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Influence of ergometer design on physiological responses during rowing

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ABSTRACT

The aim of this study was to compare the physiological responses and rowing efficiency on two different rowing ergometers: the Concept2 stationary versus dynamic ergometers. Eleven oarswomen and oarsmen rowed four minutes at 60% and 70% of peak power output on both ergometers (randomized order). Power output, stroke rate, heart rate, oxygen uptake, carbon dioxide production, lactate accumulation and rating of perceived exertion were recorded at each stage on the two ergometers. Gross and net efficiencies were computed. Exercise intensity was associated with increases in all parameters. Rowing on dynamic ergometer was associated with higher heart rate, oxygen uptake, carbon dioxide production and stroke rate, concomitantly to lower blood lactate accumulation but also lower gross and net efficiencies. The present study showed that rowing efficiency and blood lactate accumulation were lower on the Concept2 dynamic ergometer than on its stationary counterpart. If the use of the Concept2 dynamic ergometer may provide some advantages (reduced risk of injuries), its utilisation requires specific evaluation of physiological responses during an incremental exercise for an adapted management of training.

Keywords: oxygen uptake, lactate, rowing efficiency, submaximal exercise

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INTRODUCTION

Rowers extensively use rowing ergometers for training, especially during the winter season. Ergometers are also used to evaluate the performance level of the rowers and their physiological characteristics such as maximal oxygen uptake and blood lactate kinetics in response to exercise which are closely related to rowing performance on water and on ergometer [18,23]. In that sense, results obtained on ergometers are sometimes used as selection criteria by some rowing national teams [11]. Although to a lower extent than on water, performance on ergometer is also related to mechanical efficiency [4,12]. On classic stationary ergometers, previous experiments, but not all [25], have shown that rowing efficiency increased when exercise power output augmented [4,9,22]. This increase in rowing efficiency with work rate may at least in part account for the higher gross efficiency observed in adults than in young rowers since the former exercised at higher power outputs [22].

Dynamic ergometers have been developed in order to mimic more closely on-water rowing movement and feelings [7]. Contrary to the stationary design where the rower moves forth and back on the ergometer, the centre of mass of the rower is much less displaced on the dynamic ergometers where it is the system that moves: foot stretcher and flywheel on RowPerfect or ergometer as a whole in the case of Concept 2 with slides. Furthermore, the total mass of the system that moves is lower than the mass of the rower [15]. In that case, the energy spent to move the body of the rower [6,9] and the system (*vide supra*) back and forth might be lower on the dynamic ergometers since the inertial forces to develop for each stroke are expected to be lower. Following this line of reasoning, rowing efficiency can be expected to be higher on the dynamic ergometers. However, and although peak handle forces were also lower on the dynamic ergometers [1,5,15], the physiological responses to a given exercise intensity have been observed to be comparable on stationary and dynamic ergometers [15,19], suggesting similar overall

energy expenditure and consequently rowing efficiency on the two ergometer designs. Worst, contrary to this inference, Benson et al. [1] found lower rowing efficiency at maximal pace on dynamic rowing ergometer than on the stationary. They attributed these alterations in rowing efficiency to the higher stroke rate on the dynamic ergometer, inducing higher energy expenditure. They also evoked the low rowing performance level of their subjects. Indeed, these alterations in rowing efficiency have not been observed in oarswomen of higher ranking. Nevertheless, Holsgaard-Larsen and Jensen [15] also reported a lower economy while rowing on slides (dynamic condition) than without (stationary) in high-level Danish rowers. They also attributed this lower efficiency to the higher stroke rate on the dynamic ergometer.

Recently, a new dynamic ergometer appeared (Dynamic, Concept 2, Morrisville, USA). In that new frame, only the segments of the rower and the stretcher move, so that the masses to displace are minimised. This could induce a lower internal mechanical work to accelerate the segments mass at each stroke, which could result in a higher efficiency than on other dynamic design ergometers. Consequently, it is possible that the difference in rowing efficiency between the brand-new dynamic and other stationary ergometers does not exist anymore, despite still a higher stroke rate on the former device.

Thus, the aim of this study was to compare the physiological responses and rowing efficiency on two different rowing ergometers: the Concept2 stationary (model D) versus dynamic ergometers. Specifically, we hypothesized that the higher energy expenditure related to stroke rate would be compensated by a low energy expenditure related to the masses to displace, so that rowing efficiency would be similar on the dynamic and stationary Concept 2 rowing ergometers.

METHODS

Study population

Eleven competitive rowers, 6 men and 5 women (age: 20.0±2.6 years, body mass: 71.4±12.5 kg, height: 176±13 cm and body fat: 15.0±5.2 %) participated in this study. The present study was approved by the local ethics committee (n°: 20145) and was performed in accordance with the ethical standards of the IJSM [14] Before giving their written consent, the subjects were fully informed of the objectives, experimental design, all risks, possible discomforts, and potential benefits of the experiments.

Ergometers

Two rowing ergometers with different designs were used: a stationary (fixed-foot stretcher) rowing ergometer (SRE: model D, Concept2, Morrisville, VT, USA; Figure 1a) and a dynamic (free-floating stretcher) rowing ergometer (DRE: dynamic, Concept2, Morrisville, VT, USA; Figure 1b). The two rowing ergometers were new at the time of the experiment. They were equipped with Concept2 Performance Monitor 4 (PM4) calculator (Concept2, Morrisville, VT, USA), which measures stroke rate ($\text{cycles} \cdot \text{m}^{-1}$) and mean power outputs (W) continuously. Both ergometers were equipped with the same PM4 calculator giving the same power output measurements in both conditions. Note that these PM4 calculators are actually used for international and national indoor rowing competitions and in many scientific studies [1,16,17]. Subjects were thus able to adjust exercise intensity according to the required power output.

Experimental Design

The experiment consisted successively in i) a familiarisation period, ii), an incremental exercise up to exhaustion, and iii) a standardized submaximal exercise session.

Familiarization period. All subjects underwent eight of their regular training sessions on rowing ergometer in the laboratory. Each training session lasted between 40 and 60 min each. Half of the training session was performed on one of the ergometer and the other half on the other ergometer. The order between SRE and DRE was randomized. This procedure allowed the rowers to become accustomed with the environment and the dynamic ergometer.

Incremental exercise up to exhaustion (session1). The graded exercise was performed on SRE. It started at 120 W for the women and 150 W for the men. After 3 min of exercise at this load, the work rate was increased by 35 W for the women and 50 W for the men every 3 min thereafter. The exercise was stopped when the subjects were no longer able to sustain the work rate. This exercise session was performed for determination of maximal heart rate (HR_{peak} , beats/min) and peak power output (P_{peak} , W) [3].

Standardized submaximal exercises (session 2). This session intervened at least 3 days after the incremental exercise. After 10 min of self conducted light warm-up, rowers performed on SRE and DRE ergometers three consecutive exercises of 4-min duration each at 50% (to standardize the end of the warm-up and reach a steady state level for all rowers), 60% and 70% of P_{peak} , respectively. After a 20-min rest period, rowers performed the same exercise procedure but on the other ergometer. The order of ergometers was randomized between subjects. The participants were asked to adopt their preferred stroke rate during rowing on each ergometer. Drag factor was set on both ergometers at 110 and 130 for women and men, respectively. [These values of drag factor were i\) those used by the rowers of the present study during their training sessions and during indoor rowing competitions, and ii\) in accordance with those advocated/recommended \[13\].](#)

Measurements

Oxygen uptake (VO_2), carbon dioxide production (VCO_2) and respiratory exchange ratio (VCO_2/VO_2) were measured by portable system for pulmonary gas exchange measurements using a breath-by-breath analysis device (K4 b², Cosmed, Rome, Italy) and averaged over 15 s. These variables were recorded every 15 s during the last minute of each stage of sessions 1 and 2 and averaged. Heart rate (HR) was recorded continuously (RS800CX, Polar, Finland) during session 1 and 2 while rating of perceived exertion (RPE) was recorded using the 15-point Borg scale (6-20) after each of the two studied intensities (i.e., 60 and 70% of P_{peak}). Lactate concentration was measured on capillary blood samples taken from micropunctures performed at the earlobe at the end of all exercise intensity stages (i.e., 60 and 70 % P_{peak}) using a Lactate Scout (EKF diagnostics, Barleben, Germany). In that purpose, submaximal exercises were separated by thirty seconds of rest. Lactate accumulation ($\Delta[\text{La}]$, mmol.l^{-1}) during stages of the two studied intensities (i.e., 60 and 70% of P_{peak}) were calculated.

Calculations

Standard equations were used to estimate the percentages of energy derived from CHO (%CHOox) and lipid (%Lipidox) as well as their absolute oxidation rates (CHOox and Lipidox, respectively). These calculations take into account a non-protein VO_2 and VCO_2 (considering a standard protein oxidation rate leading to urinary nitrogen excretion of $0.01 \text{ g}\cdot\text{min}^{-1}$) and providing a non-protein respiratory quotient (NPRQ) [8,29].

$$\text{CHO} = 4.55 \cdot \text{VCO}_2 - 3.21 \cdot \text{VO}_2 - 2.87 \cdot 0.01 \quad (\text{g}\cdot\text{min}^{-1}) \quad (\text{Eq. 1})$$

$$\text{Lipid} = 1.67 \cdot \text{VO}_2 - 1.67 \cdot \text{VCO}_2 - 1.92 \cdot 0.01 \quad (\text{g}\cdot\text{min}^{-1}) \quad (\text{Eq. 2})$$

$$\text{NPRQ} = [\text{VCO}_2 - (0.01 \cdot 4.89)] / [\text{VO}_2 - (0.01 \cdot 6.04)] \quad (\%) \quad (\text{Eq. 3})$$

Therefore,

$$\%CHO_{ox} = [(NPRQ - 0.707) / 0.293] \cdot 100 \quad (\%) \quad (\text{Eq. 4})$$

$$CHO_{ox} = (\%CHO_{ox} / 100) \cdot VO_2 \cdot 5.05 \quad (\text{kcal} \cdot \text{min}^{-1}) \quad (\text{Eq. 5})$$

$$\%Lipid_{ox} = (100 - \%CHO_{ox}) \quad (\%) \quad (\text{Eq. 6})$$

$$Lipid_{ox} = (\%Lipid_{ox} / 100) \cdot VO_2 \cdot 4.7 \quad (\text{kcal} \cdot \text{min}^{-1}) \quad (\text{Eq. 7})$$

where: 5.05 and 4.7 are the numbers for kilocalories provided from CHO and lipid per liter of consumed oxygen, respectively.

Because lactate accumulation ($\Delta[La]$) was really modest, the “lactic” component in energy supply was neglected [20]. Therefore, metabolic power (P_{metab}) during exercise was computed as the sum of CHO_{ox} and $Lipid_{ox}$, divided by 69.78 to obtain results in watts.

173 ***Efficiencies***

174 Gross and net efficiencies were calculated as proposed by Gaesser and Brooks [10]:

$$175 \quad GE = P_{mecha} / P_{metab} \quad (1)$$

$$176 \quad NE = P_{mecha} / (P_{metab} - P_{rest}) \quad (2)$$

177 where GE is gross efficiency, NE is net efficiency, P_{mecha} is actual mechanical power output, and
178 P_{rest} is resting metabolic power taking into account a resting VO_2 of $5.0 \text{ ml} \cdot \text{min}^{-1} \cdot \text{kg}^{-1}$ [20].

180 ***Statistical analysis***

181 Mean values and standard deviations were calculated for each variable. Normal distribution
182 of the data was checked by the Shapiro-Wilk normality test. A two-way (*Ergometer* \times *Intensity*)
183 analysis of variance (ANOVA) with repeated measures was used to determine the effects of
184 ergometer and intensity on each variable. Significant results were followed by post-hoc

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185 comparisons using Newman-Keuls post-hoc tests. The critical level of significance was set to
186 $p \leq 0.05$.
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RESULTS

A comparison of mean mechanical, physiological, psychological and kinematic variables recorded during submaximal exercise on SRE and DRE is summarized in table 1.

Effect of exercise Intensity

The repeated-measures ANOVA showed a significant effect of exercise *Intensity* on power output ($F_{(1,10)}=110.808$), heart rate ($F_{(1,10)}=91.605$), RPE ($F_{(1,10)}=54.950$), blood lactate accumulation ($F_{(1,10)}=5.502$), VO_2 ($F_{(1,10)}=136.859$), VCO_2 ($F_{(1,10)}=204.933$), stroke rate ($F_{(1,10)}=17.396$) (table 1). Gross efficiency ($F_{(1,10)}=17.046$) was on average 5.3% higher at 70% compared to 60% of P_{peak} and net efficiency ($F_{(1,10)}=8.173$) was 3.4% lower at 60% than 70% of P_{peak} (table 1).

Effect of Ergometer

No difference was observed on power output and RPE between SRE and DRE. On the contrary, significantly higher heart rates ($F_{(1,10)}=12.930$) (2.5% and 2.5% for 60% and 70% exercise intensity, respectively) and stroke rates ($F_{(1,10)}=9.861$) were observed on DRE compared to SRE. Moreover, VO_2 ($F_{(1,10)}=13.731$) and VCO_2 ($F_{(1,10)}=8.630$) were significantly higher (by 5.1% and 4.6%, respectively) on the DRE compared to SRE. Consequently, statistical analysis showed a significant effect of *Ergometer* on gross efficiency ($F_{(1,10)}=12.694$) which was on average 5.1% higher on the SRE compared to DRE (Figure 2a) and net efficiency ($F_{(1,10)}=13.133$) which was on average 5.4% higher on the SRE compared to DRE (Figure 2b). However, it is interesting to note that blood lactate accumulation was significantly lower on DRE than on SRE ($F_{(1,10)}=5.734$).

DISCUSSION

The aim of the present study was primarily to compare rowing efficiency on Concept2 stationary and dynamic ergometers. Specifically, we hypothesized that rowing efficiency would not be different between the two ergometers. Contrary to this hypothesis, rowing efficiency was significantly lower on the dynamic Concept2 rowing ergometer than on the stationary. Another unexpected result of the present study was that blood lactate accumulation was lower on the dynamic ergometer than on the stationary.

Effect of exercise intensity

As expected, HR, RPE, VO_2 , VCO_2 , lactate accumulation and stroke rate were higher at 70% than at 60% P_{peak} . Gross and net efficiencies were also higher at 70% than at 60% P_{peak} . This result is not surprising on the stationary ergometer. Previous experiments, but not all [25], have shown that rowing efficiency increased when exercise power output augmented [9,12,22]. The new information concern the dynamic ergometer for which the same evolution pattern is observed i.e., rowing efficiency is higher at 70% than at 60% P_{peak} . Interestingly, the increase in efficiency from 60% to 70% P_{peak} is of similar magnitude on the stationary and dynamic ergometers (concerning gross efficiency +5.2% and +4.8% for SRE and DRE, respectively; concerning net efficiency +4.1% and +3.8% for SRE and DRE, respectively).

Effect of ergometer

Contrary to our hypothesis, gross and net rowing efficiencies were still lower on the dynamic than on the stationary ergometer. In the present study, gross efficiency was 4.7% and 5.2% higher on DRE than on SRE at 60% and 70% P_{peak} , respectively. Moreover, the difference between DRE and SRE was not even reduced by the new frame from Concept2. Indeed, Benson

et al. [1] found a 5.6% difference in economy at maximal power on Concept2 with and without slides and Holsgaard-Larsen and Jensen [15] found 4.3% and 2.6% differences in gross efficiency at 40% and 55% on fixed and free RowPerfect dynamic ergometer. Thus, the reduction of the displacement of the body centre of mass on the dynamic Concept2 ergometer which should had reduced the internal mechanical work to accelerate the segments mass at each stroke is not sufficient to counterbalance the other factors contributing to increase the energy expenditure. Note that the kinetic mechanical energy require to move the body mass relative to the ergometer is *a priori* associated with “internal” work since it does not contribute directly to the power output on rowing ergometers. As a whole, the kinetic internal work seems to have low impact on the mechanical efficiency, which is in line with the similar gross efficiency reported in lightweight and heavyweight rowers by Bourdin et al. [3].

As it has been previously reported for other dynamic ergometers [1,5,15], stroke rate was higher on the dynamic Concept2 than on the stationary ergometer. As Benson et al. [1] and Holsgaard-Larsen and Jensen [15] did, we could incriminate the higher stroke rate (which induces an extra energy expenditure for body mass displacement) to explain the lower efficiency on DRE than on SRE. However, the literature is consistent with the fact that the higher stroke rate on DRE is counterbalanced by lower peak force development on this type of ergometer [1,5,15], that should induce a lower energy expenditure and mitigate the negative effect of the higher stroke rate, but again this does not seem to be the case. Because i) work rate was the same and ii) stroke rate was higher on the dynamic ergometer, we can speculate that the cycle-averaged handle force was lower on the DRE. Our results, interpretation and speculation are reminiscent with the results of Colloud et al. [5] who found, for similar drag factors and stroke rate, lower handle force and power output on the dynamic ergometer than on the stationary one.

One possible explanation for the consistent higher ergometer rowing efficiency on SRE may be that the kinetic work required to accelerate the body centre of mass at each stroke is partly transferred/transformed as external (propulsive) work in the second part of the drive phase. Consequently, the higher energy expenditure associated with this internal work is partly used to produce power output, and in turn contribute to increase mechanical efficiency. This advantage, in addition to a lower stroke rate, may at the end lead to a higher rowing efficiency on the SRE than on the DRE.

An unexpected result of the present study was that blood lactate accumulation was lower on the DRE than on the SRE. This result was consistent whatever the work rate i.e., 60% or 70% P_{peak} (Table 1). At the present time, one can only speculate on the fact that the lower peak force for a given power output during rowing on DRE than on SRE may preferentially involve oxidative fibres and metabolism that may induce a lower lactate production and a higher removal/recycling [2,24,26,27,28]. However, this hypothesis should be taken with caution since to our knowledge, no studies have investigated to date the effects of changing the couple force/motion frequency on lactate kinetic parameters i.e., production, exchange and removal.

Effect of drag factor

In the present study, the drag factor was set at 110 and 130 for women and men, respectively. This raises the question of knowing whether the present results and interpretations would have been different if other drag factors had been used. Kane et al. [16] found very little effects of the drag factor on physiological aspects of rowing. Only maximal minute ventilation was affected. More importantly, no physiological responses to rowing were affected by using different drag factors (i.e., 100 and 150) during submaximal exercises [16], including the

[intensities used in the present study. So even if the drag factors had been different, it would have been unlikely that the results and conclusions of the present study would have been different.](#)

Consequences for training management [and performance achievement](#)

Rowing ergometers are extensively used during training. Results obtained during an incremental exercise (mainly VO₂, HR and lactate curves) are sometimes used to monitor training of the athletes (e.g., [21]). If the use of a dynamic rowing ergometer can be advocated because it may reflect more closely on-water rowing [7,18] and reduce the risk of injuries [5] compared to a stationary one, the present study highlighted that for a given power output, VO₂, HR and lactate accumulation are different while exercising on Concept2 SRE and DRE. Thus, the transfer/application of the results obtained on a Concept2 stationary ergometer to a dynamic one is not recommended. Specific evaluations of physiological responses to an incremental exercise should be performed on a Concept2 DRE to manage training on this ergometer. [Furthermore, the lower rowing efficiency on DRE may potentially alter the ability to sustain an elevated work rate over the race distance, affecting performance on this type of ergometer. However, this hypothesis has never been tested and further studies are necessary to conclude on this point.](#)

CONCLUSIONS

The present study showed that rowing efficiency and blood lactate accumulation were lower on the Concept2 dynamic ergometer than on its stationary counterpart. If the use of the Concept2 dynamic ergometer may provide some advantages (reduced risk of injuries), its utilisation requires specific evaluation of physiological responses during an incremental exercise for a good management of training.

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FIGURE LEGENDS

Figure 1: Diagram of a rower at catch (black) and finish (grey) positions on the stationary (a) and dynamic ergometer (b). It can be observed the greater horizontal displacement of the rower's center of mass on stationary ergometer.

Figure 2: Mean \pm SD of gross (a) and net efficiency (b) for SRE (\square) and DRE (\blacksquare) ergometer at 60% and 70% P_{peak} . *: statistical difference between SRE and DRE and between 60% and 70% P_{peak} with $p \leq 0.05$.

Table 1: Effect of exercise *Intensity*, *Ergometer* and their interaction during standardized submaximal exercise on SRE and DRE.

	60%		70%		<i>Intensity</i>	<i>Ergometer</i>	Crossed
	SRE	DRE	SRE	DRE			
<i>N</i>	11	11	11	11			
<i>Mechanical, physiological and psychological data</i>							
Power (W)	176.4±44.8	176.8±44.5	206.0±53.2	206.8±53.8	p<0.05	NS	NS
Heart rate (beats/min)	163±14	168±12	171±14	176±12	p<0.05	p<0.001	NS
RPE (6-20)	11±2	11±2	13±2	13±2	p<0.05	NS	NS
Δ[La] (mmol.l ⁻¹)	0.77±0.39	0.63±0.36	1.28±0.83	1.09±0.67	p<0.05	p<0.05	NS
VO ₂ (l.min ⁻¹)	3,35±0,84	3,51±0,84	3,65±0,82	3,87±0,88	p<0.05	p<0.05	NS
VCO ₂ (l.min ⁻¹)	2,99±0,77	3,12±0,77	3,44±0,84	3,62±0,87	p<0.05	p<0.05	NS
Gross efficiency (%)	15.4±0.9	14.7±0.9	16.2±1.1	15.4±1.2	p<0.05	p<0.05	NS
Net efficiency (%)	17.2±1.2	16.4±1.0	17.9±1.3	16.9±1.3	p<0.05	p<0.05	NS
<i>Kinematic data</i>							
Stroke rate (min ⁻¹)	18±1	19±2	19±2	20±1	p<0.05	p<0.05	NS
Values are mean±SD. SRE and DRE: stationary and dynamic rowing ergometer; RPE: rate of perceived exertion.							

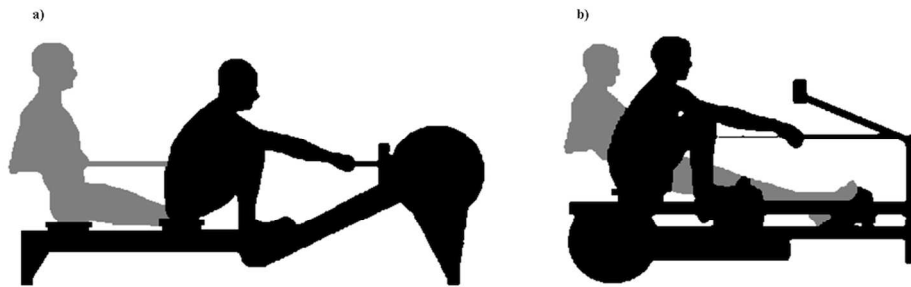


Figure 1
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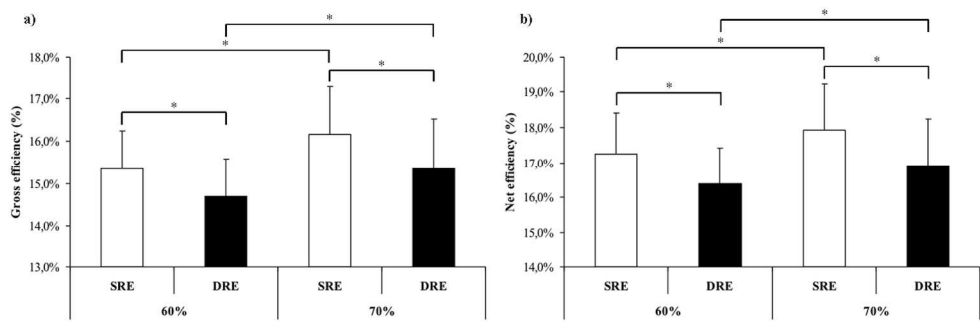


Figure 2
244x82mm (300 x 300 DPI)

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