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ORIGINAL ARTICLE

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Dynamic calibration of mechanically, air- and electromagnetically braked cycle ergometers

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Abstract In this study we measured the accuracy of the following types of cycle ergometer against the criterion of a dynamic calibration rig (DCR): 35 friction-braked (Monark), 5 research-grade air-braked (Repco) and 5 electromagnetically braked (2 Siemens, 1 Elema-Schonander, 1 Ergoline, 1 Warren E. Collins). Monark ergometer power outputs over the range 58.9–353.2 W significantly ($P < 0.001$) underestimated those registered by the DCR with mean accuracies of 91.7–97.8%. The least accurate individual reading for each of the six up-scale (0–353.2 W) power outputs ranged from 81.5 to 91.6%; corresponding down-scale (353.2–0 W) accuracies were 85.1–92.5%. A hysteresis effect was furthermore evident for this ergometer in that up-scale measurements were significantly ($P < 0.05$) greater than down-scale ones. In addition, when the oldest [mean (SD): 11.3 (2.3) years old] and newest [1.4 (0.8) years old] eight ergometers were compared, the latter were significantly ($P < 0.05$) more accurate over the range 117.7–294.3 W. Apart from the two lowest power outputs of 47 W (62.2–96.0% accuracy) and 127 W (88.0–97.7% accuracy), the individual up-scale and down-scale accuracies of the Repco ergometers ranged from 98.0 to 104.2% for power outputs of 272.7–1137.8 W and the means were not significantly different from those of the DCR. There was also no evidence of hysteresis. Except for the initial power output of 50 W (40 rev/min: 83.8–99.2% accuracy; 60 rev/min: 93.2–122.6% accuracy), the individual accuracies of the electromagnetically braked ergometers ranged from 89.3 to 101.4% over the up-scale range of 100–400 W, and none of the means were significantly different from those of the DCR. The variability of individual errors for the preceding data emphasises that all cycle ergometers should be validated against the criterion of a DCR if accurate power outputs are required.

Key words Torque balance · Dynamic calibration rig · Power output calibration · Cycle ergometers

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Introduction

Mechanically, air- and electromagnetically braked cycle ergometers are used for measurement of the following in the exercise physiology laboratory: maximum aerobic power or $\dot{V}O_{2max}$, mechanical efficiency, anaerobic capacity, peak power and the Åstrand-Ryhming (1954) and W_{170} tests (Sjostrand 1947) which both assess aerobic fitness from the "steady-state" heart rate during submaximal work. Mechanically braked Monark cycle ergometers are normally calibrated statically prior to use by checking the zero and then suspending known masses from the balance at the point of belt attachment. However, such a procedure ignores the frictional resistance of the transmission from the pedal shaft which is additional to the power output calculated solely from pedal cadence and the braking force on the flywheel. Furthermore, many experimenters rely entirely on the manufacturer's original calibration of air- and electromagnetically braked cycle ergometers. It is therefore not surprising that eight (Clark and Greenleaf 1971; Cumming and Alexander 1968; Jones and Kane 1979; Russell and Dale 1986; Stein et al. 1967; Telford et al. 1980; Wilmore et al. 1982; Woods et al. 1994) independent investigations using dynamic calibration rigs (DCR) have reported differences between assumed and true power outputs of −12–79.7% ($n = 10$), 0–1.2% ($n = 1$) and −10–70% (by interpolation; $n = 13$) for mechanically, air- and electromagnetically braked cycle ergometers, respectively.

Although the total number of instruments examined in these 8 studies was only 24, the variability of these errors is of real concern. The aims of this study were therefore to gain access to as many cycle ergometers as possible in the Adelaide area so that we could:

1. Measure their accuracy against the criterion of a DCR.
2. Determine the extent to which any errors in power output affect physiological measurements.
3. Ascertain the effect of age on the accuracy of cycle ergometers.

Methods

The sample

The accuracy of 45 instruments was tested. This sample comprised 35 friction- (Monark-Crescent, Varberg, Sweden), 5 aerodynamically (Repco: 5 research grade, Repco Cycle Company, Huntingdale, Victoria 3166, Australia) and 5 electromagnetically (2 Siemens; 1 Elema-Schonander; 1 Ergoline; 1 Warren E. Collins) braked cycle ergometers.

The DCR

The construction, operation and accuracy of this instrument, which is essentially a torque-measuring device, have been described previously (Woods et al. 1994). A spirit level was used to check that the lever arm/ergometer assembly was level and the rig was calibrated before each ergometer was tested. Movement during calibration was minimised by securing each ergometer to a reinforced concrete floor using four brackets which were attached to masonry anchors.

Test protocols

The true power output from the DCR was based on the average of 60 readings taken during the last minute of a "2-min at each workload" setting of the continuous calibration trials:

1. Monark cycle ergometer. After a 2-min warmup against zero load at 60 rev/min, the following braking forces were applied to the ergometer's flywheel: 0, 9.8, 19.6, 29.4, 39.2, 49.1, 58.9, 58.9, 49.1, 39.2, 29.4, 19.6, 9.8 and 0 N. The belt was detached for 0 N.
2. Repco cycle ergometer. After a 2-min warmup at 50 rev/min, the following pedal cadences were applied: 50, 70, 90, 110, 130, 150, 150, 130, 110, 90, 70 and 50 rev/min.
3. Electromagnetically braked ergometers. After a 2-min warmup each machine was loaded from 0 to 300 W in 25-W increments. None of these ergometers permitted decreases in power output so it was not possible to test for any hysteresis effect.

Calculations

The DCR's computer monitored the true power output at the pedal shaft of the cycle ergometer. This was calculated as follows:

$$\text{Power} = \frac{\text{force} \times \text{distance}}{t\ (s)}, \qquad (1)$$

where, force (in N) = mass (m, in kg) $\times$ a (i.e. 9.81 m/s^2) and $d = 2\pi r$ (in m) for each revolution.

Hence,

$$\text{power} = \frac{m \times a \times d \times f}{t}, \qquad (2)$$

where, r is the length (0.739 m) of the lever arm between the pedal shaft axis and the reaction point on the load cell and f is the rotational frequency in revolutions per minute.

While the preceding calculations were appropriate for the friction- and electromagnetically braked ergometers, a further adjustment was needed for the aerodynamically braked instruments. This is because air resistance is directly proportional to barometric pressure and inversely proportional to temperature (Daish 1972). The handbook for the aerodynamically braked Repco cycle ergometer states that the instrument is factory calibrated such that the pedal cadencies yield power outputs that apply to an ambient pressure and temperature of 760 mmHg and 295 K, respectively. The following correction factor was therefore used to transform the DCR's power outputs to those applicable to the environmental conditions of the factory calibration:

$$\frac{P2}{P1(760\ \text{mmHg})} \times \frac{T1(295\ \text{K})}{T2},$$

where, $P1$ is the barometric pressure during the original calibration, $T1$ is the ambient temperature during the original calibration, $P2$ is the barometric pressure during the subsequent test, and $T2$ is the ambient temperature during the subsequent test.

Physiological significance

1. The effect of the W_{170} test error for the mechanically and electromagnetically braked cycle ergometers was determined by comparing the DCR data for set power outputs with that for a phantom male (W_{170} = 211.9 W) who registered heart rates of 105, 130, 155 and 180 beats/min at 58.9, 117.7, 176.6 and 235.4 W, respectively.

2. Previously reported data (Withers et al. 1993) on a 60-s all-out test were used to calculate the error for the five air-braked ergometers for peak power (1 s) and mean power (60 s). The calibration graphs for the five ergometers were used to calculate the DCR scores for the work monitor unit (WMU) equivalents of the means published by Withers et al. (1993). The resultant data were then compared with the published means.

Statistical analyses

1. All data are presented as mean power outputs, means and standard deviations for percent (%) accuracy (ergometer reading/DCR reading × 100).
2. Single-sample t-tests ($P \leq 0.05$) were computed between the DCR power outputs and those based on braking force/pedal cadence and workload setting for the friction- and electromagnetically braked ergometers, respectively.
3. For the Repco research-grade ergometers, dependent t-tests ($P \leq 0.05$) were conducted between the DCR's means and those of the instruments' WMUs.
4. Independent t-tests ($P \leq 0.05$) were conducted between: (a) the DCR data for the eight oldest and eight youngest Monark ergometers, and (b) the W_{170} scores for the five least accurate and most accurate Monark ergometers.
5. Single-sample t-tests ($P \leq 0.05$) were calculated between: (a) the W_{170} scores for the five most accurate Monark ergometers, five least accurate Monark ergometers and the five electromagnetically braked ergometers at 60 rev/min and the phantom value of 211.9 W, and (b) the DCR values (peak power; mean power) for the five air-braked ergometers and their published means.

Results

The results presented in Table 1 indicate that the mean power outputs from the DCR for the 35 Monark cycle ergometers were significantly greater ($P < 0.001$) than

Table 1 Calibration data for the 35 mechanically braked Monark cycle ergometers. (*DCR* Dynamic calibration rig, *SD* standard deviation)

Parameter	Up-scale power output[a] (W)					
	58.9	117.7	176.6	[b]235.4	[b]294.3	[c]353.2
Mean power (W) from DCR	64.2	125.9	187.7	246.9	309.4	373.7
Mean accuracy (%)	91.7	93.5	94.1	95.4	95.1	94.5
SD accuracy (%)	5.3	3.8	3.9	3.1	2.7	2.1
Least accurate ergometer (%)	81.6	86.3	87.0	90.3	90.4	91.6
Most accurate ergometer (%)	98.8	100.0	101.5	101.5	99.8	98.4
[d]t (upscale power output versus DCR)	10.191	10.715	9.473	8.860	10.772	8.398
	Down-scale power output[a] (W)					
	58.9	117.7	176.6	235.4	294.3	353.2
Mean power (W) from DCR	62.1	121.7	182.1	240.7	306.0	371.1
Mean accuracy (%)	94.9	96.7	97.0	97.8	96.2	95.2
SD accuracy (%)	5.1	3.2	3.4	2.5	2.6	2.2
Least accurate ergometer (%)	85.1	87.2	87.7	93.4	90.8	92.5
Most accurate ergometer (%)	103.7	102.3	102.7	103.2	100.5	98.7
[d]t (down-scale power output versus DCR)	6.233	6.330	5.387	5.205	8.743	6.920
[d]t (up-scale mean versus down-scale mean)	4.605	5.761	6.851	4.941	4.968	*2.707

[a] Up-scale/down-scale power output: based on pedal cadence and braking force
[b] n = 32 because 3 child ergometers, which do not have a setting above 3 kp, were tested
[c] n = 9
[d] t: $^{*}P < 0.05$, all other t values are significant beyond the 0.001 level

the following six ergometer power outputs which were based on pedal cadence and braking force: 58.9, 117.7, 176.6, 235.4, 294.3 and 353.2 W. The mean power outputs when going up the scale (0–353.2 W) were significantly greater ($P < 0.05$) than those going down the scale (353.2–0 W). This hysteresis effect is illustrated in Fig. 1. The means of the 12 underestimations for the 6 power outputs ranged from 2.2 to 8.3%, with a maximal individual error of 18.4%. The largest range for % accuracy of 81.6–98.8% occurred for the lowest power output of 58.9 W, whereas the smallest range of 91.6–98.4% occurred for the highest power output of 353.2 W. When the oldest and newest eight ergometers were compared, the latter were found to be significantly more accurate ($P \leq 0.05$) over the range 117.7–294.3 W. These data are presented in Table 2. The five most accurate of all the Monark ergometers yielded a W_{170} mean of 212.7 W which was not significantly different ($t = 1.24$; $P = 0.283$) from the phantom value of 211.9 W; the individual errors ranged from −1.1 (−0.5%) to 3.1 W (1.5%). On the other hand, the five least accurate of all the Monark ergometers produced a W_{170} mean of 235.3 W which was significantly different ($t = 11.18$; $P = 0.0004$) from the phantom value; the individual errors ranged from 18.4 (8.7%) to 30.3 W (14.3%).

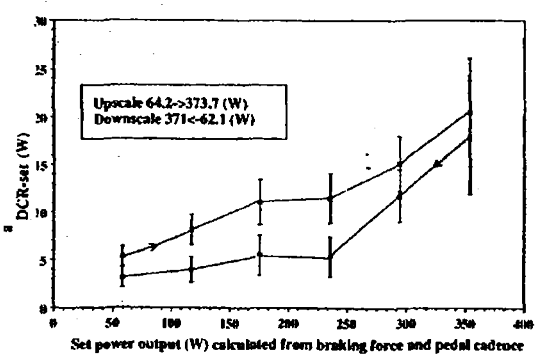

Fig. 1 Mean hysteresis effect for the 35 Monark cycle ergometers. [a]Power output difference (W) between the dynamic calibration rig (*DCR*) and that calculated from pedal cadence and braking force on the flywheel. *Vertical bars* are 95% confidence intervals

The test data on five research-grade Repco cycle ergometers are summarised in Table 3. None of the differences between the mean power outputs for these Repco ergometers were significantly different ($P > 0.05$) from those of the DCR. The differences between the six pairs of means ranged from 0.0 to 10.4 W. The lowest mean accuracies were those of 92.2 and 89.2% for the two lowest power outputs of 52.4 (50 rev/min up the scale) and 51.7 W (50 rev/min down the scale), respectively. The mean accuracy improved to 100.0–101.6% going up the scale over the range 90–150 rev/min, which spanned power outputs of 274–1120 W. Corresponding accuracies going down the scale were 99.6–101.4%. There was no evidence of hysteresis when up-scale measurements were compared with down-scale ones; differences between the six pairs of means from the WMUs ranged from 0.2 to 2.8 W. The WMU means of 879 W (peak power) and 534.4 W (average power) were not significantly different from the DCR published values of 887 W ($t = 0.94$; $P = 0.399$) and 539 W ($t = 0.87$; $P = 0.436$), respectively. Individual errors ranged from

Table 2 Calibration data for eight old [mean (SD) 11.3 (2.3) years] and eight new [1.4 (0.8) years] mechanically braked Monark cycle ergometers

Parameter	[a]Up-scale power output (W): old ergometers				
	58.9	117.7	176.6	235.4	294.3
Mean power (W) from DCR	64.2	125.7	190.6	250.7	309.7
Mean accuracy (%)	91.8	93.6	92.7	93.9	95.0
SD accuracy (%)	4.3	3.0	3.6	2.7	1.9
Least accurate ergometer (%)	84.3	88.1	88.1	90.3	92.1
Most accurate ergometer (%)	97.7	97.1	98.1	97.0	98.6
[b]t (up-scale power output versus DCR)	4.931	5.539	5.301	6.061	7.04
	[a]Up-scale power output (W): new ergometers				
	58.9	117.7	176.6	235.4	294.3
Mean power (W) from DCR	62.6	122.0	182.8	240.7	302.5
Mean accuracy (%)	94.2	96.5	96.6	97.8	97.3
SD accuracy (%)	2.7	2.6	2.1	2.7	2.2
Least accurate ergometer (%)	89.9	93.7	93.4	94.3	94.6
Most accurate ergometer (%)	98.8	100.0	98.6	101.5	99.8
[b]t (up-scale power output versus DCR)	5.882	3.686	4.428	2.261	3.406
[b]t (up-scale old mean versus up-scale new mean)	1.824	2.420	2.662	2.706	2.863

[a] Up-scale power output: based on pedal cadence and braking force
[b] t: 0.05 = 2.145, t 0.01 = 2.977, t 0.001 = 4.140 for 14 degrees of freedom

−3.3 to 1.5% for peak power and from −3.3 to 2.0% for mean power.

The data on the five electromagnetically braked ergometers presented in Table 4 indicate that none of the differences between the DCR and the ergometers were statistically significant ($P > 0.05$). The average errors at 40 rev/min ranged from 1.1 (247.4 W) to 4.0% (48.1 W), while those at 60 rev/min ranged from 0.5 (348.2 W) to 3.5% (96.6 W). These ergometers yielded a W_{170} mean of 206.8 W (60 rev/min) which was not significantly different ($t = 1.313$; $P = 0.259$) from the phantom value of 211.9 W, but the individual errors ranged from −14.9 (−7.0%) to 7.6 W (3.6%).

The least accurate (%) ergometer and largest standard deviation for accuracy (%) for all three types of ergometer occurred at the lowest power output (see Tables 1, 3 and 4). This is because a constant error comprises a greater percentage of a lower value.

Table 3 Calibration data for the five Repco research-grade air-braked cycle ergometers. (*WMU* Work monitor unit)

Parameter	Up-scale pedal cadence (rev/min)					
	50	70	90	110	130	[b]150
Mean power (W) from WMU	48.3	127.6	274.1	497.2	807.2	1137.8
Mean power (W) from DCR	52.4	132.3	274.1	489.3	797.2	1120.0
Mean accuracy (%)	92.2	96.5	100.0	101.6	101.3	101.6
SD accuracy (%)	27.3	5.5	2.2	2.0	2.5	1.6
Least accurate ergometer (%)	64.5	89.4	103.7	103.8	104.2	103.0
Most accurate ergometer (%)	89.2	97.6	99.8	100.5	99.3	99.4
[a]t (WMU mean versus DCR mean)	0.675	1.387	0.012	1.927	1.185	2.060
	Down-scale pedal cadence (rev/min)					
	50	70	90	110	130	[b]150
Mean power (W) from WMU	46.1	126.2	272.7	494.4	807.0	1136.6
Mean power (W) from DCR	51.7	132.6	273.9	489.4	796.6	1120.8
Mean accuracy (%)	89.2	95.2	99.6	101.0	101.3	101.4
SD accuracy (%)	25.7	6.2	2.4	2.3	2.4	1.8
Least accurate ergometer (%)	62.5	88.0	103.8	103.5	104.3	103.0
Most accurate ergometer (%)	96.0	97.7	98.9	100.2	100.0	99.0
[a]t (WMU mean versus DCR mean)	0.926	1.642	0.415	0.993	1.194	1.605
[a]t (up-scale mean versus down-scale mean)	0.647	0.304	0.254	0.268	1.383	2.645

[a] t: 0.05 = 2.776 for 4 degrees of freedom
[b] 150: n = 4 because gearing ratio problems prevented one ergometer from being tested at this cadence

Table 4 Calibration data for the five electromagnetically braked cycle ergometers. (*DRM* Digital readout meter)

Parameter	Power output (W) at 40 rev/min from DRM							
	50	100	150	200	250	300	350	400
Mean power (W) from DCR	48.1	96.9	147.3	196.1	247.4	293.9	–	–
Mean accuracy (%)	104.0	103.2	101.8	102.0	101.1	102.1	–	–
SD accuracy (%)	10.9	6.1	3.8	3.0	2.4	3.0	–	–
Least accurate ergometer (%)	83.8	91.1	93.6	94.3	95.1	94.7	–	–
Most accurate ergometer (%)	99.2	98.6	99.7	99.0	99.6	98.6	–	–
[a]t (DRM mean versus DCR mean)	0.777	1.144	1.046	1.511	0.964	1.501	–	–
	Power output (W) at 60 rev/min from DRM							
	50	100	150	200	250	300	350	400
Mean Power (W) from DCR	48.5	96.6	146.6	197.1	247.7	296.4	348.2	392.9
Mean accuracy (%)	103.0	103.5	102.3	101.5	100.9	101.2	100.5	101.8
SD accuracy (%)	14.5	7.9	5.0	3.7	3.0	2.5	2.8	1.8
Least accurate ergometer (%)	122.6	89.3	93.7	94.1	94.8	95.5	95.9	96 1
Most accurate ergometer (%)	93.2	96.8	97.5	99.1	101.4	100.9	98.9	101 1
[a]t (DRM mean versus DCR mean)	0.462	0.961	1.012	0.872	0.678	1.070	0.416	2.190
[a]t (DCR mean at 40 rev/min versus DCR mean at 60 rev/min)	0.246	0.233	0.526	0.635	0.244	0.463	–	–

[a] t: ' 0.05 = 2.776 for 4 degrees of freedom

Discussion

The manufacturer's handbook for the Monark cycle ergometer acknowledges that the frictional resistance of the transmission from the pedal shaft results in a true power output which is approximately 9% higher than that calculated from the braking force on the flywheel and the pedal cadence. However, the data shown in Table 1 and on Fig. 2 emphasise that it is inappropriate to implement an across the board 9% increase because of the large variability between the 35 ergometers for % accuracy at any one power output. The ranges were greatest at the lowest power output (up-scale: 17.2%; down-scale: 18.6%) and smallest at the highest power output (up-scale: 6.8%; down-scale: 6.2%). Also, the true power outputs were not approximately 9% higher than those calculated from braking force and pedal cadence. The six up-scale means ranged from 4.9 to 9.0% higher, while comparable values for the six down-scale means were 2.3–5.4%. Telford et al. (1980) have also reported that the % error is variable over the range tested rather than the constant 9% suggested by the manufacturer's handbook.

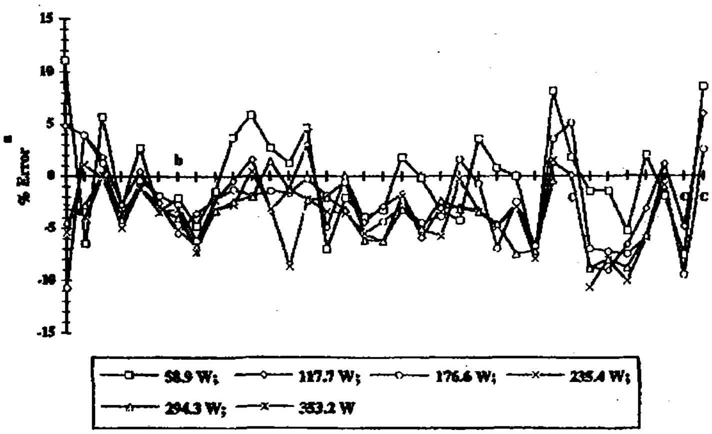

Fig. 2 The up-scale [a]percentage errors for each of the 35 Monark ergometers.

$$^{a}: \% \text{ error} = \frac{(\text{power output from DCR} - \text{power output based on braking force and pedal cadence})100}{\text{power output based on braking force and pedal cadence}}$$

[b] Note that each *cross tick* on the horizontal axis at 0% error represents one ergometer. [c] These were child ergometers which do not have a setting above 3 kp (29.4 N)

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One ergometer was serviced after producing an overall accuracy of 86%. This service included: cleaning and regreasing the front bearings, cleaning and reapplying lubricant to the chain, optimising the chain tension, refitting the chain guard so that it did not rub against the chain, and increasing the tension in the cores. Recalibration indicated an overall improvement in accuracy to 93%. These data on just one ergometer therefore suggest that the accuracy of cycle ergometers which yield aberrant power outputs can be improved by a service. Hence, it is possible that the differences in accuracy between the new and old ergometers presented in Table 2 would be decreased by servicing the latter. While the variability of these errors will not affect a subject's measured $\dot{V}O_{2max}$, they do challenge the validity of comparisons of aerobic fitness scores which are based on the heart rate response to submaximal power outputs on statically calibrated but different Monark cycle ergometers. Similar problems exist for mechanical efficiency and power output during anaerobic-type tests, both of which will be erroneously low unless adjustments are made for the additional frictional resistance. Furthermore, the hysteresis illustrated in Fig. 1 is not a problem with $\dot{V}O_{2max}$ and submaximal work tests because they involve increments and not decrements of power output. The situation is highlighted when comparing the five most accurate Monark cycle ergometers with the five least accurate ones. The former yielded physiologically insignificant W_{170} errors of −1.1–3.1 W. However, the corresponding range for the latter errors of 18.4 (8.7%)–30.3 W (14.3%) contained unequivocally physiologically significant individual errors of 18.4, 19.7, 23.3, 24.8 and 30.3 W. Furthermore, the W_{170} error breakdown (n = 35) showed that there were 5, 9, 4, 8, 5, 3, 0 and 1 ergometers with error ranges of 0–2.0, 2.1–4.0, 4.1–6.0, 6.1–8.0, 8.1–10.0, 10.1–12.0, 12.1–14.0 and 14.1–16.0%, respectively. These data emphasise that it would be easy to mask a training effect by conducting the pre- and post-test submaximal work tests on different ergometers. While it is impressive that 40% (n = 14) of the sample produced W_{170} errors of ≤4.0%, ≈25% (n = 9) of the ergometers registered errors of ≥8.1%, which could approximate a training effect. Interestingly, the age of these (n = 9) ergometers was far greater [mean (SD); 10.4 (4.7) years] than their more accurate (n = 14) counterparts [6.3 (4.4) years], thereby demonstrating the strong inverse relationship between age and accuracy. While the calibration data on the Monark is the least impressive of the three types of ergometer, its inexpensiveness and non-dependence on an electrical supply are major advantages. Our data emphasise that it is prudent to check the accuracy of all Monark cycle ergometers against the criterion of a pre-calibrated DCR.

One interesting observation is that the pendulum of a statically calibrated Monark cycle ergometer frequently fails to return to zero after use. This is caused by the accumulation of static charges on the belt during rotation and can be corrected by temporarily removing the belt. An oxide film, which reduces frictional resistance, also accumulates on the flywheel due to constant rubbing against the belt during rotation. Another observation was load creep which was caused by the elevation in temperature increasing the coefficient of sliding friction between the polyester belt and the flywheel (Lancaster 1972). This was corrected by adjusting the hand wheel. It should be noted that an up-scale misalignment equivalent to the thickness (2 mm) of the red lines on the ergometer's pendulum and scale results 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.

The Repco cycle ergometer utilises a unique air displacement system to create the resistance. It was developed by Lindsay Hooper who was a design engineer at the former Repco Research Centre in Dandenong, Victoria. The flywheel, which has six rectangular vanes equidistantly placed around a regular bicycle rim, is indirectly geared to the cranks via a double chain drive. As the flywheel rotates it produces a resistance which must be overcome by a power output that is proportional to the cube of the pedal cadence. Hence, doubling the pedal rate results in an eightfold increase in power output.

Aerodynamically braked cycle ergometers are ideal for the dual measurement of peak power output and the maximal accumulated O_2 deficit (MAOD) using all-out or variable-load tests (Withers et al. 1993). The power output is proportional to the cube of the flywheel's velocity; hence, the reduction in pedal cadence associated with fatigue is accompanied by a decrease in power output, thereby facilitating test continuity. On the other hand, if just the MAOD is measured by a constant-load test then preliminary trials are needed to determine the exercise intensity that will cause exhaustion in a given time, or the $\dot{V}O_{2max}$ must be measured if the subjects are to exercise to exhaustion at a given % $\dot{V}O_{2max}$. The calibration data presented in Table 3 for the Repco air-braked ergometers demonstrate accuracies that are all within the normal biological variability for motivated athletes performing peak power and anaerobic capacity tests. Our previously published data (Withers et al. 1993) yielded standard errors for the differences between two trials of 33.2 and 20.4 W for peak power (1 s) and average power (60 s), respectively. While these standard errors comprise combinations of technical error and biological variability, all five air-braked ergometers produced differences between the WMU and DCR which are less than these standard errors. The Repco cycle ergometer is therefore a valid instrument for the measurement of peak power and mean power during all-out tests.

Water vapour is less dense than dry air. A correction should therefore be made for relative humidity since the greater this value the lower the air resistance. This can be accomplished by subtracting 0.38 of the partial pressure (mmHg) of water vapour from both barometric pressures in the correction factor (see Methods section) for the Repco aerodynamically braked cycle ergometers (Daish 1972). However, we were unable to do this because the prevailing humidities when the instruments were factory calibrated are unknown. Nevertheless, the adjustment is very small; a variation of the humidity alone from 10 to 90% at 760 mmHg and 295 K changes the correction factor by 2.1%.

An advantage of electromagnetically braked cycle ergometers is that the power output is independent of the pedal cadence. Hence, resistance is varied as the rate of pedalling changes in order to maintain a constant power output. This is not so with friction-braked Monark and aerodynamically braked Repco cycle ergometers because their power outputs are respectively proportional to pedal cadence and the cube of pedal cadence. DCR data collected on the latter two instruments are therefore not representative of the total error that can occur in practice. For example, an extra pedal revolution at a set cadence of 50 rev/min on the Monark will result in a 2.0% error at all power outputs, whereas the same deviation on the Repco will result in errors of 6.1 and 3.0% at 50 and 400 W, respectively. The W_{170} errors for the five electromagnetically braked cycle ergometers were: 1.6, 2.0, 3.6, 5.0 and 7.0%. The two largest errors are of concern and they emphasise the need to calibrate this type of instrument using a DCR.

Some investigators calibrate their cycle ergometers biologically by measuring oxygen consumption at specified power outputs. However, this is only an approximate method because of interindividual variability in the mechanical efficiency of cycling. The variability of the present accuracy data presented in Tables 1–3 emphasise that cycle ergometers must be calibrated against the criterion of a DCR if valid measures of power output are required.

The calibrating device should measure force exactly where it is applied by the subject. Hence, while our DCR's axis of rotation is connected to the ergometer's pedal shaft such that the recording is a combination of the power output of the flywheel plus that needed to overcome frictional resistance in the bottom bracket, the frictional losses in the pedal bearings are unaccounted for. However, it has been hypothesised that these frictional losses are small (Russell and Dale 1986).

In summary, a DCR was used to determine the accuracy of friction-, air- and electromagnetically braked cycle ergometers. Our findings indicate that:

1. The variability of errors challenges the validity of comparisons of submaximal work test scores which have been conducted on ergometers that have not been dynamically calibrated.
2. Older friction-braked ergometers are less accurate than more recent purchases, but accuracy appeared to be improved by a comprehensive service.
3. All cycle ergometers that are used for monitoring fitness and for research should be dynamically calibrated.

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