Friction-loaded cycle ergometers: Past, present and future

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Abstract: The first friction-cycle ergometers of the end of the nineteenth century and the beginning of the 20th century are presented before the description of more recent ergometers such as Fleisch ergometer (1954), Ergoméca™ (1985), sinus-balance ergometer, and weight-basket loaded ergometer. The limits of each ergometer are debated. The interest of friction-loaded ergometers was renewed with the proposal of different protocols enabling the assessment of maximal power during short all-out sprints on a cycle ergometer. These protocols are succinctly presented: corrected peak power protocol, force–speed test during repeated all-out sprints against different loads, torque–velocity relationship during a single all-out sprint. The different calibration procedures (static, dynamic, and physiological calibrations) of friction-loaded ergometers are described before the presentation of their results in the literature. Some improvements for the future friction-loaded ergometers are presented at the end of the paper.

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PUBLIC INTEREST STATEMENT

The history of the first friction-cycle ergometers (end of the nineteenth century) is presented before the description of more recent ergometers: Fleisch ergometer (1954), sinus-balance ergometer (von Döbeln, 1954), Ergoméca™ (1985), and weight-basket loaded ergometers. The interests and limits of each ergometer are debated. The interest of these friction-loaded ergometers was renewed with the proposal of different protocols enabling the assessment of maximal power during short maximal sprints on a cycle ergometer. These protocols are succinctly presented. The different calibration procedures of the cycles ergometers and theirs results are also presented: static calibration (calibration of the braking mechanism without pedal rotation), dynamic calibration (comparison of the displayed power and the torque exerted by a motor on the cranks), and physiological calibration (measure of oxygen uptake during cycling at different power outputs). Some improvements for the future friction-loaded ergometers are presented at the end of the paper.
1. Introduction

Treadmills and cycle ergometers are the devices generally used in medical and physiological testing or aerobic training. Many kinds of cycle ergometers have been designed in relation to their usage. The braking mechanism of most of these ergometers is either electromagnetical or mechanical or aerodynamical.

In experiments carried out between 1898 and 1900, Atwater and Benedict (cited in Benedict & Cady, 1912) studied human metabolism at rest and during long lasting exercises performed on a cycle ergometer that consisted of a pulley mounted on the shaft of a small dynamo pressing against the rear wheel of an ordinary bicycle. Thereafter, Benedict and Carpenter (1909) described and constructed an electromagnetically braked cycle ergometer that was modified by Benedict and Cady (1912). The work done per revolution was estimated from the intensity of the current employed for actuating the magnets. However, the work done per revolution depended not only on the magnetizing current but also varied with the speed. Krogh, Nobel prize in medicine in 1920, described an electromagnetic ergometer measuring the reaction torque acting on the magnets by means of a balance, instead of measuring the magnetizing current as in the Benedict ergometer (Krogh, 1913). Thereafter, many improvements in electromagnetic cycle ergometers were proposed (Atkins & Nicholson, 1963; Atkins & Nünlist, 1966; Harrison 1967; Kelso, Hellebrandt, & Madison, 1933; Tuttle & Wendler, 1945; Williams, Barnes, & Signorile 1988). But the most significant advance in electromagnetic ergometer was the description of hyperbolic ergometers, i.e. ergometers with constant work power at varying pedal rate (Holmgren & Mattsson, 1954; Lanooy & Bonjer, 1956). Indeed, errors in pedal cadence are probably one of the main causes of errors in power output with non-hyperbolic ergometers in subjects who are not habituated to cycling exercises. Nowadays, the electrically braked ergometers generally includes a compensatory circuitry measuring cadence and torque continuously to maintain a constant power input from the subjects over a range of pedal rates (e.g. 40–100 rpm). Expensive hyperbolic electromagnetic cycle ergometers are generally used in medicine and physiology for the stress tests in cardiac patients and the evaluation of aerobic metabolism (maximal oxygen uptake). Generally, the users of these hyperbolic cycle ergometers do not perform any calibration procedure but rely entirely on the original calibration by manufacturer. Indeed, dynamic calibration procedure needs an expensive calibrator and is time consuming. However, hyperbolic ergometers cannot be used for the evaluation of maximal anaerobic power (Driss & Vandewalle, 2013). As for car motors, the rotational speed optimal for maximal anaerobic power (100 rpm in elite endurance athletes up to 130 rpm in elite sprinters) is higher than the rotational speed optimal for the efficiency (60–90 rpm) of submaximal and maximal aerobic exercises. Therefore, the range of pedal cadence with a hyperbolic ergometer is adapted to the study of aerobic metabolism (submaximal and “maximal” exercises) but, generally, not to the evaluation of anaerobic metabolism (“supramaximal” exercise). In addition, the durations of the all-out anaerobic exercises are too short (a few seconds) for the adjustment of power by hyperbolic cycle ergometers and the required power outputs (600 W in endurance athletes up to 2,000 W in elite sprinters) are generally higher than the maximal powers of these ergometers.

Aerodynamically braked ergometers have been used for anaerobic testing (Withers, Van Der Ploeg, & Finn, 1993). For aerodynamical ergometers, resistance is not only proportional to the square of pedal rate but also depends on air density, that is, on barometric pressure, temperature, and air humidity. In contrast with the mechanical and electromagnetic ergometers, power output is proportional to the cube of pedal rate with aerodynamical-braked ergometer. For example, the errors in power-output corresponding to a one-revolution error in pedal rate are equal to 5 and 3.8% at 60 and 80 rpm, respectively. These ergometers are mainly used for training (cycling, rowing) but seldom in physiological and medical testing, although the accuracy of these ergometers has been found correct in studies comparing the accuracy of different kinds of cycle ergometers (Balmer, Davison, Coleman, & Bird, 2000; Maxwell et al., 1998).

Friction-loaded cycle ergometer is less expensive, do not need electricity, and can be statically calibrated. On the other hand, power of the friction-braked ergometer depends on pedal cadence which is generally given by a metronome and is displayed on an analogical tachometer or a digital
device. Therefore, the hyperbolic electromagnetic ergometer is preferred for the medical testing in subjects not habituated to cycling exercises. However, the interest of friction-loaded cycle ergometers was renewed when different protocols were proposed for anaerobic metabolism testing with this kind of ergometers (Ayalon, Inbar, & Bar-Or, 1974; Bar-Or, 1987; Driss & Vandewalle, 2013). Moreover, some maximal anaerobic power tests based on the relationship between pedal rate and maximal torque (Sargeant, Hoinville, & Young, 1981; Vandewalle, Pérès, Heller, & Monod, 1985) cannot be performed with hyperbolic ergometers. Different models of friction-loaded cycle ergometers are available but most of the users do not know which ones are the most suitable (testing and/or training, aerobic and/or anaerobic exercises, children and/or adults ...) and how to assure the maintenance and calibration of these ergometers.

The present paper is focused on the friction-braked cycle ergometers used in physiology and medicine. It begins with the evolution and description of the first cycle ergometers before the presentation of the friction-loaded ergometer currently used in medical and physiological studies (Hollmann & Prinz, 1991). Thereafter, the mechanical basis of the measurement of maximal anaerobic power with friction-brake ergometers is presented. The last chapters concern the calibration methods, the maintenance, and the future of friction-loaded cycle ergometers.

2. Friction-loaded ergometer: Past
Mechanically braked cycle ergometers are based on the transformation of power output in heat by dissipative friction forces. The first ergometers were derived from the dynamometers and brakes which have been proposed by engineers for the first industrial machines: Prony’s brake and rope brakes.

2.1. Prony cycle ergometer
In Austria, a crank ergometer called “Ergostat” (Gaertner, 1887) based on the principle of the Prony brake was used in the study of exercises performed with the arms. The same kind of crank ergometer was used by Zuntz (1899) at Berlin. It is likely that the first cycle ergometer was the ergometer constructed in France by E. Bouny in collaboration with J.E. Marey, a pioneer of motion analysis (Bouny, 1896a, 1896b). This cycle ergometer was made of a bicycle whose ordinary wheel was replaced with a flywheel and a Prony brake mounted on the same axle. The work performed on this device was compared with the simultaneous measures of force by means of Marey’s ergometric pedals modified by Bouny. The work measured with ergonomic pedal was approximately 5% higher than the work measured with the Prony brake, which was attributed to energy loss in the transmission between pedal and braking device. Although it is theoretically possible to design Prony brakes with constant torque (Poncelet, 1876), the arm lever of a Prony brake tends to oscillate (Jervis-Smith, 1915). Therefore, the position of the arm lever of the Prony brake and pedal rate was continuously recorded to know the amount of work performed on the Bouny’s ergometer. In fact, the purpose of Bouny was not the measurement of work in man but the validation of his modifications of Marey’s ergonomic pedal. An adaptation of the Prony brake with a lever exerting a torque on the ergometer flywheel by means of a brake shoe has been presented by Harrison (1967) but has not been used in physiological or medical studies.

2.2. Rope brake ergometers: General principles
Let a rope wrapped around a rotating cylinder (Figure 1), the force $F_T$ exerted on the tight extremity of the rope by the friction force of the rope sliding on the cylinder is given by the following equation:

$$F_T = F_S e^{\nu \mu}$$

(1)

$$\frac{F_T}{F_S} = e^{\nu \mu} = k$$

where $F_S$ is the force exerted on the slack extremity of the rope, $\nu$ corresponds to the winding (angle in radian) of the rope around the cylinder, and $\mu$ is the dynamic friction coefficient. The value of $F_S$ necessary to the production of $F_T$ is given by the following equation:
If there is no other external force acting on the rope, the force $F$ exerted by the rotating cylinder is:

$$F = F_T - F_S$$

When the rope consists of two elements in series (e.g. a belt and a rope), the values of $F_T$ and $F_S$ are:

$$F_S = F_T e^{-\theta \mu}$$

$$F_S / F_T = 1 / k$$

If there is no other external force acting on the rope, the force $F$ exerted by the rotating cylinder is:

$$F = F_T - F_S$$

$$F = F_T - F_S = (k - 1) F_S$$

$$F = F_T - F_S = (e^{\theta \mu} - 1) F_S$$

$$F = F_T - F_S = (F_T - F_T/k) = (1 - e^{-\theta \mu}) F_T$$

$$F_T = F / (1 - e^{-\theta \mu})$$

$$F_S = F / (e^{\theta \mu} - 1)$$

When the rope consists of two elements in series (e.g. a belt and a rope), the values of $F_T$ and $F_S$ are:

$$F_{S1} = F_T e^{-\theta_1 \mu_1}$$

$$F_{S2} = F_{S1} e^{-\theta_2 \mu_2}$$

$$F_{S2} = F_T e^{-\theta_1 \mu_1} e^{-\theta_2 \mu_2} = F_T e^{-(\theta_1 \mu_1 + \theta_2 \mu_2)}$$

$$F_{S2} = F_T e^{-\beta} \text{ with } \beta = \theta_1 \mu_1 + \theta_2 \mu_2$$

If $\theta_1 = a \theta$ and $\theta_2 = (1-a) \theta$

$$\beta = a \theta \mu_1 + (1-a) \theta \mu_2$$

$$\beta = \theta [\mu_2 - a (\mu_2 - \mu_1)]$$

$$F_T / F_{S2} = k = e^\beta$$

where $\theta_1$ and $\mu_1$ correspond to the winding and friction coefficient of the belt, whereas $\theta_2$ and $\mu_2$ correspond to the winding and friction coefficient of the rope.

Working with one of the first transatlantic cable companies, W. Thomson (Lord Kelvin) registered a patent in 1858 for the improvement of the braking of the cable-laying system (cited in Jervis-Smith, 1915). This friction brake consisted of a rope wrapped around the circumference of a rotating cylinder.
wheel, with a weight \( W \) applied at one end and a spring balance fixed to the other end. In this brake, the value of \( F_T \) was equal to \( W \) and \( F_S \) to the force that was registered by the spring balance. If product \( \mu \theta \) was sufficiently large, the value of \( k \) was high and \( F_S \) was low, which rendered the errors in the observation of the spring balance negligible.

However, this friction-brake design was not used in most of the first friction-braked cycle ergometers. For example in the Martin’s ergometer used in the studies by Dickinson (1928), the values of \( F_T \) and \( F_S \) were given by spring-dynamometers linked at both extremities of the belt. The friction force \( (F_{FW}) \) of the flywheel sliding on the belt was equal to the difference of \( F_T \) and \( F_S \) (Figure 2).

2.2.1. Amar’s “Cycle ergométrique”
In his study on the efficiency of human machine, Amar used an ergometer (Figure 3) made of the frame of a bicycle with a 36 kg flywheel in the place of the ordinary wheel (Amar, 1909). A steel ribbon was laid in a channel in the circumference of the flywheel with one end attached to a traction dynamometer and the other end carrying a platform for weights. But, in contrast with the friction-brake designed by Lord Kelvin, the weight-platform was attached to the slack end of the ribbon. One pedal revolution corresponded to three flywheel revolutions and a point of the circumference of the

![Figure 2. Braking mechanism of the first friction-loaded ergometers; braking force acting on the flywheel \((F_{FW})\) is equal to the difference between tight \((F_T)\) and slack \((F_S)\) forces which were displayed by means of scale.

Note: Pedal rate, \( F_T \) and \( F_S \) had to be continuously recorded or adjusted to know the actual work.

![Figure 3. Amar’s cycle ergometer; D, P, and R correspond to the dynamometer, platform for weight, and steel ribbon, respectively.

Note: Red and blue arrows correspond to \( F_T \) and \( F_S \), respectively.](image)
wheel travelled 6.18 m as the perimeter of the wheel measured 2.06 m. Therefore, power output was close to 1 W for a pedal rate equal to 1 rpm and a one kilogram-force difference between $F_T$ (force measured by the dynamometer) and $F_S$ (weight on the platform), as 1 kgm min$^{-1}$ is equal to 6.11 W.

Twenty years later, Dickinson replaced one spring-dynamometer (slack or tight end of the rope?) with a weight to improve the accuracy of the estimation of work at low braking torque in her study on the efficiency of bicycle pedaling (Dickinson, 1929). Holzer and Kalinka (1935) presented a cycle ergometer based on the same mechanism: $F_S$ was equal to a weight and $F_T$ was measured with a dynamometer as in Amar’s ergometer. However, in the description of the Holzer–Kalinka ergometer by Mellerowicz (1962), $F_T$ and $F_S$ were swapped: $F_T$ was equal to a weight and $F_S$ was measured with a dynamometer in agreement with the friction-brake designed by Lord Kelvin.

2.2.2. Fleisch ergometer
In the same year Carpentier (1880) and Thomson (cited by Beaumont, 1889) presented, the same kind of brake dynamometers (Figure 4) “in which the same principle of automatic government of friction is employed. In order to keep $e^{\mu\theta}$ constant, $\dot{\theta}$ is made to vary inversely as $\mu$.” (Jervis-Smith, 1915). This kind of brake dynamometers consists of two pulleys of the same diameter placed side by side on a revolving shaft. The first pulley (fast pulley) is rigidly fixed to the shaft, the other (loose pulley) runs freely on the shaft.

Figure 4. Thomson brake (drawing adapted from Beaumont, 1889, p. 33; Jervis-Smith, 1915, p. 82).

Notes: L corresponds to the loose pulley and F to the fast pulley, rigidly fixed to shaft S; P: fixation of the tight rope (in red). C: connection between the loose pulley and the rope (in blue) rubbing on the fast pulley.
Fleisch (1950) who previously invented the differential pneumotachometer in 1925 presented a friction-loaded ergometer whose braking torque was constant. This cycle ergometer (Figure 5) was based on the Carpentier–Thomson brake. The braking force acting on the flywheel ($F_{FW}$) is equal to the difference between $F_T$ and $F_S$ which depends on the friction coefficient ($\mu$) and the winding ($\theta$) of the belt ($B$) around the flywheel (fast pulley, $F$):

$$F_{FW} = F_T - F_S$$

$$F_T/F_S = e^{\mu\theta} \quad \text{and} \quad F_S/F_T = e^{-\mu\theta}$$

$$F_{FW} = F_T - F_S = (e^{\mu\theta} - 1) F_S = (1 - e^{-\mu\theta}) F_T$$

If $F_T$ and $F_S$ are set by weights $W_1$ and $W_2$, the value of $F_{FW}$ is constant if $\theta$ adequately increases when $\mu$ decreases and vice versa. Weight $W_1$ is attached to a rope $R$ wrapped around a loose pulley $L$ that is linked to belt $B$ by a rigid link $C$. Therefore, the forces acting on belt $B$ that rubs on the fast pulley are: weight $W_2$, the friction force ($F_{TW}$), and the traction exerted by connection $C$. As the traction exerted by connection $C$ is equal to weight $W_1$, $F_{FW}$ is equal to the difference between $W_1$ and $W_2$. When $F_{FW}$ is lower than the difference $W_1 - W_2$, the mass $W_1$ moves down and connection $C$ moves up: the winding of the belt around $F$ and $F_{FW}$ increase. Inversely, when $F_{FW}$ is higher than the difference $W_1 - W_2$, the mass $W_1$ moves up and connection $C$ moves down: both the winding of the belt around $F$ and $F_{FW}$ increase or decrease.

With the previous ergometers, it was difficult to set a given braking torque because it was impossible to change $F_T$ without modifying $F_S$. In addition to the steadiness of braking torque, Fleisch ergometer presented a second advantage: it was easy to set a given braking torque because $F_{FW}$ was equal to $W_1 - W_2$. However, the use of this ergometer was limited to some laboratories probably because it was expensive when compared with the sinus-balance cycle ergometer which was proposed a few years later.
2.2.3. Ergoméca™ cycle ergometer
Brue, Melin, Lamande, and Philippe (1983) presented a friction-loaded cycle ergometer (Ergoméca™, Sorem, Toulon, France) which was designed for aerobic and anaerobic testing and whose belt tension adjustment was achieved by a cam (Figure 6). This ergometer enabled the use of a large range of loads (0–196 N, with 2.5 N increments) by means of a roman steelyard mechanism. This ergometer was mainly used in the French army. In addition to the usual iron flywheel, this ergometer was supplied with a light aluminum flywheel and its crank length could be changed. Therefore, this ergometer was also used in many studies on the development of maximal anaerobic power during growth in boys and girls (Bedu et al., 1991; Van Praagh, Fellmann, Bedu, Falgairette, & Coudert, 1990).

Force $F_B$ multiplied by length $L_p$ was equal to the weight of the counterweight $P$ multiplied by the distance $L_P$ of the counterweight (P) from the pivot. The values of $L_p$ and $P$ were adjusted to obtain the required force $F_B$:

$$F_B = P L_p / L_B$$

It was assumed that $F_{FW}$ was equal to the difference between $F_T$ and $F_S$ (Figure 6(A)). The belt tension was automatically adjusted by a cam. When $F_{FW}$ was higher than $F_T - F_S$, the cam moved up and the belt tension decreased. When $F_{FW}$ was lower than $F_T - F_S$, the cam moved down and the belt tension increased.

In fact, $F_{FW}$ was equal to $F_T - F_S$, and $F_B$ was equal to $F_T - F_{S2}$ (Figure 6(B)). It was assumed that $F_{S1}$ and $F_{S2}$ were equal, which was not true. At equilibrium, the principal moment exerted on the cam was equal to zero. If the weight of the cam was not taken into account, the value of $F_B$ was different from $F_{FW}$:

$$R_{S1} h_1 + F_{S2} h_2 = 0$$

where $R_{S1}$ was the reaction force exerted by the belt on the cam ($R_{S1} = -F_{S1}$).

$$F_{S2} = F_{S1} h_1 / h_2$$

$$F_B = F_T - F_{S2} = F_T - F_{S1} h_1 / h_2 = F_T - F_{S1} + F_{S1} - F_{S1} h_1 / h_2$$
The error in $F_{FW}$ depended on the position of the cam. $F_B$ was either an underestimation of $F_{FW}$ ($h_1 < h_2$) or an overestimation ($h_1 > h_2$) of $F_{FW}$.

When the weight of the cam was taken into account, $F_B$ was equal to:

$$R_{S1} h_1 + F_{S2} h_2 + W_C h_C = 0$$

$$F_{S2} = (F_{S1} h_1 - W_C h_C) / h_2$$

Hence,

$$F_B = F_T - F_{S2} = F_T - F_{S1} + F_{S1} - (F_{S1} h_1 - W_C h_C) / h_2$$

$$F_B = F_{FW} - F_{S1} (1 - h_1 / h_2) + W_C h_C / h_2$$

Therefore, the error of $F_{FW}$ was either partly compensated by the torque exerted by the cam ($h_1 < h_2$) or increased ($h_1 > h_2$).

Van Praagh, Bedu, Roddier, and Coudert (1992) carried out a dynamic calibration of the Ergoméca™ cycle ergometer by raising the ergometer onto a platform and adding to the crank shaft a pulley to which different weights were attached. The falling weights provided the input torque that accelerated the flywheel. The accelerations were measured for different braking forces ($F_B$). The difference between $F_T$ and actual braking force $F_B$ computed for $F_B$ equal to 0, 4.91, 7.36, and 9.81 N was equal to 0.10, 0.47, 0.38, and 0.28 N. Therefore, the underestimation of power output decreased from 9.6 to 2.9% for $F_B$ equal to 4.91 and 9.81 N, respectively.

3. Friction-loaded ergometers: Present

3.1. Sinus-balance cycle ergometer

von Döbeln (1954) designed a cycle ergometer whose the difference between $F_T$ and $F_S$ and the value of $F_{FW}$ was automatically given by a sinus-balance system (Figure 7). The resulting torque $r(F_T - F_S)$ exerted by the belt on the pulley was counterbalanced by the torque exerted by the sinus-balance system ($T_{c,s}$).
where $W$ and $r_W$ were the weight and the arm lever of the center of mass of the pendulum, respectively. The value of $F_{FW}$ was given by the position of the pendulum (Figure 6) in front of a force scale (S).

In the von Döbeln ergometer, the belt tension, brake torque, and pendulum position are adjusted by modifying the distance between the pulley axle (O) and the flywheel axis (A in Figure 7). The underlying assumption was that there was no external force acting on the belt-pulley system except the frictional force exerted at the flywheel and the force exerted by the sinus-balance system (W). The gravitational forces exerted on the slack and tight belt and their difference could be considered as negligible. The higher the tensions in the slight and tight belts, the higher the frictional force at the pulley axis (O) should be. However, this frictional force was minimized by ball-bearings.

After this publication, a sinus-balance ergometer was manufactured by Monark™ (Monark™, Varberg, Sweden) and largely used in physical testing of the athletes. However, this latter ergometer did not exactly correspond to the model proposed by von Döbeln. Indeed, the belt tension was not adjusted by modifying the distance between the pulley axle and the flywheel axle but by a pressure on the slack belt (Figure 8), which introduced a supplementary external force. The error due to this external force was minimized by a ball-bearing and was considered as low.

In contrast with Fleisch ergometer, $F_{FW}$ varies if the friction coefficient is not constant (e.g. because of the effect of temperature). Therefore, it is necessary to adjust the belt tension to maintain the brake torque by means of a handle (H in Figure 6). Moreover, it is not possible to set the brake force instantaneously before cycling with sinus-balance ergometers because the resistance must be set while the flywheel is moving.

### 3.2. Weight-basket loaded ergometer

A new Monark™ ergometer with weight basket (model 864) was proposed (Figure 9). In this model, the resulting torque exerted on the pulley by the belt is counterbalanced by the torque ($T_B$) exerted

$$rF_{FW} = r^t(F_T - F_S) = T_T - T_S = T_{S-B} = r_W W$$

Figure 8. Monark sinus-balance cycle ergometer.

Notes: O₁, axle of the sinus-balance pulley, O₂, axle of the pulley pressing on the slack belt; W, P, and $r_W$, weight, center of gravity, and arm lever of the pendulum; $F_T$ and $F_S$, tension of the tight and slack ends; $F_{SC}$, tension of the slack belt corrected by the force $F_E$ exerted by the pulley; H, handle for manual adjustment of braking torque. The force scale is not presented; S2 secondary force scale readable by the subject who pedals.
by a basket whose weight \(F_B\) is adjusted with additional masses. Small ribbons \((R_1\) and \(R_2)\), limit the vertical displacement of the basket. The tension of the belt is adjusted by means of a turnbuckle before the exercise.

\[ T_B = F_B r_T \]

At equilibrium:

\[ T_B = T_T - T_S \]

In contrast with the sinus-balance model proposed by von Döbeln, the radius of the pulley is different for the tight belt and slack rope (Figure 9). When \(T_B\) is higher than the difference between \(T_T\) and \(T_S\), the basket moves down, which provokes a winding of the belt around a large pulley \((r_T)\) and a unwinding of the rope around the smaller pulley \((r_S)\). Therefore, the belt-rope tension increases until the difference between \(T_T\) and \(T_S\) is equal to \(T_B\). Inversely, when \(T_B\) is lower than the difference \(T_T - T_S\), the basket moves up and the belt-rope tension decreases. The value of \(F_{FW}\) is given by Equation 4.

\[ \frac{F_S}{F_B} = \frac{1}{(\text{e}^{\alpha_{UT}} - r_S/r_T)} \]  
\[ \text{(7)} \]

\[ \frac{F_T}{F_B} = \frac{1}{(1 - \text{e}^{\alpha_{UT}} r_S/r_T)} \]  
\[ \text{(8)} \]

\[ F_{FW} = F_T - F_S = (F_B + F_S r_S/r_T) - F_S = F_B - F_S (1 - r_S/r_T) \]  
\[ \text{(9)} \]

\[ F_B - F_{FW} = (1 - r_S/r_T) F_S = (1 - r_S/r_T) F_{FW}/(\text{e}^{\alpha_{UT}} - 1) \]

\[ (F_B - F_{FW})/F_{FW} = (1 - r_S/r_T)/((\text{e}^{\alpha_{UT}} - 1)) \]  
\[ \text{(10)} \]

Therefore, \(F_S\) is an overestimation (Equation 9) of \(F_{FW}\) equal to \(F_s(1 - r_s/r_T)\). The value of \(F_s\) was minimized by prolonging the belt with a rope (Figure 10(B)), which added 360° to the winding (\(\theta\) equal to 590°, approximately). Ratio \(r_s/r_T\) is equal to 0.45 and, therefore, \(F_s\) corresponded to a \(F_{FW}\) overestimation equal to 0.55 \(F_s\).
We observed that the belt warp “digs” small circular grooves in the aluminum flywheels after several months of use at high power outputs. The flat belt progressively becomes similar to a multiple V-belt (Figure 10(C)), which results in an increase in the apparent coefficient of friction. Given the negative exponential relationship between $F_T$, $F_S$, $\theta$, and $\mu$, the tension of the slack rope was probably very low. For example, at low brake torques ($F_B = 10$ or 20 N), the slack rope was not straight but curved by the only action of gravity. Therefore, the overestimation due to the difference between radii $r_S$ and $r_T$ was probably negligible. The relationships (Equations 7–10) between $\mu$, $F_T$, $F_S$ and error in $F$ for $\theta = 10.4$ rad and $r_S/r_T = 0.45$ are presented in Figure 11.

The first Monark™ ergometer with weight basket (model 864) has been adapted for exercises at very high power output by modifying the design of the frame and increasing the flywheel inertia (models 824 and 834). Indeed, angular speed varies during a pedal revolution in function of the torques exerted on the cranks and the flywheel. At top dead center or bottom dead center, the pedal angular speed largely decreases when brake torque is high and flywheel inertia is low. Therefore, the aluminum flywheel of the Monark™ ergometer 864 was replaced with a heavier iron flywheel (22 kg instead of 10 kg) in models 824 and 834 to facilitate cycling against high brake torques. The coefficient of friction $\mu$ of the rope on the flywheel depends on the metal (iron or aluminum) and its state. The values of $\mu$ are close for a belt sliding on iron and aluminum. But after the digging of small grooves, it is likely that $F_S$ is lower with aluminum flywheel than with an iron flywheel.
4. Friction-loaded cycle ergometer and short all-out exercises

Until the years 1970–1980, the physical examination of athletes mainly consisted in the study of cardiovascular performances and endurance indices (maximal oxygen uptake, maximal aerobic power or speed), only. The pertinence of these aerobic tests was highly debatable for athletes specialized in short exercises whose performances were not limited by cardiovascular adaptation and aerobic metabolism. Moreover, it became obvious that the assessment of mechanical factors (strength, speed, and maximal mechanical power) determining athletic performances should be added to the usual tests mainly focused on bioenergetics. The Wingate anaerobic test (Ayalon et al., 1974; Bar-Or, 1978, 1987) consists in pedaling with maximal (all-out) effort for 30 s against a constant braking force (7.5% body mass for a Monark™ ergometer). Three indices of anaerobic performance are computed: peak power output (PP), mean power output over the 30 s of the whole test, and a fatigue index equal to the difference between peak power output and the lowest power output. Other durations of all-out cycling tests were proposed such as a 40-s all-out test against a constant resistance equal to 5.5 kg (Katch, Weltman, Martin, & Gray, 1977; Katch, Weltman, & Traeger, 1976). The fatigue index was the least reliable of the three Wingate test indices, and its validity was questioned as it largely depends on aerobic performance. The validity of mean power as an index of anaerobic capacity is as questionable as the aerobic metabolism provides a higher contribution to this energy demand in endurance athlete than in sprint athletes (Granier, Mercier, Mercier, Anselme, & Prefaut, 1995). Therefore, peak power during a Wingate test is probably the only index that merits to be measured, provided that the resistance is optimal. But there is no consensus on the optimal resistance: 7.5% (Ayalon et al., 1974), 8.7% (Dotan & Bar-Or, 1983), or 10.0% body mass (Vandewalle, Péres, et al., 1985). Although the validity of the Wingate test is debated, it is likely that this anaerobic test is the all-out cycling test, which is currently the most often used, not only in athlete testing but also in studies on the biological adaptations to strenuous exercises. The absence of consensus about the optimal resistance for the Wingate test can be explained by the results of the experimental studies on mechanical properties of isolated muscles achieved between 1935 and 1940 (Fenn & Marsh, 1935; Hill, 1938). These studies have found: (1) that the force production depends on the speed of shortening; (2) that maximal muscle power corresponds to optimal values of force \( F_{\text{opt}} \) and speed \( V_{\text{opt}} \); (3) that maximal muscle power, \( F_{\text{opt}} \) and \( V_{\text{opt}} \) largely depend on the types of muscle fibers. Because of the dependence of maximal muscle power, \( V_{\text{opt}} \) and \( F_{\text{opt}} \) on muscle fiber types, it is difficult to know the optimal conditions (loads or pedal rates) which correspond to the production of \( P_{\text{max}} \) before the completion of cycling tests. As a consequence, different protocols have been proposed for the determination of force–pedal rate relation in cycling and \( P_{\text{max}} \) on isokinetic cycle ergometers (Sargeant et al., 1981) and friction-braked ergometers (Nakamura, Mutoh, & Miyashita, 1985; Péres, Vandewalle, & Monod, 1981; Vandewalle, Péres, et al., 1985; Vandewalle, Peres, Heller, Panel, & Monod, 1987; Vandewalle, Péres, & Monod, 1983).

4.1. Force-speed test and maximal power

During an all-out sprint on a cycle ergometer, the force exerted on the pedal is used not only for the rotation of the flywheel against braking force \( F_{\text{FW}} \) but also for the acceleration of the flywheel up to peak pedal rate \( V_{\text{peak}} \). However, at \( V_{\text{peak}} \), flywheel acceleration is equal to zero, and the force exerted on the pedal is used for the rotation against \( F_{\text{FW}} \) only. Linear relationships (Figure 12) between resistance and \( V_{\text{peak}} \) have been observed for short all-out sprints on friction-loaded ergometers (Nakamura et al., 1985; Péres et al., 1981; Vandewalle, Péres, et al., 1985; Vandewalle, Peres, Heller, Panel, & Monod, 1987; Vandewalle, Péres, & Monod, 1983). This linear relationship was confirmed by a modeling approach (Yoshihuku & Herzog, 1996). Time to \( V_{\text{peak}} \) is approximately equal to 3–3.5 s for all the loads (Lakomy, 1986; Seck, Vandewalle, Decrops, & Monod, 1995; Winter et al., 1996). The flywheel inertia is probably not adapted to small subjects, which partly explains why the delay to \( V_{\text{peak}} \) is higher in children (Seck, Vandewalle, & Monod, 1991). However, the effect of an early fatigue (Kyle & Caiozzo, 1986) due to an increase in the delay to \( V_{\text{peak}} \) cannot explain the low maximal power output in children (Ratel, Omari, Duché, Bedu, & Coudert, 1996). Nonetheless, this fatigue effect should be more important with the use of cycle ergometers with 22 kg flywheel instead of 10 kg, especially in children.
The maximal power $P_{\text{max}}$ can be calculated from the linear relationship between resistance and $V_{\text{peak}}$ or its intercepts with the resistance axis ($P_{\text{max}} = 0.25 V_{\text{F0}}$) and the pedal rate axis ($V_{\text{opt}}$). Therefore, $P_{\text{max}}$ is equal to $0.25 V_{\text{0}} F_{\text{0}}$. Interestingly, $F_{\text{0}}$ and $V_{\text{opt}}$ are significantly correlated with strength indices (Driss, Vandewalle, Le Chevalier, & Monod, 2002) or muscle fiber types (Hautier, Linossier, Belli, Lacour, & Arsac, 1996), respectively. Similarly, $V_{\text{opt}}$ during sprint cycling was significantly correlated to vastus lateralis MHC-II (myosin heavy chain of fast muscle fibers) composition (Pearson, Cobbold, Orrell, & Harridge, 2006).

In theory, force-speed tests on friction-loaded ergometers could be used to estimate the muscular strength and contractility in addition to $P_{\text{max}}$.

The maximal power $P_{\text{max}}$ can be calculated from the linear relationship between resistance and $V_{\text{peak}}$ or its intercepts with the resistance axis ($F_{\text{0}}$) and the pedal rate axis ($V_{\text{opt}}$). $P_{\text{max}}$ corresponds to a resistance equal to 0.5 $F_{\text{0}}$ and an optimal pedal rate ($V_{\text{opt}}$) equal to 0.5 $V_{\text{0}}$. Therefore, $P_{\text{max}}$ is equal to $0.25 V_{\text{0}} F_{\text{0}}$. Interestingly, $F_{\text{0}}$ and $V_{\text{opt}}$ are significantly correlated with strength indices (Driss, Vandewalle, Le Chevalier, & Monod, 2002) or muscle fiber types (Hautier, Linossier, Belli, Lacour, & Arsac, 1996), respectively. Similarly, $V_{\text{opt}}$ during sprint cycling was significantly correlated to vastus lateralis MHC-II (myosin heavy chain of fast muscle fibers) composition (Pearson, Cobbold, Orrell, & Harridge, 2006). Therefore, force-speed tests on friction-loaded ergometers could be used to estimate the muscular strength and contractility in addition to $P_{\text{max}}$.

In theory, force-speed tests on friction-loaded ergometers could be used to estimate the muscular strength and contractility. Unfortunately, the values of $V_{\text{0}}$ and $F_{\text{0}}$ depend not only on muscle properties but also on crank length. The effects of crank length on $V_{\text{0}}$, $F_{\text{0}}$, and $P_{\text{max}}$ were studied in small subjects, that is, children and women (Martin, Malina, & Spirduso, 2002; Martin & Spirduso, 2001; Vandewalle, Heller, Pérès, & Monod, 1985). The value of $V_{\text{0}}$ decreased with long pedal cranks, which partly explains the lower value of $V_{\text{0}}$ in women or in children tested with cycle ergometers designed for adults (Martin et al., 2002; Vandewalle, Heller, et al., 1985). However, the crank length had opposite effects on $F_{\text{0}}$ and $V_{\text{opt}}$: $F_{\text{0}}$ increased with long pedal cranks. Consequently, there was no significant effect of crank dimension on $P_{\text{max}}$ as it was previously found for the Wingate test (Inbar, Dotan, Trousil, & Dvir, 1983). It is likely that the optimal crank length for $V_{\text{c}}$ is about 20% of leg length (Martin et al., 2002).

### 4.2. Maximal power corrected for flywheel acceleration

Lakomy (1985, 1986) and Bassett (1989) proposed to calculate the force necessary for flywheel acceleration and to transform this force in an equivalent resistance ($F_{\text{acc}}$) and to add $F_{\text{acc}}$ and $F_{\text{FW}}$ ($F_{\text{corr}} = F_{\text{acc}} + F_{\text{FW}}$). Power output during each revolution ($P_{\text{corr}}$) is equal to the product of the speed during this revolution ($V_{\text{rev}}$) and $F_{\text{corr}}$ ($P_{\text{corr}} = V_{\text{rev}} F_{\text{corr}}$). Given the relationship between force and pedal rate, $F_{\text{corr}}$ decreases while $V_{\text{rev}}$ increases up to peak pedal rate. Corrected Peak Power ($PP_{\text{corr}}$) corresponds to the maximal value of $P_{\text{corr}}$ during the acceleration phase. Therefore, it is theoretically possible to measure the maximal power from the data collected during a single all-out sprints instead of 4–6 sprints against different loads with the force-speed tests. On the other hand, this protocol does not enable the determination of parameters $V_{\text{0}}$ and $F_{\text{0}}$, that is, indices of muscle strength and contractility.

Moreover, time to $PP_{\text{corr}}$ increases with the resistance (Lakomy, 1986; Seck et al., 1995; Winter et al., 1996) and is approximately equal to 1.0 and 3.0 s for $F_{\text{b}}$ equal to 19 and 76 on Figure 13. If there were no fatigue during short all-out sprints, $PP_{\text{corr}}$ should be independent of the resistance and should be equal to $PP_{\text{max}}$. At low loads, $P_{\text{corr}}$ is approximately 10% greater than $P_{\text{max}}$ (Seck et al., 1995; Winter et al., 1996). The lower value of $P_{\text{max}}$ compared to $PP_{\text{corr}}$ was interpreted as an effect of early
fatigue (Kyle & Caiozzo, 1986) because time to $PP_{corr}$ is shorter than time to $V_{peak}$. For the same reason, $PP_{corr}$ was not independent of resistance in the study by Lakomy (1986): $PP_{corr}$ decreases (about 10%) with the increase in resistance probably because of a fatigue effect as $PP_{corr}$ are obtained later with high loads. In this study by Lakomy (1986), $PP_{corr}$ also depends on sampling time (0.5 or 1 s), and it was found that it would be better to measure mean power over one revolution instead of mean power over a given time.

Moreover, the reliability of $PP_{corr}$ is lower than the reliability of $P_{max}$. In the study by Winter et al. (1996), the test–retest coefficient of correlation is lower for $PP_{corr}$ than for $P_{max}$: 0.530 versus 0.972 in men and 0.922 versus 0.952 in women. In the same study, the coefficients of variation (CV) of $PP_{corr}$ are higher in the men (6.9% for $PP_{corr}$ versus 2.7% for $P_{max}$) but not in women (3.7% for $PP_{corr}$ versus 4.2% for $P_{max}$). Similarly, for arm exercises, CV was 2.8% for $P_{max}$ and 4.5% for $PP_{corr}$ (Smith, Price, Davison, Scott, & Balmer, 2007). It is likely that the lower reliability of $PP_{corr}$ is explained by oscillations of $P_{corr}$ (Figure 13) Different causes of the oscillations of $P_{corr}$ during an all-out sprint has been presented in the paper by Seck et al. (1995) (see Appendix 1). In a study comparing the results obtained with the protocol proposed by Lakomy ($PP_{corr}$ during the acceleration phase) and the optimization procedures (force-velocity test) Winter et al. (1996) concluded that “This adds further support to the suggestion that the use of ‘power’ with optimization procedures has securer foundations than those enjoyed by correction procedures.”

4.3. Torque–speed relationship during single all-out sprints
The determination of a torque–speed relationship during a single all-out sprint (Seck et al., 1995) on a Monark™ 864 ergometer (Figure 14) was directly derived from the study by Lakomy on the correction of peak power. The relationship between crank torque ($T$) and crank angular speed ($\omega$) was studied during
the acceleration phase of short (<7 s) all-out sprints. The mean crank angular speed $\omega$ during each revolution was measured up to peak speed. For each revolution, the mean torque $T$ exerted on the pedal was calculated as equal to the sum of $T_{\text{acc}}$ (the mean torque necessary for flywheel acceleration during each revolution) and $T_B$ (the torque necessary for flywheel rotation against $F_B$) as in the study by Lakomy (1985). The $T-\omega$ relationship was linear (Figure 14) as previously found for the load–$V_{\text{peak}}$ relationship.

A pure inertial resistance ($T_B = 0$) was experimented with the use of an intermediate gear drive which increased the gear ratio to 7.43:1 instead of 3.71:1 (Martin, Wagner, & Coyle, 1997). The mean crank torque over one revolution ($T$) was linearly related to the mean pedal rate ($V$) over one revolution.

### 4.4. Limits of the measure of $P_{\text{max}}$

Performance in many exercises as jumping, throwing, sprinting depends on impulse-generating capabilities rather than maximal power output. The question of the measure of impulse and power during maximal exercises has been debated many years ago (Adamson & Whitney, 1971). The impulse produced by the muscles depends on muscle activation, series elastic components, and muscle fiber types. The external work is not equal to the work produced by the muscle. In cycling, the work produced by the muscles is not only transformed in work at the crank level but is also used to move the leg segments and increase their mechanical energy, that is the sum of potential and kinetic energy. Similarly, “external” impulse in cycling is not equal to the impulse produced by the muscles. Left and right cranks are linked together by a rigid axle and a fraction of the impulse exerted by the descending leg increases the momentum of the ascending leg. Moreover, cycling corresponds to a movement with, at least, two degrees of freedom and the interpretation of the impulse exerted on the cranks needs 3D-dynamometric pedals and transducers measuring the crank and pedal angles and a movement analysis device (e.g. video camera).

In contrast with $F_{\text{opt}}$ and $V_{\text{opt}}$, maximal muscular power is theoretically independent of muscle dimensions (length and thickness) and architecture (pennation angle) when normalized to muscle mass. The power output measured during short all-out cycling exercises ($P_{\text{max}}$) is assumed to be related to maximal muscle power. In contrast with $F_{\text{opt}}$ and $V_{\text{opt}}$, $P_{\text{max}}$ does not depend on crank length. Moreover, it is likely that the reliability of $P_{\text{max}}$ is better than the reliability of $V_{\text{opt}}$ or $F_{\text{opt}}$ (Driss & Vandewalle, 2013). For all these reasons, $P_{\text{max}}$, that is relatively easy to measure is often the only variable computed during short all-out exercises on a cycle ergometer. However, mean power output over one pedal revolution depends not only on muscle fiber types but also on the rate of muscle activation, series elastic components, and coordination of hip, knee, and ankle muscle groups. Therefore, the interpretation of $P_{\text{max}}$ must be cautious.

### 5. Calibration

Cycle ergometers are designed to provide accurate measurement of power output during training or testing. However, the displayed power is often significantly different from the power actually produced. The first causes of this difference are the errors due to the torque setting mechanism. This error can be estimated by static calibration. Comparing the work performed on a prony cycle ergometer and the data of a dynamometric pedal, Bouny (1896b) concluded “The work measured for both feet surpassed about 5% the brake work. This was probably due to the resistance of the pedal axles, roller chain, chainwheel axle and the axle of the wheel”. Static calibration does not take into account the frictional resistance at each stage of the transmission from the pedal shaft to the flywheel axle. For the usual bicycles, this energy loss is often considered to be in the order of 5–9% (Marks, 1951). These frictional resistances increase in the old ergometers in the absence of an appropriate maintenance. Calibrators are not available in most of the departments of exercise physiology or medicine.

Moreover, cranks and shaft are single units in most of the Monark™ ergometer models and a special adapter is necessary to connect the shaft of the calibrator rig to the shaft of the ergometer. In contrast, oxygen uptake can be measured in most of the laboratories involved in exercise physiology. Physiological calibration can be achieved by comparing oxygen uptake (or heart rate) during exercises performed with a cycle ergometer and another ergometer dynamically calibrated.
5.1. Static calibration of sinus-balance ergometers

Sinus-balance cycle ergometers can easily be statically calibrated. As in any calibration, the first step consists in checking the zero (Figure 15(A)). After detaching the belt, the pendulum hangs in vertical position. The position of the force scale is adjusted with the lock nut so that the index on the pendulum weight is aligned with the zero of the scale. The second step consists in the calibration of force: known weights (at least 3 kg) are suspended at the point of belt attachment and the pendulum index must be in front of the corresponding weight on the scale. If necessary the position of the pendulum can be modified by an adjustment weight. The reading of the scale must be careful. As mentioned by Maxwell et al. (1998), a misalignment of the pendulum and scale equivalent to the thickness (2 mm) of the lines on the ergometer’s pendulum resulted in errors of 7.8 (4.6 W) and 0.7% (2.3 W) at power outputs of 58.9 and 353.2 W, respectively.

5.2. “Static” calibration of the weight-basket loaded ergometers

In theory, the value of $F_B$ is a $F_{BW}$ overestimation equal to $F_r (1 - r_s/r_T)$. Therefore, the magnitude of this overestimation could theoretically be estimated by measuring the only value of $F_r$. Frictional torque in the pulley axis is another cause of error in $F_{BW}$. Therefore, the calibration of $F_{BW}$ necessitates the measurements of both $F_r$ and $F_S$ with force transducers. However, the first step of the calibration procedure consists in verifying the weights of the baskets and the weights. Indeed, the actual weights corresponding to the 1 kilogram weights supplied with the Monark™ 864 ergometer ranged from 0.950 to 1.050 kg (unpublished personal data, weighing of fifteen 1-kilogram weights), i.e. a range of error equal to ±5%. However, this error was probably lower in the study by Gordon, Franklin, Baker, and Davies (2004) on the accuracy of Monark™ 824E ergometer.

The values of $F_r$ and $F_s$ were measured with force transducer in a study by MacIntosh, Bryan, Rishaug, & Norris (2001) on the validity of a Wingate test performed on Monark™ 834 E ergometer. The measured values of $F_r$ and $F_s$ were, respectively, equal to 95.5 and 6.17% of the weight of the basket, respectively. But, these results were dubious because $F_r$ should be higher than $F_B$ ($F_r = F_B + F_s r_s/r_T$). It was likely that the weights were not verified as this first calibration step was not mentioned in the calibration procedure. Calibration errors of the force transducers and an excessive frictional torque in the pulley were other possible explanations. Moreover, as mentioned by Franklin, Gordon, Baker, and Davies (2007), the computed brake torque in the study by MacIntosh et al. (2001) was computed from the difference between $F_r$ and $F_s$ without taking into account the difference in the radii of the pulley for the slack rope and tight belt.

Figure 15. In A, adjustment of the zero; in B, force calibration with a calibrated weight. Note: The position of the pendulum can be adjusted by dislocating the adjustment weight.
In the first part of an experimental study by Gordon et al. (2004), the flywheel was removed from a Monark™ 824E cycle ergometer, mounted in a frame, and rotated using a motor connected via a chain drive. The dynamic friction coefficient of the belt-rope was estimated by measuring the values of $F_T$ for a given value of $F_S$ (9.98 N):

$$\frac{F_T}{9.98} = e^{\mu \theta}$$

$$\ln \left( \frac{F_T}{9.98} \right) = \mu \theta$$

The value of $\ln \left( \frac{F_T}{9.98} \right)$ was computed for different values of the angle of lap of the rope around the flywheel. The slope (0.175) of the linear regression ($r^2 = 0.9956$) between the lap angle and the logarithm of ratio $F_T/F_S$ was considered as equal to the dynamic coefficient of friction $\mu$. Gordon et al. (2004) computed the value of $F_T$ and $F_S$ with the theoretical values corresponding to different calibrated basket weight (from 1 to 6 kg) with $\mu = 0.175$ and $\theta = 10.4$ rad. The conclusion of this study was that $F_S$ corresponded to a 10.8% overestimation of $F_{TW}$ with a Monark™ 824 ergometer. However, it was assumed that the experimental value of $\mu$ was exact, which was questionable (see Appendix 2).

In the second part of their study, Gordon et al. (2004) measured the values of $F_T$ and $F_S$ with force transducers attached to the brake-rope on both the tight and slack sides while a subject pedaled against different resistances on the same Monark™ 324 E ergometer (same flywheel and same belt-rope). The second part of this experimental study confirmed that $F_T$ was not negligible and, consequently, that $F_S$ was an overestimation of $F_{TW}$. However, the measures of $F_S$ were probably not accurate enough for an estimation of the errors in power output during cycling.

In Figure 2 of the study by Franklin et al. (2007), the values of $F_T$ and $F_S$ measured with force transducers for a 2 kg basket weight was equal to 20 and 0.8 N, respectively. Therefore, $F_S$ (19.62 N) was an overestimation of $F_{TW}$ (19.2 N) equal to 0.4 N, i.e. a 2% overestimation. This overestimation was in agreement with the expected overestimation $[F_S (1 - r_s/r_T) = 0.44 \text{ N}]$ as ratio $r_s/r_T$ was equal to 0.45. However, the difference between $F_T$ and $F_{TW}$ increased with weight. For example, $F_T$ was a 14.9% overestimation of $F_{TW}$ for a basket weight equal to 8 kg. But ratio $F_T/F_S$ (equal to $k$) should be constant if the values of $\mu$ and $\theta$ are independent of the basket weight. Consequently, the overestimation of $F_{TW}$ should be independent of basket weight when expressed in fraction of $F_S$:

$$f = \frac{F_{TW}}{F_S} = \frac{(F_T - F_S)}{[F_{TW} + F_S (1 - r_s/r_T)]} = \left[ \frac{(k - 1) F_S}{(k - 1) F_S + F_S (1 - r_s/r_T)} \right]$$

$$f = \left( \frac{k - 1}{k - r_s/r_T} \right) = 1 - \left( \frac{1 - r_s/r_T}{k - r_s/r_T} \right)$$

There is no mysterious force acting of the Monark™ ergometer. How to explain the basket-weight dependence of $F_{TW}$ overestimation in the study by Franklin et al. (2007)? A first explanation is a decrease in $\beta$. Indeed, the basket moves down when the weight increases and the tight belt winds around the pulley while the rear rope unwinds. Therefore, $\beta$ decreases for the belt and $\beta$ increases for the rope. If $\mu_s$ is lower than $\mu_T$, the values of $\beta$ and $k$ decrease. However, such an explanation assumes that $\mu_s$ was at least 2-fold higher than $\mu_T$ ($\mu_s/\mu_T < 0.5$; see Appendix 3), which was unlikely as suggested by the measure of the coefficient of friction of the belt-rope on the flywheel of a Monark™ ergometer in the study by Gordon et al. (2004) (see Appendix 2).

For all the friction-loaded ergometers, the underlying assumption is that there is no external force acting on the belt-rope-pulley system except the frictional force exerted at the flywheel and the force exerted by the basket ($F_S$). The design of the frames of models 824 and 834 was probably the cause of an additional error in $F_{TW}$. Indeed, the roller chain supplied with these ergometers was too short and the frame of the ergometer pressed on the slight rope (Figure 16). Therefore, the $F_{TW}$ was not equal to difference between $F_T$ and $F_S$ because of the contact of the slack rope on the ergometer frame. This importance of this frictional force due to this contact probably depends on the conditions of the friction of the rope on the frame (steady or varying tension) and on the load, which could
explain why the error in $F_{FW}$ was larger with the heavy basket weight in the study by Franklin et al. (2007). One or two links had to be added to the roller chain to avoid this contact for the specimens of this kind of weight-basket loaded ergometers, we used.

5.3. Dynamic calibration

Dynamic calibration takes into account energy losses due to friction in the chain and sprockets in addition to the errors due to the torque regulation mechanism. Dynamic calibration consists of the measurement of the torque necessary to exert on the cycle ergometer to produce the required power. This torque is produced by a motor at different rotational speeds and power input to the ergometer is equal to the product of torque (N m) and angular speed (rad $s^{-1}$). In theory, the torque should be exerted on the pedal in the same conditions as during cycling exercises, i.e. the same force (intensity and direction) as the force exerted on the pedal at each crank angle during one revolution.

In practice, the calibration rig exerts a constant couple on the crank shaft, which alters the validity of the calibration. Indeed, the action of the force exerted on the pedal ($F_1$ in Figure 17(A)) is equivalent to a force $F_2$ exerted on the crank shaft plus a couple $C$ whose moment is equal to the torque of $F_1$ about crank shaft. Therefore, the effect of $F_1$ on the ball-bearings is not taken into account in dynamic calibration as the calibration rig exerted only a couple equivalent to $C$. Moreover, the couple exerted by the calibration rig is constant (red line in Figure 17(B)), whereas there are large variations

Figure 16. Contact of the frame ($F$) with the slack extremity of the belt-rope.

Figure 17. In A decomposition of the force $F_1$ exerted on the pedal into a force $F_2$ exerted on the crank shaft and a couple $C$; in B comparison of the mean torque (red line) and the torques exerted on the left (blue dashed line, L) and right crank (blue continuous line, R) during a pedal revolution.
in the torque exerted on the pedals during one revolution (blue lines in Figure 17(B)). These variations in torque induce similar variations in the mechanical strains of the roller chain, flywheel sprocket, and bearings. The underlying assumption of dynamic calibration is that energy losses in chain and ball bearing are similar for varying and constant torques. Moreover, dynamic calibration devices are attached to crank axle. Therefore, the losses occurring in the foot-pedal bearing are not taken into account but are considered as small and negligible.

5.3.1. Dynamic calibration: Methods
The crankshaft resistance to rotation causes an opposite-direction rotation of the calibration motor which is prevented by its fixation on a frame and/or the ground. The torque exerted by the calibration motor on the crankshaft is equal to the reaction torque exerted by the motor on the frame and/or the ground. In most of the experimental studies on cycle ergometer calibration, the reaction torque has been measured by an arm lever linked to the motor and connected to different force transducer (scale with weights, spring scale, force platform, arm lever with weight, force transducers). The use of these reaction transducers is cost effective as these sensors do not utilize bearings, slip-rings, or any other rotating elements. Moreover, these calibrators are not limited in rotation speed by the torque transducer. Most of the first studies on dynamic calibration of cycle ergometers used reaction-torque measurements (Abbiss, Quod, Levin, Martin, & Laursen, 2009; Cumming & Alexander, 1968; Gardner et al., 2004; Kyle & Caiozzo, 1986; Maxwell et al., 1998; Wilmore et al., 1982; Woods, Day, Withers, Isley, & Maxwell, 1994).

The calibration can also be carried out with a motor previously calibrated with a Prony brake. First, the current necessary to exert a calibrated torque on the Prony brake is registered for different rotational speeds. Current–torque curves are determined for the usual pedal rate (e.g. current–torque curves corresponding to 40, 60, 80, and 100 rpm). Thereafter, the cycle ergometers are dynamically calibrated by measuring the current necessary for the calibration motor to produce a given power on the cycle ergometer. Thereafter, this current is compared with the current–torque curves previously determined for a given pedal cadence.

The torque exerted on the crankshaft by the motor can also be directly measured by a torque transducer mounted between motor shaft and crankshaft. For example in the study by Russell and Dale (1986), the rotating torque meter was made of the combination of a spring rotating 90° at 70 N m and a 100 kΩ multiturn potentiometer. Devices measuring the torque generated at the crank axle by means of strain gauges situated between the crank shaft and the chain wheel were described by Atkins and Nicholson (1963) and Atkins and Nünlist (1966). As for the Russel-Dale torque transducer, brass slip rings with brushes were necessary for transmission of the excitation voltage and data. Nowadays, the torque measured by this kind of device can be inductively transmitted at high frequency (500 kHz) to the data recorder as for example with the SRM™ crankset (Schoberer, 1998) is performed by means of strain gauges (2, 4, 8, and 20 depending on the model) mounted between the crank arms and the chain-rings. The accuracy of the SRM™ crankset increases with the number of strain gauges (from 2 to 0.5%, according to the manufacturer). Jones and Passfield (1998) studied the accuracy of the SRM™ transducers by comparing the work performed on a Monark™ ergometer model 814E (Figure 18) and the data of 3 SRM™ transducers (2 models with 20 strain gauges (SRM20sg) and 1 model with 4 strain gauges (SRM4sg)). The relationship between SRM™ and Monark™ data was almost perfectly linear and the 95% limits of agreement were ± 1.1 W (±0.3%) for the first SRM20sg, ± 1.8 W (± 1.0%) for the second SRM20sg, and ± 2.1 W (± 1.8%) for the model SRM4sg. However, the accuracy of the SRM™ transducer was questioned by Gardner et al. (2004) who compared the data collected with 19 SRM™ transducers (models with 4 strain gauges) (SRM4sg)) in a more recent study by Abbiss et al. (2009). Several studies have investigated the test–retest reliability of performance measured with SRM™ cranksets.
Balmer, and Bird (2001) reported standard errors of measurement lower than 2% for power output recorded on the SRM™ crankset in repeated laboratory tests with competitive cyclists. A static calibration procedure for SRM™ crankset has been proposed by Wooles, Robinson, and Keen (2005).

In recent years, most of the dynamic calibrations of new cycle ergometers (Balmer et al., 2000; Bertucci, Duc, Villerius, & Grappe, 2005; Hopker, Myers, Jobson, Bruce, & Passfield, 2010; Hurst & Atkins, 2006; Kirkland, Coleman, Wiles, & Hopker, 2008) or ergometric pedal (Stapelfeldt, Mornieux, Oberheim, Belli, & Gollhofer, 2007) were performed by means of SRM™ transducers.

5.3.2. Dynamic calibration: Results
In the study by Cumming and Alexander (1968) carried out on 4 sinus-balance ergometers, the underestimation depended on power output (Figure 12). When expressed in absolute value (watts), the underestimation increased with power output. However, the underestimation decreased when it was expressed in percent of power output. In contrast, Kyle and Caiozzo (1986) using a dynamic calibration of a modified Monark™ sinus-balance ergometer found that the losses increased with power output even when they were expressed in percentages: 2 and 4% for 150 and 300 W, respectively. As the energy loss increased with power output, Kyle and Caiozzo assumed that that energy loss was around 10% beyond 1,000 W. However, the modified Monark™ ergometer in the study by Kyle and Caiozzo consisted of a standard racing bicycle with derailleur connected to the ergometer flywheel of a von Döbeln braking device. Therefore, it was likely that there was an additional energy loss in the derailleur and that the losses were lower in a real Monark™ sinus-balance ergometer. In the study by Wilmore et al. (1982), the power output on a friction-loaded cycle ergometer was approximately 10% below the actual values given by dynamic calibration at each power output (Figure 19). This result is in agreement with the manufacturer’s handbook for the Monark™ cycle ergometer that acknowledges a 9% underestimation of the actual power output.

The dynamic calibration of friction-loaded ergometers was compared with the calibrations of air and electromechanically braked cycle ergometers in a study by Maxwell et al. (1998). Dynamic calibration was carried out in old and new Monark™ ergometer with increasing (black points in Figure 19) and decreasing (empty circles in Figure 19) power output. Unfortunately, the models of the new and old Monark™ ergometers were not specified and the numbers of ergometers were different under and beyond 180 W. Nonetheless, this interesting study indicated that the underestimation was lower than 9% and was slightly lower with decreasing loads than with increasing loads (Figure 19). This hysteresis phenomenon can probably be explained by an increase in the coefficient of kinetic friction with the increase in temperature or the belt and/or flywheel (Kauffman & Vondracek, 2005).
As mentioned above, Jones and Passfield (1998) compared the work performed on a Monark™ ergometer model 814E (Figure 18) and the data of SRM™ transducers. As the crankset of Monark™ ergometer model 814E was a single-unit piece, dynamic calibration cannot be achieved without a special adapter connecting the shaft of calibrator rig to the shaft of the ergometer. In the study by Jones & Passfield, the dynamic calibration rig consisted of a modified friction-braked Monark™ ergometer driven by a motorized treadmill (Figure 18). Thirteen braking loads were used at a pedal rate of 90 rpm, which corresponded to power outputs ranging from 90 to 625 W. At each load, the difference between power output and SRM™ data was very low (see above): the 95% limits of agreement computed from the residuals of the linear regression were inferior or equal to ±2.1 W.

5.4. Physiological calibration
Physiological calibration can be achieved by comparing oxygen uptake during exercises performed with a cycle ergometer and another ergometer dynamically calibrated. It is assumed that the individual adaptations are similar at the same power output for any cycle ergometers and that any difference in oxygen uptake would be the expression of inaccuracy in displayed power output. For example the comparison can concern either the oxygen uptake for a given power output or the slope of the relationship between power and oxygen uptake (ml O₂ min⁻¹ W⁻¹). Assuming an energy equivalent for oxygen consumption (about 20.3 J ml O₂⁻¹ for a respiratory quotient between 0.85 and 0.9), the delta efficiency (delta efficiency = delta power/delta energy consumption) can also be compared.
5.4.1. Comparison of physiological adaptations within the same laboratory

Brue et al. (1985) validated their new friction-loaded ergometer by determining the relationship between power and oxygen uptake measured during exercises on an Ergoméca™ ergometer and found the same slope (11.6 ml O₂ min⁻¹ W⁻¹) as previously collected on a Siemens-Elema™ or a Monark™ ergometer in their laboratory. Guiraud et al. (2010) compared the oxygen uptake during exercises performed by five subjects on a dynamically calibrated ergometer and different cycle ergometers. The energy cost of cycling was equivalent to 13 ml O₂ min⁻¹ W⁻¹ (delta efficiency = 0.228) for a Monark™ 824E and 12.5 ml O₂ min⁻¹ W⁻¹ for an Ergoméca™ (delta efficiency = 0.237). The oxygen uptake with the Ergoméca™ and Monark™ were higher than the oxygen uptake for the same power output with the calibrated ergometer, which indicated that power output were underestimated (mean −5 W for the Ergoméca™ and −15 W for Monark™ 824E).

The accuracy of physiological calibration depends not only on the errors of power output with both ergometers (calibrated and uncalibrated ergometers) but also on errors in the measurement of oxygen uptake during the exercise protocols performed with both ergometers. Therefore, the accuracy of physiological calibration should be significantly lower when compared with dynamic calibration of a single ergometer.

5.4.2. Comparisons with data in the literature

Physiological calibration can also be achieved by comparing the oxygen uptake measured during exercises performed with a given cycle ergometer with previous data in the literature. For example, it is possible to compare the oxygen uptake measured with a friction-loaded ergometer with the oxygen uptake corresponding to a given power output in the nomogram presented by Åstrand (1960) for exercises performed with a von Döbeln ergometer or a Krogh ergometer. In this nomogram, the cycling energy cost was equal to 13.1 ml O₂ min⁻¹ W⁻¹ for power output between 300 and 1,500 kgm min⁻¹ (i.e. between W for 1 kgm min = 6.11 W), i.e. the same energy cost as in the study by Guiraud et al. (2010) for a Monark™ 824E. The cycling energy cost can also be compared with data obtained with calibrated ergometers in the literature. For example, in the study by McDaniel, Durstine, Hand, and Martin (2002) the delta efficiency during cycling exercises on an ergometer calibrated with a SRM™ crankset was equal to 0.247, i.e. an energy cost of cycling equal to 11.9 ml O₂ min⁻¹ W⁻¹. Similarly, the regression line between power output and metabolism in Figure 2(C) of the review on cycling efficiency by Ettema & Lorås (2009) corresponded to delta efficiency equal to 0.250, i.e. energy cost equal to 11.8 ml O₂ min⁻¹ W⁻¹. The 9% higher energy cost of cycling on a Monark™ 824E ergometer in the study by Guiraud et al. (2010) when compared with either McDaniel et al. (2002) or Ettema & Lorås (2009) data suggested a 9% underestimation of power output with this kind of ergometers in agreement with the manufacturer’s handbook for the Monark™ cycle ergometers.

However, the comparison of physiological data with previous data in the literature must be cautious. For example, a lower cycling energy cost was found for a friction-braked ergometer, in the study on the dynamic calibration of different cycle ergometers by Wilmore et al. (1982). In this latter study, physiological variables were also measured in 10 subjects during incremental exercises. When power outputs were corrected according to the result of the dynamic calibration, the energy cost of cycling with a friction-loaded ergometer was equal to 10.9 ml O₂ min⁻¹ W⁻¹ in agreement with the cycling energy cost for the ACSM (10.8 ml O₂ min⁻¹ W⁻¹) (American Journal of Sports Medicine, 2007). Therefore, cycling energy cost was 20.4% higher in the study by Guiraud et al. (2010), when compared with Wilmore data. Underestimation of power output is not the only cause of differences in cycling energy cost between studies. These differences can also be explained by differences in protocols, subjects, and power range. First, the relationship between power-output and oxygen uptake is not perfectly linear: the slope of the relationship is lower at low power outputs. For example, cycling energy cost was 11.76 ml O₂ min⁻¹ W⁻¹ between 300 and 900 kgm min⁻¹ instead of 13.1 ml O₂ min⁻¹ W⁻¹ for power output between 300 and 1,500 kgm min⁻¹ in Åstrand nomogram (1960). This low value of cycling energy cost at low power outputs could explain the results in the study by Wilmore et al. (1982) obtained for exercises performed between 49 and 147 W that
corresponded to heart rates between 89 ± 14 and 131 ± 21 beats min⁻¹, only. Secondly, cycling efficiency depends on the subjects and probably on the percentage of type-I muscle fibers (Coyle, Sidossis, Horowitz, & Beltz, 1992) at low pedal rates. Thirdly, cycling efficiency depends on pedal rate (Ettema & Lorås, 2009), which could partly explain the high energy cost in Astrand nomogram corresponding to cycling exercises performed at 50 rpm. Differences in cycling energy costs can also be due to errors of measurement. These errors can be subdivided in bias errors (systematic errors) and random errors. Systematic error or bias refers to deviations that are not due to chance. Bias occurs with measuring devices that are not properly calibrated so that they consistently overestimate or underestimate the measurements. The bias error of the oxygen uptake measurements with the calibrated ergometer and uncalibrated ergometer can be similar (under or overestimation) and the effect of bias upon the comparison of cycling energy cost and/or delta efficiency is diminished or canceled. When performed in the same laboratory with the same oxygen uptake device within the same period, bias are similar and their effects on the difference in cycling energy cost are canceled. On the contrary, this effect is amplified in the case of bias with opposite directions when oxygen uptake is overestimated in a laboratory and underestimated in the other laboratory.

6. Maintenance of friction-loaded ergometers

The study by Maxwell et al. (1998) demonstrated the importance of maintenance. For example, the accuracy of a Monark™ ergometer that was equal to 86% before servicing, reached 93% after cleaning and lubrication of the bearings and roller chain, optimization of the chain tension, tightening of the cones, and readjustment of the chain guard that rubbed against the chain. The different parts of a cycle ergometer that must be maintained are presented in Figure 20. However, maintenance performed poorly can have the opposite effect to that intended and cause an increase in frictional
losses. Fortunately, this maintenance can be achieved with the help of an expert mechanic in competitive cycling. Indeed, the aims of the maintenance of cycle ergometers and race cycles are similar: to decrease energy loss.

First, the chain guard must be removed. The chain (Figure 20 (Part-2)) and cones (Figure 20 (Part-4)) can be attacked by rust. Indeed, sweat may have infiltrated between the frame and the chain guard when ergometers have been frequently used for intense and prolonged exercises. Freewheeling sprocket (Figure 20 (Part-1)) and chain must be checked and eventually changed. Indeed, chain “stretches” because of wearing away of the metal where the link pins rotate as the chain links flex and straighten. A “stretched” chain no longer matches the original pitch of the sprocket. Thereafter, the sprocket, in turn, increases its pitch to match the worn chain. Similarly, a worn sprocket induces a wearing of the chain. Therefore, it is better to change chain and freewheeling sprocket simultaneously. The wear of the chain and the sprocket is faster when they are not parallel. Abnormal wear of the chain and chainwheel is also observed when chain play is about 20 mm in the middle of its free length. On the other hand, the chain should have a minimum play of 5 mm. The chain adjuster bolts (Figure 20 (Part-7)) enable the adjustment of the chain play between 5 and 20 mm and the parallelism of flywheel sprocket and the chain. Hub bolts (Figure 20 (Part-5)) are tightened after these adjustments.

Friction in the pedal bearings (Figure 20 (Part-3)) is generally considered as negligible, which is debatable. When necessary, it is easier to remove the pedals for replacement than to service the pedal bearings. The axles of the pedals screw into the cranks. It is important to remember that pedal threads are different from right side and left side. Therefore, pedals are generally stamped “R” and “L” for right and left. The right side pedal has a right-hand thread (installs clockwise, removes counterclockwise), whereas the left side pedal has a left-hand thread (installs counterclockwise, removes clockwise).

The crankset bearing should be checked at regular intervals to see that there is no play in the bearing. Whatever, the crankset system, the tightening of the cones (Figure 20 (Part-4)) must be adequate, which requires minimal expertise. Many ergometer crankset consist of a one-piece crank and two cones. A one-piece crank consists of a single steel forging which constitutes the left crank, axle, and right crank in a single piece of steel. The left side cone of the bottom bracket has a left thread, and uses a locknut and keyed washer to secure the adjustment. The right side cone has a right thread, and secures the chainwheel to the crank. This one-piece crank set is difficult to assemble because of the loose balls.

Lubrication of the roller chain and flywheel sprocket is carried out after their cleaning. The bearing in the flywheel and crankset are lifetime greased and required normally no maintenance, unless they need to be replaced. The belt should be regularly checked and replaced if it looks worn. The brake belt contact with the flywheel (Figure 20 (Part-6)) can be cleaned with a fine sand paper to remove dust and eventually attenuate small grooves in the circumference of aluminum flywheels. This procedure is made easier if somebody pedals at very slow cadence.

7. Future of the friction-loaded cycle ergometer
The current friction-loaded cycle ergometers seem to be designed to be attractive and secure but not to be accurate. The guards that limit the risks of accidents due to moving flywheel and chain are not designed to be easily removed for regular checking and maintenance of the ergometers. The guard of the associated electronic devices measuring pedal cadence and hear rate masks the pulleys, which, for example, does not facilitate the checking of the tension of the ribbons in the basket-loaded ergometer (Figure 8). The maintenance is more difficult with the one piece-cranks than with the usual cup-and-cones or cartridge bottom brackets.

It can be hoped that a friction-loaded ergometer will be designed specifically for medical and physiological studies, i.e. designed for accuracy, maintenance, and calibration. First, one-piece cranks should be replaced with bottom brackets which are easier to service, enable the change of
crank length when small people are tested and do not require an adapter for dynamic calibration. Secondly, torque setting can be improved by a mechanism that enables the adjustment of belt tension by a change in the distance between pulley and flywheel shafts (Figure 21). Therefore, the pulley pressing on the slack belt in the sinus-balance ergometer (Figure 8) can be suppressed and the error of $F_s$ due to this external force disappears. Similarly, the adjustment of the belt tension of the weight-basket loaded ergometers will be easier and even possible during exercise without interruption.

For the basket-loaded ergometers, the error in $F_{\text{fw}}$ decreases with $F_s$ (Equation 9). The value of $F_s$ can be diminished by an increase in $\theta$ and/or an increase in $\mu$. An increase in $\theta$ can be achieved by replacing the belt-rope with a rope with three turns around the flywheel (Figure 10(D)). An increase in the apparent friction coefficient $\mu$ could be achieved by replacing the belt with a “V-belt”, for example by digging small grooves in the circumference of the flywheel. Another way to decrease the error in $F_{\text{fw}}$ is to increase ratio $r_s/r_t$ (Equation 9) by adding layers on the small pulley or by replacing both pulleys. For example, the error is 57% higher with $r_s/r_t$ equal to 0.45 instead of 0.65.

Figure 21. Example of a mechanism enabling the adjustment of the belt tension by a change in distance between the axes of the pulley ($O_1$) and the flywheel; $O_2$, axle of the mechanism; $H$, handle; $N$, locking nut.

Figure 22. Braking mechanism consisting of a friction belt made of two belts in series; in red, belt with low friction coefficient ($\mu_1$); in blue, belt with high friction-coefficient ($\mu_2$).

Note: C, connection between the belts.
About 20 years ago, we tried a basket-loaded braking mechanism (Figure 22) which consisted of a belt made of a low-friction ribbon (Teflon™, μ between 0.05 and 0.2) in series with the usual belt (μ₂ between 0.15 and 0.2). The radii of the pulleys were identical for F_S and F_FB (r_S = r_F). Therefore, at equilibrium, F_S was equal to F_FB according to equation 9 (F_FB = F_FB (1 - r_S/r_F) = F_FB).

\[ F_S = F_T e^\theta \] with \( \theta = \theta_1\mu_1 + \theta_2\mu_2 \)

Let \( \theta_{1+2} = \theta_1 + \theta_2 = \text{constant} \).

\[ \theta_1 = a\theta_{1+2} \text{ and } \theta_2 = (1 - a)\theta_{1+2} \]

\[ \beta_{1+2} = a\theta_{1+2}\mu_1 + (1 - a)\theta_{1+2}\mu_2 = \theta_{1+2} [\mu_2 - a(\mu_2 - \mu_1)] \]

\[ \beta_{1+2} = \theta_{1+2}\mu_{1+2} \]

where the effective friction coefficient \( \mu_{1+2} \) is equal to \( [\mu_j - a(\mu_2 - \mu_1)] \).

When \( F_{FB} \) was higher than \( F_S \), the basket moved up, \( \alpha \) increased and \( \mu_{1+2} \) decreased. Therefore, \( F_{FW} \) decreased as the effective friction coefficient decreased. Inversely, when \( F_{FW} \) was lower than \( F_S \), the basket moved down. Therefore, \( \alpha \), \( \mu_{1+2} \) and \( F_{FW} \) increased. Unfortunately, the pulley largely oscillated probably because of an inadequate choice of \( \mu_1 \), \( \mu_2 \), \( \theta_1 \), \( \theta_2 \), and compliance of the belt. It would be interesting to repeat this trial with new material and different values of \( \theta_1 \) and \( \theta_2 \).

In theory, force-speed tests on friction-loaded ergometers could be used to estimate the muscular strength and contractility. Unfortunately, the values of \( V_p \) and \( F_o \) depend not only on muscle properties but also on crank length. Moreover, the time to \( V_{peak} \) during an all-out sprint on a cycle ergometer is longer in children because of the flywheel inertia. Instead of changing the flywheel, it would be easier to change the ratio between chainwheel and sprocket (52/14) simultaneously with the change of crank length. Indeed, the kinetic energy of the flywheel depends on the square of its angular speed and the kinetic energy at \( V_{peak} \) is 1.94 times less if the chainwheel-sprocket ratio is 48/18 instead of 52/14. The ergometer adaptation to children testing would consist in replacing the adult crankset with shorter cranks and a chainwheel with 48 teeth. A two-sprocket freewheel (14 and 18 teeth) would be mounted on the flywheel. In a first approximation, the chain length is similar if the number of teeth of chainwheel + sprocket is the same (52 + 14 = 48 + 18 = 66). The chain wheel and the freewheel sprocket would be manually swapped after loosening the chain and changing the crankset. The tension of the chain would be adjusted without a derailleur but with the chain adjuster bolts. The power output corresponding to a given resistance must be divided by 1.39 to take into account the change in the chainwheel-sprocket ratio. On the other hand, the optimal resistance for a Wingate test must be multiplied by 1.39, that is, 10.4% body mass instead of 7.5% in children.

The measurement of \( PP_{corr} \) according to Lakomy’s method and the assessment of the torque-speed relationship during all-out sprint are based on the computation of flywheel acceleration. The inertia of the flywheel is generally measured according to Lakomy’s method, that is, the measurement of the deceleration of the flywheel rotating against different braking force (\( F_{FW} \)). The underlying assumption is that \( F_{FW} \) and \( F_o \) are equal, which is not exact. Therefore, the errors in \( PP_{corr} \) and torque-speed relationship are the consequence of errors of \( F_{FW} \) not only during the all-out sprints but also during the determination of flywheel inertia. The flywheels should be supplied with the value of its inertia calibrated by the ergometer manufacturers.

The cycle ergometers should be supplied with a digital high-accuracy speed transducer mounted on the flywheel and connectable to external computing devices. Such transducers would enable not only an accurate measurement of flywheel acceleration during all-out sprints but also the computation of the actual power output during constant-power protocols. Indeed, variability in pedal rate is the third cause of errors in power output with errors in brake torque and energy losses in chain and ball bearings.
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Appendix 1

The origins of the oscillations in power output during all-out exercises could be either mechanical or methodological or biological (due to the subjects). Mechanical flaws are possible causes of the $P_{corr}$ oscillations. If the center of mass $G$ of the flywheel does not exactly coincide with its rotation axis (Figure 21), a work $(mgh)$ must be added to or subtracted from the computed work when the center of mass goes up or down, respectively. Given the ratio between the sprockets (52/14), at 120 rpm, the time between the low and high locations of the flywheel center of mass is equal to 0.067 s [half a revolution/ (pedal revolution per second × 52/14)] and the power corresponding to this displacement is equal to 0.293 W kg$^{-1}$ mm$^{-1}$ (9.81 × 0.002 m/0.067 s), that is, an oscillation of power output approximately equal to ±3 W for a 10 kg flywheel (± 6.5 W for a 22 kg flywheel) whose center of mass is located 1 mm apart from its axis (Figure 23).

Moreover, an underlying assumption is that $F_{FW}$ is constant within a flywheel suspended from the basket demonstrated that the belt tension is not constant during a pedal revolution (Franklin et al., 2007). For example, with a 2 kg weight, flywheel speed decreased from 70 to 0 rpm in 4.65 s, with 24–25 oscillations of $F_T$ (around 5.3 Hz) whose magnitudes were equal to or lower than 0.75 N (3.75% of $F_T$). Seck et al. (1995) suggested that the belt tension varies significantly within a flywheel revolution because the flywheel is not perfectly round and centered. Another explanation is variations of the friction coefficient. The friction coefficient $\mu$ is assumed to be constant for the flywheel sliding on the belt in spite of the local effects of stain, dust, and irregularities on $\mu$ and possible differences in $\mu$ between the belt and the rope. The mean of $\mu$ increases when the part of the flywheel with the highest friction coefficient slides on the part of the belt-rope with the highest tension.

The control of $F_{FW}$ by the pulley-belt-weight system can be compared with a spring-mass system that oscillates in the absence of damping. The magnitude of the oscillations can be reduced by increasing the damping effect of external dissipative forces such as friction forces. Unfortunately, these forces mainly correspond to the friction force on the pulley axis in the case of Monark™ ergometers and this friction must be as low as possible to minimize the error in $F_{FW}$. In addition, at the beginning of the sprint without a rolling start, the system switch from a static friction coefficient ($\mu_s$) + the basket in a low position to a dynamic friction coefficient ($\mu_k$) + the basket in a high position. Therefore, the behavior of the pulley-belt-weight system at the beginning of the sprint is equivalent to the impulse response of an underdamped control system.

Figure 23. Variation of the location of the center of mass during half a revolution of the flywheel.
In theory, oscillations of $P_{\text{corr}}$ can also be the result of computing approximations and errors in flywheel rotation measurement. For example, the sensitivity of the flywheel-motion transducer was equal to $1^\circ$ in the study by Seck et al. (1995). Given the ratio between the sprockets (52/14), flywheel angular displacement is equal to 3.714 times the crank angular displacement and one pedal revolution corresponded to 1,337 impulses. These variations were computed as equivalent to accelerations of the flywheel (Seck et al., 1995). For example, at 120 rpm, the impulse frequency is 2,674 impulses s$^{-1}$ and for a 20 Hz sampling rate, the number of impulses in 50 ms was equal to 133 (2,674 $\times$ 0.05 s). Therefore, ±0.5 impulse corresponded to relative errors in $V$ equal to ±0.38%. The studies comparing corrected and uncorrected power outputs generally used a commercially available software package (Cranlea Wingate testing kit version 2.21, Cranlea, UK) with a sampling rate around 20 Hz (James, Wood, Maberly, & Croix, 2007). The sensitivity of the flywheel-motion transducer was equal to $2^\circ$ in the studies by James et al. (2007) or Smith et al. (2007), which corresponded to computation errors in $V$ about ±0.75% at 120 rpm.

Differences between the right and left legs and revolution-to-revolution fluctuations in muscle activation (Vandewalle, Maton, Le Bozec, & Guerenbourg, 1991) are possible biological causes of oscillations in $F_{\text{corr}}$ and $P_{\text{corr}}$. In the case of a significant difference between the maximal power of the right and left legs, optimal pedal speed must be reached when the most powerful leg is pushing on the crank. The effect of a difference between the maximal power of the right and left legs upon $P_{\text{corr}}$ should be more important at low brake torque because of the large variation of pedal speed between the beginning and end of a pedal revolution (see above). Biological causes of oscillations should interact with biomechanical factors (e.g. the degrees of freedom of cycling exercises). In theory, if the activations of all the agonistic and antagonistic muscles which exert their actions on the knee, ankle, and hip were similar in all the subjects and constant, there would be only one degree of freedom for cycling exercises. Otherwise, the same pedal rotation can be produced by different combinations of knee, ankle, and hip extensions and there would be three degrees of freedom for cycling exercises. Therefore, variations in the activations of the different leg muscles could contribute to oscillations in $P_{\text{corr}}$.

Appendix 2
In the study by Gordon et al. (2004), a linear regression between $\ln F_r$ and lap angle $\theta$ was expected in agreement with the relationship between $F_r$, $\mu$, and $\theta$:

$$\ln (F_r/9.98) = \mu \theta$$

The correlation coefficient between $F_r$ and $\theta$ was very high ($r = 0.978$). Consequently, the regression between the experimental values of $F_r$ and $\theta$ was assumed to be linear and the slope (0.175) was considered as an accurate estimation of $\mu$. In spite of the very high value of the correlation coefficient, the linearity of the relationship was questionable. Indeed, the “pure” error in $\ln F_r$ (the differences between each $\ln F_r$-value and the mean of the three $\ln F_r$-values corresponding to the same lap angle) was very small for several lap angles ($225^\circ$, $270^\circ$, and $450^\circ$) when compared to the errors due to the prediction of $\ln F_r$ from the computed linear regression. The linearity of the regression between $\theta$ and $\ln F_r$ can be verified with a lack-of-fit test based on variance analysis and a $F$ test:

$$F = (A/dof_A)/(B/dof_B)$$

where $A$ was the sum of squares due to lack-of-fit of the model, $B$ the sum of squares due to pure errors, $dof_A$ the degree of freedom of $A$, and $dof_B$ the degree of freedom of B. The sums of squares $A$ and $B$ can be computed from the values of $F_r$, presented in Table 1 of the study by Gordon et al. (2004). As there were 3 measures for a given lap angle and 11 lap angles (from $45^\circ$ to $495^\circ$) the total numbers of measures ($N$) was equal to 33 ($N = 3n = 33$) and $dof_A$ and $dof_B$ were equal to 9 ($n-p = 11-2$) and 22 ($N-n = 33-11$), respectively. The lack-of-fit test for a linear regression was highly significant ($F_{23,2} = 15.19$; $p < 0.01$). Therefore, the experimental regression could not be considered as linear. This discrepancy between the theoretical linear model and the experimental data could be explained by errors in lap angles ($\theta$) and/or errors in $F_r$. Moreover, the $Y$ intercept (−0.066) of the $\theta$-$\ln F_r$ regression was significantly different from zero. Therefore, it was possible that the slope (0.175) of the linear $\theta$-$\ln F_r$ regression was an overestimation of friction coefficient $\mu$. For example,
the slope of the line passing by zero and the point corresponding to the mean of all the experimental data ($\theta = 4.712$ rad and $\ln F_T = 0.765$) was equal to 0.162. In addition, the slope of $\theta$-$\ln F_T$ regression was probably not very different for $\theta$ ranging between 45° and 180° (friction of the only belt on the flywheel) and $\theta$ ranging between 45° and 495° (friction of the belt + rope). Consequently, the coefficient of friction of the belt ($\mu_1$) was close to the coefficient of friction of the rope ($\mu_2$).

Similarly, for actual basket weights between 1.007 and 6.051 kg, the actual values of $k$ (mean = 5.70) during cycling exercises ranged between 4.95 (for 6.051 kg) and 9.54 (for 1.007 kg), which corresponded to $\beta$ between 1.60 and 2.26 (mean = 1.74). Therefore, the estimated value $\mu$ was not constant and equal to 0.175 with the different loads but ranged from 0.154 to 0.217 (mean = 0.168) for $\theta = 10.4$ rad.

### Appendix 3

In the study by Franklin et al. (2007), the belt-rope was wound around the flywheel 1.65 times ($\theta = 10.4$ rad) and ratio $r_s/r_T$ was equal to 0.45. According to Figure 2 in this study, for $F_B = 2$ kg (19.62 N), $F_T$ and $F_S$ were equal to 20 and 0.8 N, respectively.

As $k = \text{e}^{\beta}$

$\beta = \ln 25 = 3.219$ and $\mu = 0.310$

For $F_B = 8$ kg, ratio $F_{FW}/F_B = 0.87$ according to Figure 3 in the study by Franklin et al. (2007). If $k$ and $f$ are, respectively, equal to ratios $F_T/F_S$ and $F_{FW}/F_B$, the relationship between $k$ and $f$ is:

$$f = F_{FW}/F_B = (k - 1) / (k - r_s/r_T)$$

$$k = (1 - f r_s/r_T) / (1 - f)$$

$$k = (1 - f r_s/r_T) / (1 - f) = 4.68$$

$$\beta = \ln 4.68 = 1.543 \text{ and } \mu = 0.149$$

Let $h_1$ and $h_2$ be the fractions of $\theta$ corresponding to the windings of the belt around the flywheel for $F_B$ equal to 2 and 8 kg, respectively.

For $F_B = 19.6$ N

$$\theta_1 = h_1 \theta \text{ and } \theta_2 = (1 - h_1) \theta$$

$$\beta = h_1 \mu_1 + (1 - h_1) \mu_2 = 3.219$$

For $F_B = 78.5$ N

$$\theta_1 = h_1 \theta \text{ and } \theta_2 = (1 - h_1) \theta$$

$$\beta = h_1 \mu_1 + (1 - h_1) \mu_2 = 1.543$$

Hence:

$$[h_2 \mu_1 + (1 - h_2) \mu_2] / [h_8 \mu_1 + (1 - h_8) \mu_2] = 3.219/1.543 = 2.09$$

$$(h_2 - 2.09h_8) \mu_1 = [2.09 (1 - h_8) - (1 - h_2)] \mu_2$$

$$\mu_1/\mu_2 = 1 + 1.09 / (h_2 - 2.09h_8)$$

$$\mu_1/\mu_2 = 1 + 1.09 / (2.09D - 1.09h_2)$$
where $D = h_2 - h_8$

As the radius of the flywheel was equal to 0.26 m, a 1-cm descent of the basket corresponded to an $h_2 - h_8$ difference equal to 0.006. The moving down of the basket from the position corresponding to 2 kg to the position at 8 kg was probably lower than 0.15 m ($D = 0.09$) in the study by Franklin et al. (2007). Ratio $\mu_1/\mu_2$ has been computed for differences between $h_2$ and $h_8$ equivalent to descents of the basket inferior to 0.15 m ($h_2 - h_8 < 0.09$). The values of ratio $\mu_1/\mu_2$ computed for $0.5 \leq h_1 \leq 0.9$ which correspond to a decrease in $k$ from 3.219 to 1.543 are presented in Figure 22.

Even for a descent of the basket equal to 0.15 m, ratio $\mu_1/\mu_2$ was lower than 0.5. Moreover, for $h_2$ equal to 0.8 and 0.9 ($\theta_1 = 5.03$ and 5.65 rad) $\mu_1/\mu_2$ was even negative (curve in red in Figure 24), which was not possible.