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ORIGINAL ARTICLE

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Physiological effects of variations in spontaneously chosen crank rate during incremental upper-body exercise

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Abstract The aims of the present study were: first, to assess the interindividual variations of a spontaneously chosen crank rate (SCCR) in relation to the power developed during an incremental upper body exercise on an arm ergometer set at a constant power regime, and second, to compare heart rate (HR) responses, expired minute ventilation ($\dot{V}_E$) and oxygen consumption ($\dot{V}O_2$) when the pedal rates were chosen spontaneously (T_{SCCR}) or set at ±10% of the freely chosen rates ($T_{+10\%}$ and $T_{-10\%}$, respectively). The mean pedal rate values were linearly related ($P < 0.01$) with the power developed during arm cranking ($r = 0.96$), although large variations of pedalling rate strategies were observed between subjects. Maximal power (MP) and time to exhaustion values were significantly higher ($P < 0.05$) during T_{SCCR} than during $T_{+10\%}$ and $T_{-10\%}$. Peak $\dot{V}O_2$ values were significantly higher ($P < 0.05$) in $T_{+10\%}$ than in T_{SCCR} and $T_{-10\%}$. The increase in HR, $\dot{V}_E$, and $\dot{V}O_2$ mean values, in relation to the increase in the power developed, was significantly higher ($P < 0.05$) when the pedal rate was set at plus 10% of the SCCR ($T_{\pm 10\%}$) than in the two other conditions. The findings of the present study suggest that the use of an electromagnetically braked ergometer, which automatically adjusts the resistance component to maintain a constant work rate, should be used in order to achieve the highest MP values during an incremental upper body exercise. A 10% increase of the SCCR should be used in order to provide the highest peak $\dot{V}O_2$ value.

Key words Crank rate · Energy cost · Arm ergometer · Heart rate · Maximal power

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Introduction

In cyclical activities such as walking, running, cycling, and swimming, numerous studies have shown that subjects use a pattern of movement of amplitude: frequency ratio so as to keep the energy cost at a minimal level (Cavanagh and Williams 1981; Swaine and Reilly 1983; Kaneko et al. 1987; Cavanagh and Kram 1989). Contrary to the case using walking or running, where cycling activities on ergocycles have been studied, the spontaneously chosen crank rate (SCCR) has not been considered in relation to the power output. Instead, researchers have sought mainly to determine the optimal pedal rate at a given power from imposed frequencies (Banister and Jackson 1967; Pugh 1974; MacKay and Banister 1976; Seabury et al. 1977; Hagberg et al. 1981; Coast and Welch 1985; Marsh and Martin 1995). These studies did not allow the subjects to choose their own frequencies as they normally do in everyday sport activities. Moreover, the range of imposed rates was often too high (from 10 up to 30 rpm) compared to the cadences used in cyclical sporting activities.

During the assessment of physical conditioning, tests are more often designed to use lower body parts than upper body parts (Sawka et al. 1983; Powers et al. 1984; Bilodeau et al. 1995). However, an arm-cranking exercise is sometimes the best means of evaluating a group of sportsmen whose activities imply upper body part movements. Indeed, the use of an arm-pedalling ergometer is sometimes the only means of soliciting the upper-body when a specific apparatus cannot easily be used, such as in rowers (Carey et al. 1974), swimmers (Bonen et al. 1980) or disabled subjects in wheelchairs

(Glaser 1989). In addition, arm-cranking exercises are useful for the physical reconditioning of subjects with lower body injuries.

The purpose of the present study was twofold: first, to assess the interindividual variations of a SCCR in relation to the power developed during an incremental upper body exercise using an arm ergometer set at a constant power regime; and second, to compare heart rate (HR) responses, expired minute ventilation ($\dot{V}_E$) and oxygen consumption ($\dot{V}O_2$) when the pedal rates were chosen spontaneously or set at $\pm 10\%$ of the preferred rates. It was hypothesized first that the freely chosen pedal rate using an arm ergometer is independent of the power developed, and second that the cardiorespiratory and metabolic responses that occur during an incremental arm-cranking exercise are independent of the pedal rate.

Material and Methods

Subjects

Twelve male students [mean (SD) age 23.83 (2.85) years] volunteered for this study. The means (SD) for height, body mass, arm length, and maximum oxygen consumption ($\dot{V}O_{2max}$) with upper body exercise were 179.92 (4.77) cm, 74.74 (6.98) kg, 78.33 (2.01) cm, and 2.71 (0.32) $l \cdot min^{-1}$, respectively. All subjects gave their written informed consent to participate voluntarily in the study and were submitted to a complete medical examination prior to the beginning of the experiment. All measurements were carried out under medical supervision.

Testing procedures:

Arm ergometer tests were conducted on a Cybex® apparatus (MET 300) that allows one to pedal under an isokinetic (the pedal rate is imposed) or constant (the pedal frequency is free) power regime. The subjects sat in a standard position with the crank-pedal axle set between 10 and 15 cm above the scapula-humeral joint level. The hips and knees were attached with straps to the seat which was set at a distance so that the elbow was at its maximum stretch capacity minus 20° when the cranks/pedals were horizontal (Sawka 1986).

Three weeks before the assessments, all subjects went through a physical conditioning program of eight 20-min sessions that included a constant power regime and an isokinetic regime where arm pedal rates were randomly set at 60, 70, 80, and 90 rpm. Laboratory testing procedures included a pre-test and three experimental tests conducted over a 1-week period. All subjects were given preliminary instructions on how to complete the different tests and were allowed to practice. The pre-test consisted of an incremental graded test and was conducted in order to determine both the maximal power (MP) and to assign the work at a percentage of MP in the following tests. Work rate began at 70 W and was increased by 5 W at each subsequent work stage, each of which lasted 90 s. The measured MP was recorded as the power at the last completed stage. All subjects then performed the same incremental graded test under three pedalling conditions. In these tests, the constant work rate was increased by 5% of MP at each stage in order to allow comparisons of metabolic responses between the subjects for the first stage set at 50% of MP and for each stage lasting 90 s. The first test (T_{SCCR}) was completed at a constant power regime, allowing the subject to pedal with a SCRR. In the second and third tests, the ergometer was set at an isokinetic regime and the pedal rate was set randomly at plus 10% ($T_{+10\%}$) or minus 10% ($T_{-10\%}$) of those recorded during the first test.

Peak $\dot{V}O_2$, $\dot{V}_E$ and HR measurements

In the pre-test and in the three experimental tests, the subjects wore a noseclip and breathed through a 100-ml dead space mouthpiece. $\dot{V}O_2$, $\dot{V}_E$, and respiratory exchange ratio (R) were measured continuously using an open circuit system (CPX Medical Graphics, St. Paul, Minn., USA). A three-lead electrocardiogram (D_{II}, V_2, V_5) (Quinton Q 3000, Seattle, Wash., USA) was recorded continuously during the exercise test and used to determine HR. To ensure that the $\dot{V}O_{2max}$ was reached (Taylor et al. 1955), the subjects were encouraged to continue for as long as possible, so that a levelling off in $\dot{V}O_2$ occurred. The test ended at the point of voluntary exhaustion. If the subject showed signs of intense effort and if his HR had levelled off prior to the final exercise intensity, or had reached a maximal value, or if his R was at least 1.0, peak $\dot{V}O2$ was accepted as a maximal index. All subjects satisfied these criteria. Before every test, the gas meter was calibrated with a Hans Rudolph 5530 3–1 syringe and the analysers were calibrated with air and a 5 (0.03)% CO_2; 12 (0.05)% O_2; 83% N_2 gas mixture. Instrument outputs were processed using an on-line IBM PC computer which calculated (in $l \cdot min^{-1}$ the $\dot{V}_E$ and $\dot{V}O_2$ (over 30-s intervals using conventional equations; Jones and Campbell 1982). The mean values were calculated from all of the recorded measurements during the last 30 s of each stage. In order to compare the results, $\dot{V}_E$, $\dot{V}O_2$ and HR values were normalized as a linear function of the percentage of the MP reached during the three tests.

Statistical analyses

The means (SD) were computed for all of the measured variables. Simple regressions were used between the power and pedal rate values registered at each stage. A one-way analysis of variance (ANOVA) and the Scheffe post hoc test were used to study the evolution of SCCR in relation to the percentage of MP. Statistical analyses were also performed using a two-way ANOVA to compare $\dot{V}O2$, $\dot{V}_E$, and HR responses under the three pedal rate conditions (T_{SCCR}, $T_{+10\%}$, and $T_{-10\%}$). In all statistical analyses, the significance threshold was set at $P < 0.05$.

Results

The mean pedal rate values reported at each stage of exercise at T_{SCCR} are shown in Fig. 1. The crank rates used spontaneously by the subjects increased significantly ($P < 0.01$) from 74.4 (8.7) to 81.4 (10.9) rpm. The freely chosen crank rates were significantly ($P < 0.05$) related to the power developed during arm cranking ($r = 0.96$), to HR ($r = 0.96$), to $\dot{V}_E$ ($r = 0.98$), and to $\dot{V}O_2$ ($r = 0.99$). However, large variations of pedal rate strategies were found between the subjects. The MP, time to exhaustion, and peak HR, $\dot{V}_E$, and $\dot{V}O_2$ values measured at the end of exercise are given in Table 1. The MP and time to exhaustion values were significantly higher ($P < 0.05$) during T_{SCCR} than during $T_{+10\%}$ and $T_{-10\%}$, (Table 1). The peak $\dot{V}O_2$ value was significantly higher ($P < 0.05$) in $T_{+10\%}$ than in T_{SCCR} and $T_{-10\%}$, [2.96 (0.3) vs 2.82 (0.3) and 2.81 (0.4) $l \cdot min^{-1}$, respectively). No significant differences between the three pedal rates were noticed for peak HR and peak $\dot{V}_E$. The effect of the pedal rate on the responses of $\dot{V}O_2$, $\dot{V}_E$, and HR, according to the increase of power output set at a percentage of MP, are presented in Table 2. The increases of $\dot{V}O_2$, $\dot{V}_E$, and HR mean values in relation to the increase in power developed

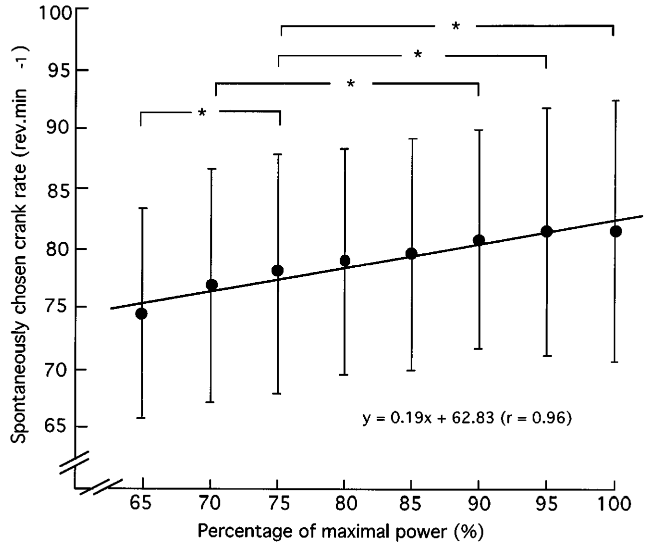

Fig. 1 Evolution of spontaneously chosen crank (SCCR) rate mean values and standard deviations in relation to the percentage of maximal power recorded during the test carried out at the SCCR. The increase significance is illustrated by asterisks ($P < 0.05$)

were significantly higher ($P < 0.05$) when the pedal rates were set at plus 10% of the SCCR than the values measured during T_{SCCR}. No significant difference was noticed when the pedal rates were set at minus 10% compared to T_{SCCR} and $T_{+10\%}$.

Discussion

The crank rates that were used spontaneously by the subjects [from 74.4 (8.7) up to 81.4 (10.9) rpm, corresponding to 65% and 100% of MP, respectively] are generally higher than those reported in previous studies (Sawka 1986; Glaser et al. 1980; Sawka et al. 1983; Powers et al. 1984). Although the imposed pedal rates ranged from 30 to 90 rpm in those latter studies, most of the rates were set within the range of 60–70 rpm. The higher cranking rates recorded in the present study may be linked to the higher percentage of power developed (from 65 up to 100% of MP).

These results are in accordance with those of Seabury et al. (1977), who reported that during bicycle ergometry, the increase in energy expenditure observed when pedalling at a rate slower than the "most efficient" is more pronounced at high power outputs than at low power outputs, while similarly, the increase in energy expenditure in response to pedalling at a rate faster than "most efficient" is less pronounced at high power outputs than at low power outputs.

All of the previous studies differ from ours in that the crank rates were imposed and did not allow the subjects to use their own rates according to the developed power output. Pedal rates in the present study increased significantly and were related to power output ($r = 0.96$, $P < 0.01$). During an incremental test with imposed pedal rates, Coast and Welch (1985) showed that the optimal rate increases according to the power requirements. The increase in SCCR in relation to incremental power output reported in the present study might result from the need to decrease the arm pressure put on the cranks/pedals (Faulkner et al. 1971; Coast and Welch 1985; Cavanagh and Sanderson 1986). This increase in the crank rate might enable subjects to reduce the local muscular strain which might have caused some of them to stop the test earlier (Sawka et al. 1983). Moreover, the muscular strain could be higher when the actions are performed with the upper limbs than when performed with the lower limbs. The smaller muscle masses involved in an arm exercise limit the blood flow when muscular tension is high (Petrofsky et al. 1981; Sawka et al. 1983), and thus limit oxygen uptake. However, the increase of pedal rate in relation to power output was very different from one subject to another. These results emphasize the interest in using testing procedures in which pedal rates can be freely chosen. During an exercise bout with cyclists performing at 80% of $\dot{V}O_{2max}$, Hagberg et al. (1981) noticed a great variation in the preferred pedal rate (from 72 up to 102 rpm). Such differences between subjects may be a reflection of the existence of different muscle fibre types among subjects (Gollnick et al. 1973; Suzuky 1979), but may also be part of a strategy linked to a certain background in sports (Marsh and Martin 1995). Kirby et al. (1989) have shown that besides the anthropometric, muscular, and physiological characteristics of the subjects, the freely chosen pedal rates were also related to HR responses according to the power output. These authors, as well as Donville et al. (1993) reported a coupling between cardiac and locomotor rhythms while subjects exercised at cadences that are natural to them. In the present study, HR was significantly related to the SCCR ($r = 0.96$).

Table 1 Peak mean (SD) values of maximal power (MP), time to exhaustion, heart rate (HR), expired minute volume ($\dot{V}_E$), and oxygen consumption ($\dot{V}O_2$) recorded at the end of the test carried out at the spontaneously chosen pedal rate (T_{SCCR}), or at ±10% of the spontaneously chosen pedal rate ($T_{+10\%}$ and $T_{-10\%}$ respectively)

$n = 12$	$T_{-10\%}$	T_{SCCR}	$T_{+10\%}$
MP (w)	154.1 (16.4)	161.1 (15.9)*	151 (15.8)
Time to exhaustion (s)	847.5 (124)	922.5 (95)*	817.5 (146)
Peak HR (beats · min^{-1})	186.1 (6.5)	189.6 (4.4)	190.7 (3.5)
Peak $\dot{V}_E$ (l · min^{-1})	126.4 (22)	125.2 (17.2)	129.5 (20.6)
Peak $\dot{V}O_2$ (l · min^{-1})	2.81 (0.4)	2.82 (0.3)	2.96 (0.3)*

* Differences statistically significant at $P < 0.05$ from the two other tests

Table 2 Normalized mean (SD) values of $\dot{V}O_2$, $\dot{V}_E$, and HR recorded at each stage of different percentages of maximal power (% MP)

n = 12	%MP	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%	100%
$\dot{V}O_2$ ($l \cdot min^{-1}$)	$T_{-10\%}$	1.27 (0.2)	1.44 (0.2)	1.60 (0.2)	1.77 (0.2)	1.94 (0.2)	2.1 (0.2)	2.27 (0.2)	2.43 (0.2)	2.60 (0.2)	2.76 (0.2)	2.93 (0.2)
	T_{SCCR}	1.18 (0.2)	1.34 (0.2)	1.51 (0.2)	1.67 (0.2)	1.84 (0.2)	2.0 (0.2)	2.16 (0.3)	2.33 (0.3)	2.49 (0.3)	2.66 (0.4)	2.82 (0.4)
	$T_{+10\%}$	1.28 (0.2)*	1.47 (0.2)*	1.66 (0.2)*	1.85 (0.2)*	2.04 (0.2)*	2.23 (0.2)*	2.42 (0.2)*	2.62 (0.2)*	2.81 (0.3)*	3.01 (0.3)*	3.19 (0.3)
$\dot{V}_E$ ($l \cdot min^{-1}$)	$T_{-10\%}$	30.8 (10.8)	38.7 (9.3)	46.6 (8.3)	54.4 (8.1)	62.3 (8.7)	70.2 (9.9)	78.6 (11.6)	87.1 (12.4)	100.8 (14.6)	117.2 (15.9)	133.5 (18.5)
	T_{SCCR}	31.3 (10.4)	37.7 (9)	44.1 (7.9)	50.4 (7.1)	56.7 (6.8)	64.3 (8.2)	72.9 (11)	82.9 (12.7)	94.7 (14.4)	109.4 (14.1)	124.9 (16.8)
	$T_{+10\%}$	33.2 (12.5)*	42.3 (11.2)*	51.4 (10.8)*	60. 6 (11.5)*	69.7 (13.2)*	79.3 (16.1)*	91.6 (23.4)*	104.4 (30.7)*	121.4 (36.2)*	138.9 (40.8)*	156.9 (45.6)*
HR (beats $\cdot min^{-1}$)	$T_{-10\%}$	117.9 (8.1)	125.7 (8.3)	133.6 (8.8)	141.4 (9.7)	149.2 (10.7)	157.1 (11.9)	164.9 (13.4)	172.7 (14.8)	180.6 (16.3)	188.4 (17.9)	196.3 (19.5)
	T_{SCCR}	122.5 (5.7)	129.7 (6)	136.9 (6.6)	144.2 (7.4)	151.5 (8.2)	158.7 (9.2)	166 (10.3)	173.2 (11.4)	180.5 (12.5)	187.8 (13.6)	195.1 (14.8)
	$T_{+10\%}$	127.7 (9.3)*	135.4 (8.1)*	143.1 (7.2)*	150.8 (6.8)*	158.5 (6.8)*	166.2 (7.4)*	173.9 (8.3)*	181.5 (9.5)*	189.2 (10.5)*	196.9 (12.4)*	204.6 (14.1)*

*Differences statistically significant at $P < 0.05$ from the T_{SCCR} test

MP values were significantly higher ($P < 0.01$) in T_{SCCR} than in $T_{-10\%}$ and $T_{+10\%}$. The rather low variations in pedal rates (± 10%) significantly influenced the MP performed at the end of the test. These results are in agreement with those of Cox et al. (1994) and McNaughton and Thomas (1996), measured during a test performed with the lower limbs, as well as those of Sawka et al. (1983), measured during an incremental test performed with the upper limbs in which the imposed variations were ± 20 rpm. MP values [161 (16) W in T_{SCCR}] were slightly lower than those measured by Sawka et al. (1983) [169 (7) and 179 (7) W at 50 and 70 rpm, respectively] in a homogeneous group of subjects. Moreover, the time to exhaustion performed in T_{SCCR} [922 (95) s] was significantly longer than in $T_{-10\%}$ and $T_{+10\%}$ [847 (124) and 817 (146) s, respectively] and confirm the results observed for variations in MP and those recently reported by Mc Naughton and Thomas (1996).

The mean peak HR responses measured during the three experimental tests (Table 1) were not significantly different and were close to those reported by Sawka et al. (1983) during an incremental upper body exercise. The $\dot{V}_E$ peak values recorded in $T_{+10\%}$ showed a tendency to be higher than in the two other conditions. Sawka et al. (1983) recorded higher $\dot{V}_E$ peak values ($P < 0.05$) when exercise was performed at 70 rpm than when performed at 50 rpm. In agreement with Sawka et al. (1983), the peak $\dot{V}O_2$ values recorded in $T_{+10\%}$ were significantly higher ($P < 0.05$) than the values measured in T_{SCCR} and $T_{-10\%}$. The use of high crank rates in the testing procedure might thus be limited by the shorter duration of the test due to local muscle fatigue (Sawka et al. 1983). This might, however, enable the subjects to reach their maximal physiological limits more easily. For exhaustive tests on an ergocycle such results may lead one to ask the subjects to increase their crank rates during the few last stages of the test.

Mean values for HR, $\dot{V}_E$ and $\dot{V}O_2$ were significantly higher in $T_{+10\%}$ ($P < 0.05$) than in T_{SCCR} and $T_{-10\%}$ (Table 2). During rectangular tests, Powers et al. (1984) have observed the influence of variations in crank rates ranging from 50 to 90 rpm on the kinetics of the HR, $\dot{V}_E$, and $\dot{V}O_2$ responses. These authors reported an increase in energy cost linked to the increase in pedal rate. However, the results of the present study are more in agreement with results reported by Hagberg et al. (1981) who studied cyclists. By measuring and modelling the evolutions obtained during an exercise performed at the preferred pedal rate, Hagberg et al. (1981) showed that the freely chosen rate is the more economical. The rates above and below the preferred rate caused $\dot{V}O_2$ and $\dot{V}_E$ to increase significantly. It must be pointed out, however, that Hagberg et al. (1981) did not choose to change the pedal rates starting from the freely chosen pedal rate, but to impose rates from 60 to 120 rpm, increasing in steps of 15 rpm. The variations of ± 10% of the SCCR imposed in the present study are high enough to cause significant changes in $\dot{V}O_2$ and $\dot{V}_E$ between the T_{SCCR}

and $T_{+10\%}$ tests. Only HR values were significantly lower ($P < 0.05$) at $T_{-10\%}$ in the first two stages (50 and 55% of the MP; Table 2). When the pedal rate decreased by 20 rpm, Powers et al. (1984) recorded a decrease in HR, $\dot{V}_E$, and $\dot{V}O_2$. Hagberg et al. (1981) recorded a linear increase in HR with increases in pedal rate. As observed by Seabury et al. (1977), the use of a low pedal rate entails minimal energy costs during low-power exercises.

During the pre-test, the mean value of MP was 167 (17) W and was significantly higher than that reported in T_{SCCR}. The longer duration of exercise during the T_{SCCR} tests [11.2 (1.7) vs 15.4 (1.5) min] probably caused a higher muscular strain. Such a local muscular strain is a feature of the lower stamina of the upper limbs (Davies and Sargeant 1974). In a recent review, Sawka (1986) suggested that the combination of power, exercise duration, and crank rate should be carefully chosen to obtain an optimal evaluation during exhaustive events. The results of the present study are in agreement with these recommendations, but they also show that it is necessary to allow the subjects to use their own rates. Indeed, variations from minus 10% to plus 10% of the SCCR cause MP to decrease by 4.3 and 6.9%, respectively. The present results also show that a crank rate lower than the SCCR results in a greater contribution of the heart and lungs/breathing apparatus than when cranking at rates higher than the SCCR. On the contrary, using rates that are slightly lower than the freely chosen rates does not seem to affect energy costs significantly (Hagberg et al. 1981).

In summary, the results of the present experiment show that the use of an electromagnetically braked ergometer, which automatically adjusts the resistance component to maintain a constant work rate, should be used in order to achieve the highest MP values during an incremental aerobic upper body exercise. The relationship between the SCCR and the power output increases in a linear way, but individual strategies may vary considerably from one person to another. An untrained individual who is not used to performing upper body exercises may, however, be asked to increase the crank rate gradually during an incremental test. A 10% decrease in the SCCR does not cause significant differences as far as HR, $\dot{V}_E$, and $\dot{V}O_2$ are concerned. A 10% increase in the SCCR may be better in order to provide the highest value of peak $\dot{V}O_2$ and seems to be less economical at each stage of exercise intensity. Finally, an increase in the SCCR during the last stages of an incremental task is advisable in order to elicit the higher peak levels of HR, $\dot{V}_E$, and $\dot{V}O_2$. These findings suggest, as reported in studies on walking (Cavanagh and Williams 1981), running (Cavanagh and Kram 1989), or swimming (Swaine and Reilly 1983), that upper body exercise performed on an ergocycle should be conducted using the most effective freely and spontaneously chosen pedal rate. The results also indicate, to the benefit of coaches, that variations in individual and spontaneous rhythms during cyclical sport activities in which the work is mostly performed with the arms can result in higher energy costs. When only the upper limbs can be used to achieve the physical reconditioning of injured, handicapped, or cardiac patients, it seems advisable to use an ergometer that allows the pedal rates to be set in order to determine accurately the intensity of power output.

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