Power Responses of a Rowing Ergometer: Mechanical Sensors vs. Concept2® Measurement System

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Abstract

The aim of this study was to compare the power provided by a recent ergometer with the power developed by the rower determined using mechanical sensors set on the same apparatus. Six rowers and six non-rowers performed a power graded test and an all-out start on an instrumented ergometer (Concept2® system, model D, Morrisville, VT, USA). Power values displayed by the ergometer were recorded with a specific software. A strain gauge placed near the handle and a position sensor installed on the chain allowed the calculation of the power developed by the rower. Power values provided by the ergometer were strongly correlated to those determined with a direct measurement and calculation of power. However, power values given by the Concept2® system were lower (– 17.4 to – 72.4 W) than those calculated using mechanical sensors. This difference in power measurements was lower at a steady pace and for rowers. The Concept2® system underestimates the power produced by the rower by approximately 25 W. This difference in power seems to be independent of the level of power developed but increases with variations in intensity and pace. The deletion of the first strokes following changes in power production allows to limit this phenomenon. According to the use of the power parameter in the experimental design, it could be appropriate to correct values provided by the Concept2® ergometer.

Key words
Instrumentation · expertise level · rower · exercise intensity

Introduction

Rowing is an Olympic sport requiring a high level of training. The training volume of rowers participating in the World Championships has been estimated to be 3 hours a day [9]. Ergometers play an important role in rowers' training and are used to select national crews [7]. The power produced by the rower at the handle is a decisive factor in the performance [1]. Thus, ergometers have been instrumented with mechanical sensors in order to record the power developed by the rower [4, 6]. Today, most commonly used ergometers are those using wind-resistance made by Concept2®. These ergometers are equipped with monitors and display stroke parameters such as speed, pace and power. The power displayed by monitors is used to carry out progressive and maximal tests and to study physiological responses induced by rowing [2]. However, only one study [5] presented results about the reliability of the power measurements of ergometers and reported a strong correlation between the power displayed by the ergometer and the power measured with mechanical sensors. Authors also indicated that mean values obtained from the ergometer display were 6.8 % lower. These results need to be confirmed as authors used an old ergometer model (Concept2®, model A) which calculated the power developed by the rower (P_{C2A}) as depicted in equation 1 (E_1) [3], whereas recent ergometers (Concept2®, models C and D) determine power (P_{ergo}) with a different formula provided by Concept2® (equation 2, E_2).

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$$P_{C2A} = \frac{\int_{t_1}^{t_3} J\alpha\dot{\theta}dt}{t_3 - t_1} \quad (E_1)$$

$$P_{ergo} = \frac{\int_{t_1}^{t_2} C_1\dot{\theta}^3 dt + \frac{1}{2}J(\dot{\theta}_3^2 - \dot{\theta}_1^2)}{t_3 - t_1} \quad (E_2)$$

θ: angular position of the flywheel (rad), α: deceleration of the wheel assessed during a calibration protocol ($rad \cdot s^{-2}$), J: moment of inertia of the flywheel ($kg \cdot m^2$), t_1: starting time of the rowing cycle i.e., the catch (s), t_2: end of the pull, i.e., the finish (s), t_3: end of the rowing cycle, i.e., the next catch, C_1: constant calculated for each stroke on the previous recovery ($kg \cdot m^2$):

$$C_1 = -\frac{\int_{t_2}^{t_3} \frac{J\ddot{\theta}}{\dot{\theta}^2}}{t_3 - t_2}$$

Using E_1, the power was calculated as the product of the torque applied to the flywheel (T) by its angular velocity ($\dot{\theta}$) [3]. The absence of torque sensors in rowing ergometers made it necessary to determine T using an indirect method. With this method, considering that the flywheel had a nearly constant velocity between two successive strokes, the torque was assessed by calculating the flywheel deceleration (α) using a calibration protocol and applying the equation of motion ($T = J\alpha$). Thus, E_1 did not take into account factors such as changes in friction on the flywheel bearings with time or changes in air properties. Moreover, E_1 considered that the power was close stroke to stroke and the assessment of α seemed to be less reliable at low and high angular velocities [3]. Using E_2, these problems are solved. Indeed, the power at the level of the flywheel is considered to be the sum of the power dissipated by air resistance and the power developed to accelerate the flywheel between two successive strokes. Therefore, it could be hypothesized that the use of a more recent ergometer allows to obtain a better accuracy of power measurements. Considering E_2, no calibration is required since the power dissipated is calculated using a constant (C_1) assessed for each stroke with the flywheel deceleration measured during the previous recovery. Nevertheless, to our knowledge, the accuracy of this power assessment model has not been tested in the literature. Moreover, both E_1 and E_2 calculate the power at the level of the flywheel and then do not take into account the energy dissipated in the chain. Consequently, differences between the power assessed by the Concept2® model D (C2D) ergometer and the power produced by the rower could remain and has to be determined. The influence of rowing at an expertise level on differences between power measurements has not been studied yet. As Smith et al. [8] observed that trained rowers developed a better stroke to stroke consistency compared to novices, it can be interesting to test if this ability has an incidence on the accuracy of power measurements.

The aim of this study was to compare the power displayed by the last Concept2® ergometer with the power developed by the rower determined using mechanical sensors installed on the same apparatus. This work also focused on the potential influence of the expertise level on these power measurements.

Methods

Twelve subjects distributed into two populations volunteered for this study. Six studying physical education, non-specialists in rowing, formed the "novices" population (22.0 ± 2.3 years, 181.3 ± 10.9 cm, 77.3 ± 11.5 kg). Six rowers practicing since 9.3 (± 2.7) years composed the "experts" population (22.2 ± 2.2 years, 185 ± 5,7 cm, 78.2 ± 6.9 kg). All subjects signed informed consent documents.

After a specific warm-up, subjects realized an all-out start of 15 strokes and a power graded test (in reference to power values displayed by the ergometer). Initial power was 100 W for both populations and was increased every 30 seconds, by 25 W for novices and by 50 W for experts, until subjects were unable to maintain the requested power during 5 consecutive strokes. Tests were carried out on an instrumented wind braked rowing ergometer C2D (Concept2®, Morrisville, VT, USA) equipped with a strain gauge placed at the handle (DPSystèmes®, 2 kN, Cournon, France) and a position sensor installed on the chain (PT1 Scaime®, Annemasse, France). These mechanical sensors, previously calibrated, allowed the measure of the force at the handle and its position variations. Hence, the power developed by the rower was calculated by multiplying the force produced at the handle by its velocity (determined by derivation of the position). This power was averaged on the whole rowing cycle (i.e., between two successive catches) and called $P_{sensors}$. Power values displayed by the ergometer for each stroke (P_{ergo}) were calculated by the C2D system as presented in E_2 and were recorded using the RowPro™ 1.7 software (Digital Rowing Inc., Boston, MA, USA).

Changes in P_{ergo} and $P_{sensors}$ were studied with Bravais Pearson correlations coefficients (r). Differences in power measurements (DIPM) were determined for each stroke and calculated as the differences between $P_{sensors}$ and P_{ergo}. Student's *t*-tests were used to compare differences between P_{ergo} and $P_{sensors}$ and differences in DIPM between novices and experts. A second set of the same statistical analysis was carried out after the removal of data from the first three strokes of each grade of the graded test and of the first three strokes of the start. This deletion was realized in order to study strokes achieved at a relative steady pace. The level of statistical significance was set at $p < 0.05$.

Results

Results are presented as means and ranges (Table **1**). Correlations between P_{ergo} and $P_{sensors}$, considering all the subjects were strong for the graded test ($r = 0.96$, $p < 0.001$, Fig. **1 A**) and good for the start ($r = 0.75$, $p < 0.001$). However, P_{ergo} were significantly lower than $P_{sensors}$ (– 26.0 W for the graded test and – 68.2 W for the start, $p < 0.001$).

After the deletion of initial strokes, correlations between P_{ergo} and $P_{sensors}$ increased ($r = 0.97$, $p < 0.001$; $r = 0.93$, $p < 0.001$, for the graded test [Fig. **1 B**] and the start respectively), and differences between P_{ergo} and $P_{sensors}$ fell to 22.7 W ($p < 0.05$) for the graded test and to 31.6 W ($p < 0.001$) for the start. Highly significant differences between P_{ergo} and $P_{sensors}$ were observed, except

Table **1** Averaged ± standard deviation of P_{ergo} and $P_{sensors}$ (W), mean differences in power measurements (DIPM) and ranges (min-max) for novices, experts and both populations (n = 12) for both experimental situations and the two statistical analyses

Graded test								*Start*						
All strokes	P_{ergo}	$P_{sensors}$		*DIPM*	*n*	*r*	*p*	P_{ergo}	$P_{sensors}$		*DIPM*	*n*	*r*	*p*
Novices	210.7 ± 72.6	228.5 ± 77.5	#	29.2 18.3 – 35.4	848	0.90	***	451.5 ± 130.7	503.1 ± 103.9	Ø	72.4 48.1 – 103.2	84	0.67	***
Experts	308.8 ± 113.6	327.1 ± 113.9		21.6 14.4 – 30.6	610	0.98	***	634.8 ± 98.5	683.3 ± 55.8		62.9 58.0 – 72.0	83	0.27	***
n = 12	252.7 ± 103.9	269.7 ± 106.2		26.0 14.4 – 35.4	1458	0.96	***	539.0 ± 151.2	588.4 ± 127.4		68.2 48.1 – 103.2	167	0.75	***
Except first 3 strokes														
Novices	212.0 ± 72.1	227.9 ± 76.2	#	26.3 14.9 – 33.5	683	0.92	***	492.8 ± 96.5	505.9 ± 100.2	#	39.7 15.0 – 61.1	66	0.86	*
Experts	320.0 ± 111.4	334.9 ± 111.4		17.4 10.5 – 25.0	466	0.99	***	673.8 ± 48.7	677.1 ± 51.1		21.8 14.2 – 25.8	65	0.82	n.s.
n = 12	255.8 ± 104.5	271.3 ± 106.0		22.7 10.5 – 33.5	1149	0.97	***	578.7 ± 123.1	586.3 ± 121.1		31.6 14.2 – 61.1	131	0.93	*

"*All strokes*" all the strokes were analyzed; "*Except first 3 strokes*" the first three strokes were deleted; "n" number of studied strokes; "r" Bravais Pearson correlation coefficient between P_{ergo} and $P_{sensors}$; "p": level of significant difference between P_{ergo} and $P_{sensors}$; ns: $p > 0.05$, * $p < 0.05$, *** $p < 0.001$; # $p < 0.001$ significant difference in DIPM between novices and experts; "Ø": no significant difference between novices and experts

after the removal of the first three strokes of the start. Differences in power measurements were always higher for novices than for experts ($p < 0.001$), except when considering all strokes of the start (72.4 W vs. 62.9 W, for novices and experts respectively, $p > 0.05$).

Discussion

The purpose of this study was to compare the power displayed by the C2D ergometer with the power developed by the rower determined by the mechanical sensors. The major finding of this study showed that the ergometer underestimates the power developed by the rower. Results also indicated that this difference in power measurements was enhanced by the variability in power production and this was higher for novices than for experts.

Differences in power measurements

As Lormes et al. [5] used a different apparatus (model A) and Concept2® upgraded the power calculation method of ergometers, it was hypothesized that the C2D system would provide more accurately the power developed by the rower. In our study, despite a strong correlation between power measurements ($r = 0.98$, $p < 0.001$), the power developed by the rower during a graded test realized by trained subjects was 7.4% higher than the power provided by the ergometer. These two results are close to those reported by Lormes et al. [5]. Consequently, our hypothesis of a better accuracy of power measurements is rejected. It can be supposed that the manufacturer has modified the C2D with the main objective to reproduce the speed of the boat rather than to assess the actual power developed by the rower. More precise information from the manufacturer (Concept2®) and more methodological indications in the article of Lormes et al. [5], such as the way of recording power values from the ergometer and the number of data used to establish the linear correlations, could have helped us to compare results of this previous study with ours whereas two different power calculation methods were used by ergometers. The remaining difference in power measurements could be due to phenomena which are not still taken into account in E_2, i.e., the power used to stretch the shock cord chain return, the energy dissipated at the level of the chain, the power stored in the flywheel and some limitations in the model of power dissipation.

A constant shift in power measurement

Despite differences between P_{ergo} and $P_{sensors}$, these two power measurements evolved in the same way as illustrated by high correlations coefficients values ($0.67 < r < 0.99$, $p < 0.001$). The low coefficient obtained for the start of the experts ($r = 0.27$, $p < 0.05$) could be explained by the ability of experts to rapidly produce high power values which induced differences in power measurements. The strong correlations between P_{ergo} and $P_{sensors}$ added to the parallelism of the linear regression and the $P_{sensors} = P_{ergo}$ line (Fig. **1**) would indicate that the difference in power measurements was relatively constant. This is in line with the results exhibited by Lormes et al. [5] (linear regression: $P_{sensors} = 1.01 \times P_{ergo} + 13.70$). Furthermore, considering differences in power measurements calculated during the graded test at steady pace, the ergometer underestimated the power by 22.7 W. This finding is close to the y-intercept value presented in Fig. **1B**, which strengthens the idea of a constant shift in power measurements by the C2D ergometer.

DIPM variability and expertise level

The deletion of initial strokes in both experimental situations improved correlations between P_{ergo} and $P_{sensors}$ and reduced DIPM. During the first strokes of a new grade or of the start, rowers have to change the intensity and the pace of the rowing strokes. So, it can be hypothesized that differences in power

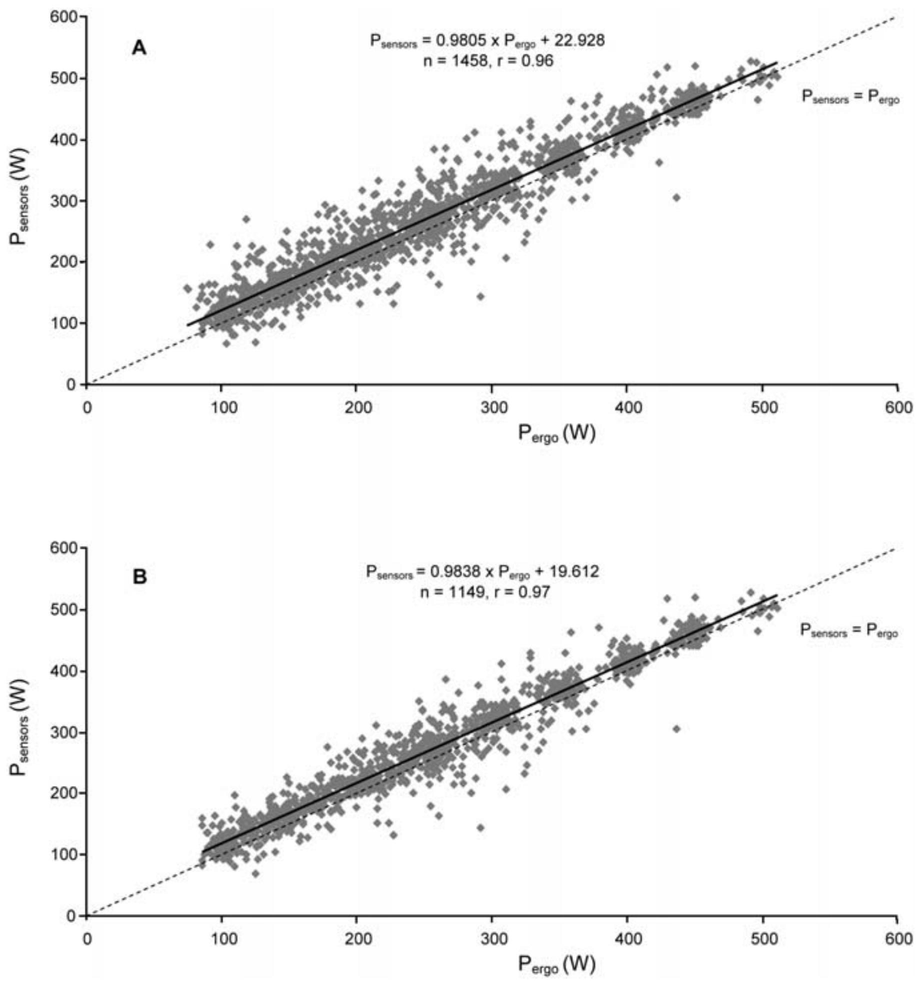

Fig. **1 A** and **B** Correlations between P_{ergo} and $P_{sensors}$ for all the subjects. **A** graded test. **B** graded test, except the first three strokes of each grade. $P_{sensors} = a \times P_{ergo} + b$: equation of the linear regression (solid line). n = number of studied strokes. r = Bravais Pearson correlation coefficient. $P_{sensors} = P_{ergo}$: dotted line.

measurements are enhanced by the variability of the power produced by the subject between two successive strokes. Smith [8] indicated that novices rowed with a lower stroke to stroke consistency than trained subjects, and so with more variations in power production. Power values displayed by the C2D ergometer do not take into account the additional power due to an uneven pace. These elements associated with a higher DIPM for novices than for experts confirm that rowing at an uneven pace induces higher differences in power measurements than rowing with consistency.

Conclusions

The Concept2® system (model D) underestimates the power developed by the rower by approximately 25 W. This difference in power measurements seems to be independent of the level of the power produced, but increases with variations in intensity and pace. The removal of the first strokes following changes in power production allows to limit this phenomenon. According to the use of the power parameter in the experimental design, it could be appropriate to correct power values provided by the ergometer.

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