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A comparison of physiological responses to rowing on friction-loaded and air-braked ergometers

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The physiological responses of 10 trained rowers to a progressive incremental rowing protocol to exhaustion were investigated on Gjessing, Rowperfect fixed-mechanism and Rowperfect free-mechanism rowing ergometers. Heart rate, oxygen uptake ($\dot{V}O_2$), ventilation ($\dot{V}_E$) and blood lactate were determined at matched power values for each ergometer. The mean power and heart rate at the lactate anaerobic threshold were determined by graphical interpolation of data for each ergometer. Analysis of variance and linear regression showed differing responses at matched power and an approximate 40–50 W difference in power at the lactate anaerobic threshold when comparing the friction-loaded Gjessing with the air-braked Rowperfect fixed and Rowperfect free ergometers ($P < 0.01$). No significant differences were noted when comparing the air-braked Rowperfect fixed and Rowperfect free ergometers. However, comparisons of $\dot{V}O_2$, $\dot{V}_E$ and blood lactate at given heart rates and of heart rate at the lactate anaerobic threshold showed no significant differences between ergometers. Our results indicate similar physiological profiles for all ergometers tested when compared at equivalent heart rates, but differences when compared at matched power. A direct comparison of the data from Gjessing (friction-loaded) with Rowperfect fixed and Rowperfect free (air-braked) ergometers would therefore require a correction factor for inter-ergometer variation in displayed power data.

Keywords: heart rate, lactate, oxygen uptake, rowing ergometry, ventilation.

Introduction

Rowing ergometers were developed in an attempt to reproduce movement and resistance of on-water rowing. They are widely used to describe the physiological profiles of rowers. Resistance to rowing on-water is simulated on most ergometers by rotation of a flywheel loaded either by friction of a weighted belt or by air resistance created by rotating vanes. Popular versions of these two types of ergometer are the Gjessing (A.S. Haby, Norway) and the Concept II (Morrisville, VT, USA) respectively.

Competitive rowers often train using ergometers. Both physiological and biomechanical advances in ergometer design, which result in greater sport specificity, are important for rowers when training and for exercise physiologists involved in research and testing. The physiological responses of elite rowers have been documented longitudinally by Hagerman (1984), Secher (1983, 1993) and Steinacker (1993). Ergometer assessment has allowed group and individual training programmes to be monitored and optimized (Kramer *et al.*, 1994).

The effect of variations in test protocol and ergometer design have been studied during 6-min all-out and progressive incremental test protocols (Mahler *et al.*, 1984; Urhausen *et al.*, 1987) and in comparisons of friction-loaded Gjessing versus air-braked Concept II ergometers (Hahn *et al.*, 1988; Lormes *et al.*, 1993). Optimization of physiological responses to rowing ergometry has been studied using incremental loading (Jensen and Katch, 1991). Biomechanical studies have investigated skill factors by analysing force–time profiles of the rowing stroke and kinematic body segment analysis (Martindale and Robertson, 1984; Roth *et al.*, 1993). The reproduction of efficient rowing patterns, stroke-to-stroke consistency and greater mean propulsive power per unit body mass have been reported to be accurate predictors of on-water performance (Smith and Spinks, 1995). The rowing ergometers used in these studies are extremely useful tools for the investigation of rowing physiology. However, rowers

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themselves have criticized the subjective 'feel' of fixed friction-loaded and air-braked mechanisms. During the recovery phase of on-water rowing, the mass of the boat slides underneath the rower (the rower allows the foot stretcher to move towards him). The opposite occurs during ergometer rowing; with the loading mechanism and slide bar fixed, the mass of the rower must move up and down the slide bar during the recovery and propulsive phases of the rowing stroke.

The Rowperfect is a new ergometer which has a freely moving air-braked system. This mechanical variation incorporates extra elements of skill and feel to control movement of the free mechanism during the recovery phase of the rowing action. Whether this new biomechanical simulation of the rowing action results in any changes in physiological efficiency compared with the older fixed-mechanism devices is unknown.

In this study, we investigated the physiological responses of rowers to a progressive incremental test protocol using three ergometers. Variation in the loading mechanism was examined by comparing the friction-loaded Gjessing with the air-braked Rowperfect with a fixed mechanism. The effect of the recent innovation in ergometer design – the Rowperfect free-floating mechanism – was investigated by comparing Rowperfect ergometers with a fixed and free mechanism respectively.

Materials and methods

Ten rowers, all of whom were members of a national lightweight team, provided written informed consent to participate in the study. Their mean ($\pm s$) physical characteristics were as follows: age 24.0 ± 3.5 years, height 183 ± 3 cm, body mass 76 ± 3 kg, body fat $10 \pm 2\%$. All rowers had international rowing or sculling experience; nine of the rowers had rowed or sculled for more than 10 years and the youngest rower had sculled for 5 years. In addition to a medical questionnaire and physical examination, the following investigations were performed before testing to rule out asthma, anaemia and subclinical infection: spirometry, blood haemaglobin concentration, haematocrit and white cell count. To avoid glycogen depletion and dehydration, the rowers were given nutritional advice and were required to undertake light training only on the days before testing.

The rowers completed the following rowing test schedule over 6–8 days: (1) Gjessing, (2) Rowperfect fixed-mechanism and (3) Rowperfect free-mechanism. This non-random order of testing allowed familiarization on the Rowperfect free-mechanism ergometer during recovery after completion of tests 1 and 2. After recording data at rest, the participants rowed for 3 min at each power output with a 1-min blood sampling interval between increments. Power was measured by ergometer power display units. The initial power was 160 W, with increments of 40 W until exhaustion.

Heart rate was measured by short-range radio telemetry (Polar Electro, Kempele, Finland). Expired air was collected using a Hans Rudolph face mask connected by a hose system to a Mihnjardt Oxycon 4 gas analyser (Odijk, The Netherlands). Oxygen uptake and ventilation values were displayed at 30-s intervals. Blood lactate was measured using a YSI 1500 Sport analyser (Yellow Springs Instruments, Yellow Springs, OH, USA). Blood samples were taken from the earlobe using heparinized capillary tubes and transferred to the analyser by micropipette.

The Rowperfect ergometer (CARE, The Netherlands) has a conventional sliding seat and air-braked flywheel. The foot stretcher and flywheel are incorporated into a free-floating mechanism which moves up and down the single, centrally placed slide bar. A self-recoiling chain with attached oar handle drives the flywheel. The inner cog setting for the chain and a 31-cm plastic disc attached to the side of the flywheel housing (for increasing or decreasing the cavitation effect) were used as the constant resistance settings for both the Rowperfect fixed and Rowperfect free ergometers.

On the unmodified Rowperfect free ergometer, the sliding seat remained almost static (movement <2 cm) on the slide bar, whereas the free-floating mechanism was driven away from the rower during the propulsive phase of the rowing stroke, returning towards the rower during the recovery phase. The biomechanics of this ergometer, therefore, were in direct contrast to those of the other two ergometers (Gjessing and Rowperfect fixed), for which the loading mechanisms are fixed and where rower and seat move up and down the slide bar.

On the friction-loaded Gjessing ergometer, an oar handle on a metal pole was used to drive a cam system, which, in turn, drove a friction-loaded rotating drum. The circumference of the drum was loaded by applying tension to a friction belt which could be adjusted by a cantilever system. A load of 3 kg was applied to the rotating drum for each Gjessing ergometer test. Power per stroke, elapsed time, number of turns and stroke rate for the Gjessing were recorded from the ergometer's 'Microw' display unit. Mean power for each increment of the Gjessing tests was calculated using the following formula:

$$\text{mean power} = 2\pi r \cdot N \cdot g \cdot m \qquad (1)$$

where r = the radius of the rotating drum = 15.9 cm (therefore, $2\pi r = 1$ m), N = the total number of turns per second, g = acceleration due to gravity and m = the mass applied to the friction-loaded belt = 3 kg.

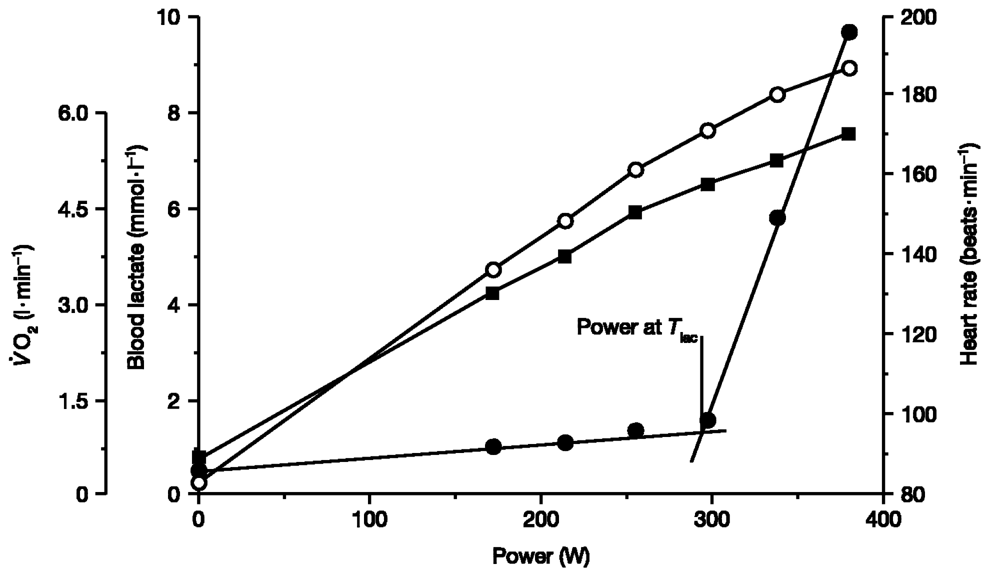

Figure 1 Sample raw data plot showing the physiological response to increasing power during incremental rowing and interpolation of power at the lactate anaerobic threshold (T_{lac}). ●, blood lactate concentration; ■, $\dot{V}O_2$; ○, heart rate.

Similar data for the Rowperfect fixed and Rowperfect free tests (power per stroke, elapsed time, stroke rate and mean power per increment) were provided by the computer interface and software package and recorded from the monitor. The calculation of Rowperfect power was dependent on several factors, including the moment of inertia of the flywheel, the power characteristics of the fan and the tension of the elastic cord (recoil mechanism). The relationship of power dissipated to the speed of the fan is given by:

$$\text{power} = K \times v^3 \qquad (2)$$

where K = the fan resistance factor and v = the rotational speed of the fan.

When the fan is rotating in open air, without any restriction on the open side, data thus derived have been shown to be within ±1% of directly measured power from analysis of force and displacement of the oar handle. Power measurements on the Rowperfect have been verified for a range of strokes (U. Grossler *et al.*, unpublished data), with varying force profiles of the stroke and with different resistance settings (provided the discs were placed centrally over the open side of the fan).

Plots of the results were constructed for each ergometer test and showed typical responses for all incremental test protocols, with approximately linear relationships between power and $\dot{V}O_2$ and between power and heart rate up to a maximum value (peak $\dot{V}O_2$ and maximum heart rate), and a curvilinear relationship with an upward inflection for blood lactate concentration against power. Data recorded at standard power outputs (160, 200, 240, 280 W) were interpolated from graphical plots, tabulated and used for statistical comparison. Power and heart rate at the lactate anaerobic threshold were interpolated from the graphs using construct lines, as shown in Fig. 1. Power at a blood lactate concentration of 2 and 4 mmol·l^{-1} were also determined graphically by interpolation.

Statistical analysis of the measured physiological parameters and the lactate anaerobic threshold was performed to compare the ergometers. Linear regression analyses, correlation coefficients and analyses of variance for repeated measures were applied. A value of $P < 0.05$ was used to establish statistical significance and *post-hoc* analysis of detected differences was performed using the Scheffè F-test.

Results

Ten incremental tests were completed on the Gjessing and Rowperfect fixed ergometers and eight tests on the Rowperfect free. Non-completion of the Rowperfect free test schedule was due to an unexpected work commitment on the part of one rower and a minor recurrence of an injury in another. The rowers' body mass was 71–82 kg (76 ± 3.1 kg), typical for lightweight rowers and scullers in early season training when not required to make competition body mass (≤72.5 kg). A comparison of mean maximal physiological variables for the three ergometers is given in Table 1.

Maximum power and power at the lactate anaerobic threshold were approximately 40–50 W less on the

Table 1 Comparison of maximal physiological variables and the lactate anaerobic threshold (mean ± *s*)

	Ergometer		
	Gjessing (n = 10)	Rowperfect fixed (n = 10)	Rowperfect free (n = 8)
$\dot{V}O_{2max}$ ($l \cdot min^{-1}$)	5.6 ± 0.3	5.6 ± 0.4	5.6 ± 0.5
$\dot{V}_{Emax}$ ($l \cdot min^{-1}$)	165 ± 11.7	163 ± 6.5	160 ± 6.3
HR_{max} (beats $\cdot min^{-1}$)	186 ± 8	186 ± 6	188 ± 10
BLa_{max} ($mmol \cdot l^{-1}$)	7.2 ± 2.9	7.5 ± 0.9	7.8 ± 4.1
Power @ BLa 2 $mmol \cdot l^{-1}$ (W)	*269 ± 25	320 ± 29	319 ± 28
Power @ BLa 4 $mmol \cdot l^{-1}$ (W)	*308 ± 19	360 ± 38	368 ± 32
Power @ T_{lac} (W)	*273 ± 19	316 ± 26	312 ± 28
HR @ BLa 2 $mmol \cdot l^{-1}$ (beats $\cdot min^{-1}$)	163 ± 8	167 ± 8	167 ± 9
HR @ BLa 4 $mmol \cdot l^{-1}$ (beats $\cdot min^{-1}$)	175 ± 10	177 ± 9	178 ± 8
HR @ T_{lac} (beats $\cdot min^{-1}$)	165 ± 7	166 ± 8	164 ± 7

* Significant at $P < 0.01$: Gjessing versus Rowperfect fixed and Rowperfect free. $\dot{V}O_2$ = oxygen uptake, $\dot{V}_E$ = ventilation, HR = heart rate, BLa = blood lactate, T_{lac} = lactate anaerobic threshold.

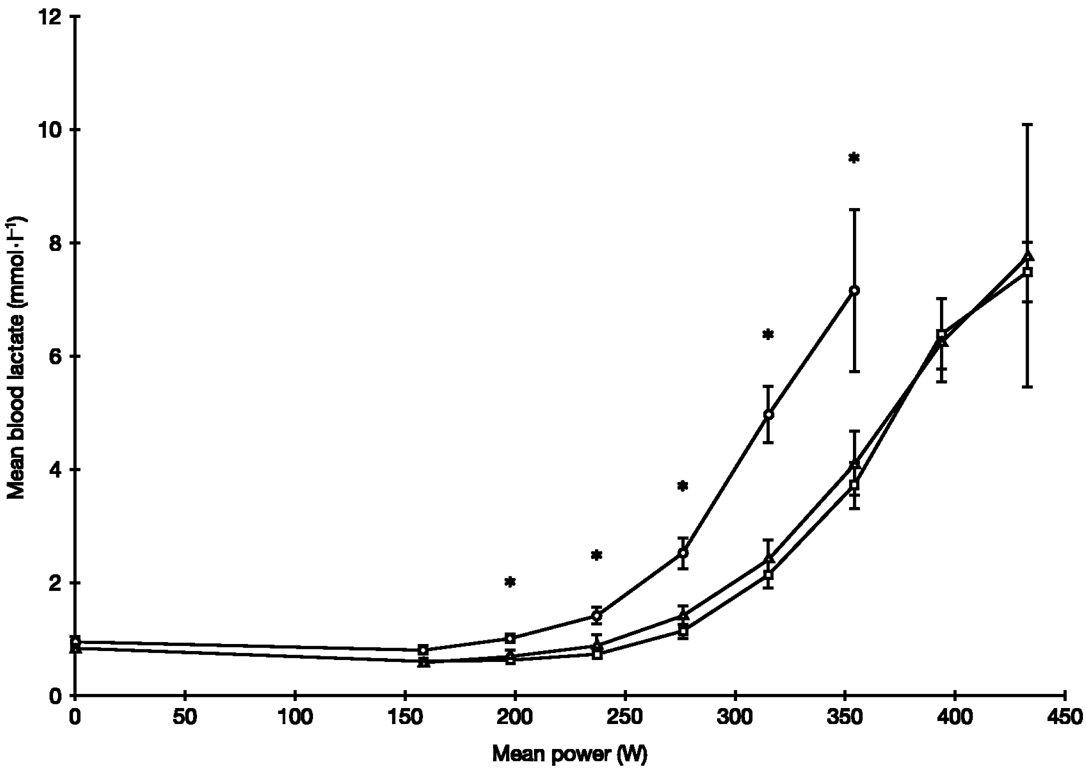

Figure 2 The relationship between blood lactate concentration and power for the Gjessing (○), Rowperfect fixed (□) and Rowperfect free (△) ergometers. The blood lactate concentration was higher during incremental rowing on the Gjessing for matched power of ≥200 W. Loads were calculated using equation (1) for the Gjessing ergometer and derived from display units for the Rowperfect fixed and free ergometers (error bars represent the standard error of the mean; * denotes statistical significance, $P < 0.01$).

Gjessing than on the Rowperfect fixed and Rowperfect free ergometers. The average maximal values of the physiological variables ($\dot{V}O_2$, $\dot{V}_E$, heart rate) were similar for all three ergometers. The maximum blood lactate concentrations, although similar, were lower than would be expected for 'all-out' ergometer rowing or after a 2000-m row during regatta competition.

The mean power at the lactate anaerobic threshold on the Gjessing was significantly lower than on the air-braked Rowperfect fixed and Rowperfect free ergometers; there was no such difference between the air-braked ergometers. However, since the mean heart rate at the lactate anaerobic threshold was similar on all three ergometers, we hypothesized that, from the initial tabulated data comparison, a discrepancy existed between power output derivation for the friction-loaded Gjessing and the air-braked Rowperfect fixed and Rowperfect free ergometers. To confirm or refute this hypothesis and, therefore, compare ergometer types independently of machine-derived power, the physiological data were compared at a given heart rate.

Interpolation of the power and heart rate at the lactate anaerobic threshold demonstrated a significant difference ($P < 0.05$) in power at the lactate threshold when comparing the Gjessing with the Rowperfect fixed and Rowperfect free ergometers, but no difference in heart rate at the lactate threshold for any of the ergometers. Ergometer-derived power data at a blood lactate concentration of 2 and 4 $mmol \cdot l^{-1}$ also showed highly significant differences between the Gjessing and the Rowperfect fixed and between the Gjessing and Rowperfect free ($P < 0.01$) ergometers, but not between the Rowperfect fixed and Rowperfect free ergometers. The heart rates at blood lactate concentrations of 2 and 4 $mmol \cdot l^{-1}$ were not different between the three ergometers.

Figures 2 and 3 show mean blood lactate concentration in response to increasing power and heart rate respectively. Figure 2 plots the blood lactate response to increasing power. At powers ≥200 W, as derived from the ergometer displays, the blood lactate concentration was higher on the friction-loaded Gjessing than on the air-braked Rowperfect fixed and Rowperfect free ergometers. The air-braked ergometers showed a similar response of blood lactate concentration versus power. Figure 3 illustrates a convergence of data points across ergometer types when mean blood lactate concentration was considered in relation to a given heart rate.

Oxygen uptake reached peak values at 320–360 W during the Gjessing tests and 400–440 W during the Rowperfect fixed and Rowperfect free tests. The $\dot{V}O_2$ was significantly higher at each derived power on the Gjessing compared with the Rowperfect fixed and Rowperfect free ergometers (Scheffè F-test = 27.0, $P < 0.01$). Linear regression analysis, however, showed $\dot{V}O_2$ to be highly correlated ($r > 0.9$), and when matched for equivalent heart rate, $\dot{V}O_2$ was similar for all ergometers. Scatter plots of $\dot{V}O_2$ versus heart rate also show convergence of the data points across all ergometer types, similar to that for blood lactate concentration versus heart rate.

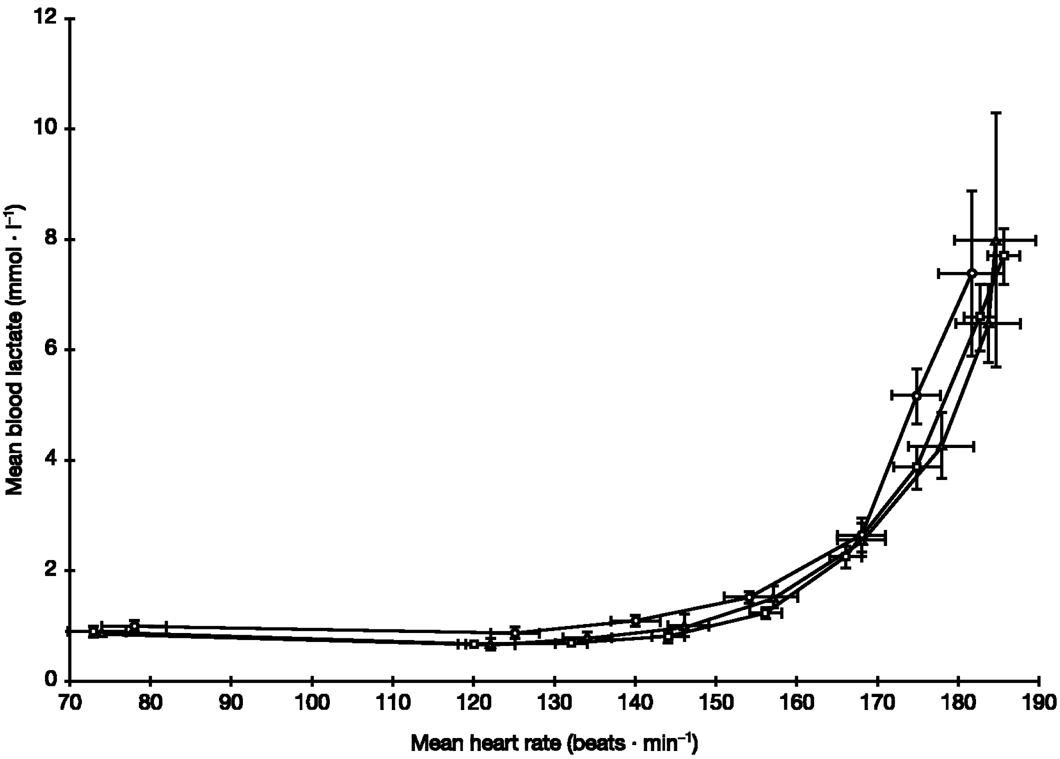

Figure 3 The relationship between lactate concentration and heart rate for the Gjessing (○), Rowperfect fixed (□) and Rowperfect free (△) ergometers. The blood lactate concentration was similar during incremental rowing on all ergometers when compared at given heart rates (error bars represent the standard error of the mean).

The stroke rate response to increasing power and at a given heart rate was examined. In response to increasing power, there were no significant differences in stroke rate across the three ergometers at 160 and 200 W. However, at 240 W, highly significant differences were noted between the Gjessing and Rowperfect fixed ergometers ($P < 0.01$). With further increases in power to 280, 320 and 360 W, there were significant differences in stroke rate between the Gjessing and both Rowperfect ergometers ($P < 0.01$). A comparison of stroke rate for the air-braked ergometers showed no significant differences. To provide stroke rate data at equivalent heart rates, third-order polynomial curves were plotted ($r^2 \geq 0.98$ for all data plots). Stroke rates at heart rates of 130–170 beats $\cdot$ min^{-1} were calculated and compared for all three ergometers. All stroke rates at matched heart rates were similar, except for the Gjessing versus Rowperfect fixed ergometer at a heart rate of 170 beats $\cdot$ min^{-1}. Essentially, there was no apparent difference in stroke rate between the ergometers at ≤200 W or at any submaximal heart rate (<170 beats $\cdot$ min^{-1}).

Discussion

In this study, we found significant differences between the Gjessing ergometer and the Rowperfect fixed and Rowperfect free ergometers when power was calculated and read from individual ergometer display units. Physiological parameters (heart rate, $\dot{V}O_2$ and blood lactate concentration) compared at matched powers showed significant differences between the mechanically braked Gjessing and the air-braked Rowperfect fixed and Rowperfect free ergometers. Comparisons of $\dot{V}O_2$ and blood lactate concentration at a given heart rate revealed no significant differences between the ergometers.

When comparing the other physiological variables with heart rate, we assumed negligible or no training effect in the heart rate response over the short timeframe of the study. The experimental design was such that confounding variables of diurnal variation in performance, dehydration and glycogen depletion were kept to a minimum. We conclude, therefore, that there were no physiological differences during incremental rowing on the Gjessing, Rowperfect fixed and Rowperfect free ergometers and that a discrepancy of approximately 40–50 W exists in power derivation between the Gjessing and Rowperfect ergometer display units. Lormes *et al.* (1993) suggested a higher anaerobic effort on the friction-loaded Gjessing compared with the air-braked Concept II; the results of our study do not support this view. Lormes *et al.* used a slightly different progressive incremental test protocol (initial power of 100 W increasing by 50 W every 3 min until exhaustion with a 30-s blood sampling interval). They found similar maximum values for blood lactate concentration and heart rate on the Gjessing and Concept II, but found blood lactate concentration to be lower on the Concept II than on the Gjessing at any given heart rate. In this study, there may have been biomechanical differences in the force–velocity profiles of the rowing stroke on each ergometer; however, the heart rate–blood lactate concentration relationship across ergometer types was similar.

Hahn *et al.* (1988) and Lormes *et al.* (1993) cited energy losses in the transmission system – the return of the Gjessing sliding pole during the recovery phase of the rowing stoke – as one explanation for the difference in power between ergometers. The power discrepancy of 40–50 W was caused either by greater frictional losses in the more complex gearing system on the Gjessing or by the Rowperfect display unit overestimating power. The Rowperfect display, however, has been verified by measurements of force and displacement on the oar handle to within ±1% (U. Grossler *et al.*, unpublished data).

When comparing the air-braked ergometers (Rowperfect fixed *vs* Rowperfect free), for which power was derived from the same display unit, no differences in physiological response were noted. A greater physiological cost might be expected on the fixed ergometer, as the greater body mass of the rower (≈75 kg) has to move up and down the slide bar compared with the movement of the lighter mass of the mechanism (≈17.5 kg) on the free-floating ergometer (Rowperfect free). A comparison of 'no-load' rowing on the Rowperfect fixed and Rowperfect free ergometers has shown differences in heart rate of 10 beats $\cdot$ min^{-1} at any given stroke rate (C. Rekers, unpublished data); in the present study, however, with loaded rowing on both types of ergometer, no difference was found.

Statistical analysis of blood lactate concentration (2 mmol $\cdot$ l^{-1}, 4 mmol $\cdot$ l^{-1}, heart rate at the lactate anaerobic threshold) and $\dot{V}O_2$ versus heart rate showed no significant differences across all three ergometers. Analysis of the stroke rate data provides similar findings to the comparison of physiological data versus power and heart rate; that is, significant differences in stroke rate versus power but essentially similar data for stroke rate versus heart rate (with only one exception in the comparison of the Rowperfect fixed and Gjessing ergometers at near maximal effort). The stroke rates at submaximal heart rates (≤170 beats $\cdot$ min^{-1}) were essentially the same; at higher heart rates, however, individual variation between rowers became apparent.

In conclusion, we found no differences in physiological variables between the Gjessing, Rowperfect fixed and Rowperfect free ergometers. Our results support the use of the Rowperfect ergometer as a viable alternative for the physiological testing of rowers, many of whom believe the 'feel' of rowing on the Rowperfect free is better than on both the Gjessing and Rowperfect fixed ergometers.

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