure 2.6 illustrates three typical examples of P-V relationships for which the model fits the data very well (i.e. extremely high R^2 values: from 0.968 to 0.982) and the P_{max} values nicely represent the differences in the power capacity of the three subjects. Beyond that, the visual inspection of data in respect to the fitted curve remains important to avoid some over-interpretation. The gold standard should correspond to the typical example A for which both P_{max} and V_{opt} extracted from the model exactly correspond to the real values obtained. For the example B, while P_{max} remains very reliable (only 1.1% of difference between P_{max} and the mean of the three higher power values: P_{Peak}), it appears that V_{opt} determined by the model (120 rpm) is partly overestimated in the sense that P_{peak} is almost reached at a 12.5% lower pedaling rate (around 105 rpm). That means that the athlete B is actually not prevented from producing his maximal power for pedaling rates around 100 rpm as it is predicted by the quadratic model. For the athlete C, $P_{\max}$ assessed by the model is almost 50 W lower than P_{peak} which corresponds to a non-negligible difference of almost 3%.

Consequently, in the context of the longitudinal follow-up of training it can be advised to primary consider $P_{\max}$, $F_{\max}$ and V_{opt} to better quantify gains in force and velocity capacities in response to the training period. In the same time, in the cases where modeling has the aforementioned limitations it is advisable to refer to real values for some practical application: (i) for choosing the suitable gear ratio to adapt pedaling rate with the goal to maximize the power during a sprint on the field (for example for the cyclist B) or (ii) for comparing and better interpreting the peak power obtained using powermeter on the field in comparison with the maximal power obtained during the stationary cycle ergometer testing procedure (for example for the cyclist C). Finally, note that P-V model often used a more constrained equation by setting the y-intercept as 0 (i.e. constant $c = 0$, in all the figures presented in this chapter). This process can slightly influence the capacity to fit the true data but is interesting to extrapolate more realistic power at extreme cadences (low or high). So, that is important to control for inter and intra-individual comparisons.

2.4.3 Main Factors to Control that may influence Maximal Power Output

Different parameters can influence the force and/or the velocity produced on the pedals and the question is to know whether it might alter the maximal power capability. Among them, the seat height and the crank length, the nature of the shoe-pedal interface and the use of a standing versus seating position are the main recognized factors but they do not act on the same manner and with the same extent on the power output. Rather than presenting a detail analysis of these factors, the purpose here is just to insist on their main effect, in order to (i) select them appropriately and (ii) control these parameters in both the context of longitudinal follow-up of training and evaluation/detection of athletes.

Ergometer setup: seat height and crank length. Seat configuration (seat tube angle and height) can theoretically influence the pedal power by altering the lower limbs kinematics (specifically the range of motion of each joints) and ultimately the force produced by each muscle groups. However, by simulation (Rankin and Neptune 2010) it was demonstrated that the influence of seat tube angle is actually limited (i.e. almost 1% for a wide range of 65°–110°) when considering only the classical cycling configuration (i.e. not the recumbent cycling). For these authors, the seat height has a greater impact and they proposed an optimal value corresponded to 102% of greater trochanter height (and an average knee flexion angle of 101.7° with min = 59.6° at TDC and max = 153.6° at TDC). Actually and despite the more and more popularity of the bike-fitting consulting activity, the setting of these parameters is not obvious. The problem is that too many parameters interact to be able to conclude about an "optimization": the anthropometric (segment lengths), the comfort (depending on the duration of the effort, the joint flexibility, etc.), the alteration of upper body posture and hence the aerodynamic resistances, the degree of freedom allowed by the natural displacement of the hip on the saddle. Moreover, it should be examined in concert with the choice of the crank length since they can together alter the kinematics and then the range for force generation by each joint based on the force-length relationship. Overall, different trials (e.g. force-velocity test) should be done to experimentally confirm that a position is better for each individual.

By itself the crank length does not drastically influence the maximal power (Martin and Spirduso 2001) because even if it changes the link between the force and the velocity, $P_{\max}$ is not deteriorated in a large range of crank lengths (i.e., 145–195 mm). Although a standard crank length (170–175 mm) can therefore be confidently used in adults without concern of decreasing maximal power, an optimal crank length of 20% of leg length was still suggested by these authors. It is interesting for specific population such as very short athletes or the children and adolescents (Martin et al. 2002). One practical consequence however is that the optimal pedaling rate increases with the decrease of crank length. When different bicycles equipped with different crank sizes are used by the athletes on the field, it is therefore interesting to take into account this influence to adapt pedaling rate and gear ratio. Basing on the previous studies and the testing database of elite sprint cyclists (personal unpublished data), we can confidently state that a change in 10 mm of the crank length corresponds to almost an alteration of 4–5 rpm in V_{opt}.

Pedal and toe-clips. It was early demonstrated that during the upstroke phase of the pedal, athletes can actively pull on the pedal to partially transmit additional force to the crank (Beelen et al. 1994; Dorel et al. 2010; Martin and Brown 2009). As a consequence, presence of toe-clips with straps or clipless pedals necessary induce significant change in the maximal values obtained during a torque-velocity test (Capmal and Vandewalle 1997). Hence an almost 10–20% difference has been reported in $P_{\max}$ or $F_{\max}$ in the last study depending on the shoe-pedal interface, and we can reasonably think that it also significantly influences the value of $V_{\max}$ (or V_{opt}). As we will discuss in the next chapter, the relative contribution of the muscles involved in the flexion phase should not be neglected especially during the sprint compared to the submaximal exercise (Dorel et al. 2010; Driss and Vandewalle 2013; Elmer et al. 2011). If the use of flat pedals would theoretically be interesting to better isolate on the work of the lower limb extensors only, it is not advised for two reasons: it does not avoid a partial non-controlled contribution of the contralateral leg during the flexion phase (at least the partial effect of its weight) and it remains very challenging to follow the pedal trajectory in this phase, especially at very high pedaling rates.

Effect of body position: seating/standing. Standing position when sprinting allows to produce a higher maximal power output compared to seating (Driss and Vandewalle 2013; Hug et al. 2011; Reiser et al. 2002). This is mainly explained by the effects of a higher participation of the body weight over the pedals, an additional recruiting of the upper limb and trunk musculature (Turpin et al. 2017), along with some positive adjustment of muscle coordination such like a higher or longer recruitment of some muscles throughout the pedaling cycle (hamstring during the extension-flexion transition, quadriceps and gluteus maximus during the second part of the pushing phase; (Hug et al. 2011) and personal unpublished data). In this context, further studies are still needed to better elucidate all the biomechanical and neuromuscular factors of influence. If some studies reported a gain of about 8–15% (Driss and Vandewalle 2013; Reiser et al. 2002; Vandewalle et al. 1988) it is not easy to state on a 'typical' mean value regarding the amount of the benefit. Indeed, the benefit can be very different between the subjects and sometimes very poor (e.g., 50 W = +2.2%, on an elite male sprint cyclist with 2250 W of $P_{\max}$ in seating position) or very important (e.g. 160 W = 16.7% on an elite female sprint cyclist with 960 W of $P_{\max}$ in seating position; unpublished personal data). It is often accompanied by difference in the optimal velocity which are often slightly lower (0–10 rpm) in standing position; however, it is again difficult to draw up a general rule because few subjects can also exhibit a slight higher V_{opt} in standing position (e.g., elite BMX or sprint track riders). Maybe specific skills and segment length can also partially explain this interindividual variability in the seating/standing difference observed regarding the maximal power and velocity abilities. Both values can have the same practical interest if the athlete rides in both positions on the field, but it is then more appropriate (and very recommended) to test cyclist in the same position in laboratory and field conditions to gain a better overview of his capabilities.

2.5 Field Measurement in Ecological Condition

As detailed above, the force-velocity test on cycle ergometer is specific of the cycling performance and then is a largely accepted method to describe and predict the mechanical behavior of the cyclist in sprint condition on the field. However, in addition to this classical reference method, the use of additional "field" data bring real benefits for both coaches and sports scientists:

- firstly, little changes in body configuration can occur in field condition (especially lateral oscillation of the cyclist and his bicycle commonly observed when sprinting) and hence may slightly influence the power produced (Faria et al. 2005);
- consistent with that, this would be particularly right at very high level of force during a sprint starting performance and then the classical stationary force-velocity test does not perfectly evaluate the real-life practice specifically

for conditions at extremely high force and low cadence (i.e., lower than 70 rpm);

- additionally, power measurement allow today to better characterize the effort on the field, and to better identify and control the muscular quality worked during training sessions (e.g., force or power predominance);
- finally, beyond all of that, the external resistance and mechanical constraints applied on the cyclist on the field are strongly different compared to the stationary force-velocity test and could be very diversified. Although that should not impair the maximal power capability of the subject (except if optimal velocity condition is not verified), it largely influences the relative contribution of each resistance/constraint on the power demand and hence factors of performance such like the maximal speed or the acceleration of the athlete.

2.5.1 Mathematical Model of Sprint Cycling

Since the first work of di Prampero et al. (1979), different mathematical model were developed to estimate the power produced on the field by the cyclist. Historically, the challenge was really to determine the power demand basing on the different applied external resistances and the variation in the mechanical energy in order to infer a reliable estimation of the muscular power produced by the athlete. Whatever the model proposed (Martin et al. 2006, 1998; Olds 2001; Olds et al. 1993) that corresponds to the power required to overcome air resistance and rolling resistance and the power required to change the kinetic energy and/or the potential energy of the system (Eq. 2.12):

$$\mathrm{P} = \mathrm{C}_d\mathrm{A} \cdot \frac{1}{2} \cdot \rho \cdot V^3 + \mu.\mathrm{Fn}.V + \frac{\Delta\mathrm{Ep}}{\Delta\mathrm{t}} + \frac{\Delta\mathrm{Ek}}{\Delta\mathrm{t}} \tag{2.12}$$

with $\mathrm{C}_d\mathrm{A}$ represents a coefficient including both the effective frontal area and the drag coefficient of the system (cyclist + bicycle); ρ is the air density, μ is a global coefficient of friction, F_n is the normal force on the surface due to the weight of the system, V, the velocity of the system cyclist + bicycle (in absence of wind) and ΔEp and ΔEk the variation on the period of interest (Δt) of potential and kinetic energy, respectively.

When looking in detail this equation it appears not simple to use this model to evaluate maximal power of the cyclist in routine on the field. Indeed, measuring (or reliably estimating) the different coefficients requires complex, expensive and less accessible methodologies especially for the aerodynamic coefficient (e.g., wind tunnel), which often represents the most important factor due to the importance of the air resistance with the increased speed. For that, it is possible to use field-derived values for modeling $\mathrm{C}_d\mathrm{A}$ and μ coefficients (thanks to testing sessions by means of a portable powermeter system, see the next part) and to apply the