International Journal of Industrial Ergonomics 41 (2011) 261–267

Contents lists available at ScienceDirect

International Journal of Industrial Ergonomics

journal homepage: www.elsevier.com/locate/ergon

Pedal power for occupational activities: Effect of power output and pedalling rate on physiological responses

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ARTICLE INFO

Article history:
Received 31 March 2010
Received in revised form
23 February 2011
Accepted 23 February 2011
Available online 21 March 2011

Keywords:
Pedal work
Power output
Pedalling rate
Physiological responses
Acceptable workload

ABSTRACT

Because of the socio-economical conditions of farmers in developing countries including India, human muscle power is going to contribute energy requirements for performing many farm activities for the next two decades. Pedalling is the most efficient way of utilising power from human muscles. Pedal power enables a person to drive devices at the same or higher rate as that achieved by hand cranking, but with far less effort and fatigue. However, the use of pedal power for occupational work such as stationary farm operations has got scant attention in the past. Keeping these points into consideration a study was planned to optimise power output and pedalling rate for stationary farm operations. Physiological responses of 12 male subjects were studied on a computerised bicycle ergometer at five levels of power output (30–90 W) and seven levels of pedalling rates (30–90 rev min^{-1}). Analysis of data indicated that physiological responses were significantly affected with power output as well as pedalling rate. Increase in physiological responses (heart rate and oxygen consumption rate) over rest (delta values) were significantly higher when pedalling frequency was 30 rev min^{-1} and above 50 rev min^{-1}. There was no significant difference between physiological responses at 40 and 50 rev min^{-1}. Physiological responses increased linearly with power output and were significantly different at different power outputs. The delta values of physiological responses at 60 W power output and 50 rev min^{-1} pedalling rate ($\Delta HR = 40$ beats min^{-1} and $\Delta VO_2 = 0.56$ l min^{-1}) were within acceptable limits for continuous pedalling work. From the results of the study it was concluded that for daylong pedalling work the power output from an Indian agricultural worker should be limited to 60 W and pedalling rate should be 50 rev min^{-1}.
Relevance to industry: The optimal power output and pedalling rate may be used for the ergonomic design of a dynapod or any pedalling device for efficient utilization of human muscle power with reduced drudgery and fatigue.

1. Introduction

Until about two and half centuries ago, muscle power was the prime source of energy for performing all the physical activities on our earth, and much of this power had been from human muscles. Because of the socio-economic conditions of farmers in several developing countries including India, human muscle power will go on contributing energy requirements for performing many farm activities at least for next two decades. In remote villages in India, where electric power supply is not available and repair and maintenance facilities for internal combustion engines are scarce, human power is still one of the major contributors of energy for production agriculture as well as for post harvest agricultural operations.

Human energy has generally been utilised through arms, hands, and back. It was only with the invention of the bicycle, that legs also began to be considered as a means of developing power from human muscles. Maximal power produced with legs is generally limited by adaptations within the oxygen transport system. On the other hand, the capacity for arm exercise is dependent upon the amounts of muscle mass engaged (Shephard, 1967). Owing to these limitations, a person can generate more power (about four times) by pedalling than by hand cranking (Wilson, 1986). Pedal power enables a person to drive devices at the same or higher rate as that achieved by hand cranking, but with far less effort and fatigue.

The main use of pedal power in the high-power range (75 W and above) is still for bicycling during exercise training, sports and rehabilitation activities. In the low-power range the major occupational use of pedal power is for transport of people using cycle rickshaw. However, pedal power seems to be potentially

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doi:10.1016/j.ergon.2011.02.011

advantageous in agriculture, construction and electrical power generation, when electrical or internal combustion engine power is unavailable/expensive. Common applications of stationary pedal power in agricultural operations may include water pumping, threshing, winnowing, groundnut decortication, maize shelling, grain grinding, fodder shredding, etc.

The power levels that a human being can produce through pedalling depend on how strong he/she is and on how long he/she can pedal. If the task to be powered has to continue for hours at a time, 75 W mechanical power is generally considered the limit for a larger, healthy non-athlete. A person who is smaller and less well nourished, but not ill, would produce less; the estimate for such a person should probably be 50 W for the same kind of power production over an extended period (Wilson, 1986). Power levels are also directly related to the environment in which the person is doing pedalling. To be able to continue pedalling over an extended period, a person must be able to keep cool – whether because the ambient temperature is low enough, or because there is adequate breeze.

Looking into the increasing prices and unreliable supplies of petroleum fuels and non-availability of repair and maintenance facilities in remote villages in India, the internal combustion engines are not so attractive power source especially for stationary farm operations and pedal-powered devices may be much more suitable. Pedal power can be utilised for the operation of any stationery farm machine by simply using the chain and sprockets used on cycle rickshaws, however, the efficiency is lower. A dynapod is a portable pedal operated power device that consists of a stand, saddle, handlebar, chain, sprocket wheels, cranks and pedals. Sometimes, a flywheel is used to get uniform speed of operation. The device may be used as an interface between human worker and any of the above-mentioned equipment with appropriate combination of sprocket wheels to obtain the desired speed/power. A dynapod can operate a pump during the crop-growing season, run a thresher at harvest time, and power a grain mill throughout the year. Its portability allows it to be moved from site to site. Dynapod power varies according to the size and fitness of the operator and the length of time spent in pedalling.

Performance during pedalling work on a dynapod is affected by the interaction of a number of variables including pedalling technique (workload, pedalling rate and posture), pedalling device (pedal type, saddle height, crank length and head angle), environment (temperature, humidity and air velocity), and human factors (age, gender, weight and training level). Human beings are very adoptable and may produce power in pedalling mode over a wide range of power outputs and pedalling rates. However, a person can produce more power, or the same amount of power for a longer time, if he/she pedals at a certain rate. Keeping these points into consideration this study was planned for the optimisation of power output and pedalling rate for design of a dynapod to be used as an interface between human worker and process machine for daylong occupational activity by Indian agricultural workers.

2. Materials and methods

2.1. Measurement of basic physical and physiological characteristics of the subjects

In order to determine the optimum power output for long duration pedalling work and optimum pedalling rate corresponding to that power output, the physiological responses of 12 male subjects at different power outputs and pedalling rates were studied on a computerised bicycle Ergometer (Monark, Ergomedic 839 E; Varberg, Sweden). These subjects were selected from the workers who carry out different agricultural activities at the Institute farm. Basic physical and physiological characteristics namely age, weight, stature, trochanteric height, maximum heart rate and maximum oxygen consumption rate of the selected subjects were measured in the laboratory. Personal weighing balance (100 kg capacity with least count of 0.5 kg) was used for the measurement of weight of the subjects. Stature of the subjects was measured using Harpenden stadiometer (least count 1 mm). The mean (±SD) age, weight and stature of subjects were 27.6 ± 7.5 years, 58 ± 8.5 kg and 1675 ± 41.67 mm, respectively. Trochanteric height was measured using a 1.5 m length metallic scale. Maximum heart rate of agricultural workers was determined by subtracting the age of the subjects from 220 and aerobic capacity (VO_{2max}) was determined using the technique proposed by Maritz et al. (1961).

2.2. Experimental design

Most efficient pedalling rate for cycling had been reported as 50 to 60 rev min^{-1} (Seabury et al., 1977; Coast et al., 1986; Marsh and Martin, 1993; Annaheim et al., 2010). On the other hand, the most preferred pedalling rate for cross-country cycling had been about 90–100 rev min^{-1} (Marsh and Martin, 1993; Neptune and Hull, 1999). However, for occupational work, where minimum energy expenditure and body discomfort are desired and work has to be performed under stationary conditions, the most efficient pedalling rate would depend on work intensity and work duration. Therefore, this experiment was conducted for pedalling frequencies ranging from 30 to 90 rev min^{-1} in steps of 10 rev min^{-1}.

Studies on Western populations had indicated that for continuous power generation a workload of about 75 W would be reasonable for a young, healthy person (Wilson, 1986). On the other hand the maximum power for intermittent uses might go up to 200 W. However, these values might be on the higher side for Indian agricultural workers, because of their lower (about 2.0 l min^{-1}) aerobic capacity (Nag et al., 1978; Nag, 1981). Therefore, the power range for this experiment was taken as 30–90 W in steps of 15 W.

The experiment was planned in split-plot design with 5 levels of power output as main treatments and 7 levels of pedalling speeds as sub-treatments. The subjects were taken as replications. Thus, there were 35 trials for each subject and a total of 420 trials were conducted for the experiment. The order of main treatments for each subject was randomised and within the main treatments the sub-treatments were again randomised.

2.3. Protocol for the measurement of physiological responses

Every day, three subjects were asked to report in the laboratory at 10 AM for the measurement of physiological responses on the bicycle ergometer. The subjects were instructed to have a light breakfast about 2 h before they report in the laboratory. All the trials were conducted between 10:00 AM to 01:30 PM and 02:30 to 05:00 PM in a controlled environment condition. The dry bulb temperature in the laboratory varied from 23 to 27 °C and relative humidity varied from 50 to 60% during the experiment. A minimum gap of 2 h was maintained between food intake and start of a trial. After arrival in the laboratory, each subject was given a warm up exercise on a computerised treadmill (Jaeger, Model: LE 200 CE) for 10 min at a speed of 4.5 km/h and slope varied from 0 to 12° in steps of 2° after every 1 min and then lowered to 0°. The subject was then asked to have a rest of about 30 min so that his physiological responses reached to resting level.

Physiological responses were measured using an ambulatory metabolic measurement system, METAMAX® II (MOBILE CPX TESTING, Cortex Biophysic, The Netherlands). After about 30 min rest the subject was prepared for trial by fastening the Polar chest belt and facemask with other accessories. Physiological responses for first 5 min were taken while the subject was resting, sitting on a chair.

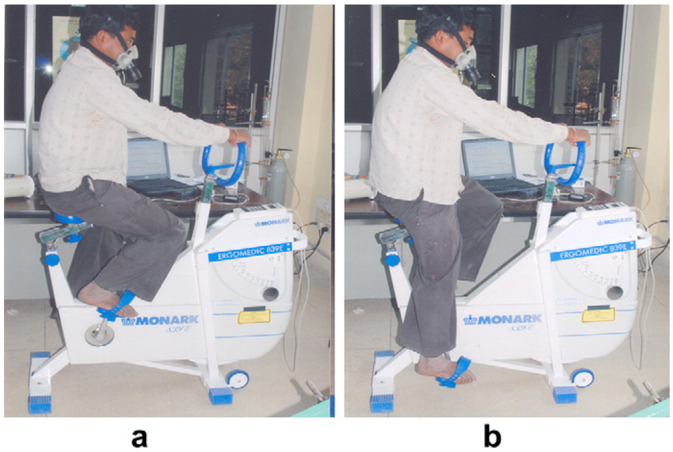

Fig. 1. A subject performing pedalling work on computerised bicycle ergometer (a) right leg posture at top dead centre of pedal (b) right leg posture at bottom dead centre of pedal.

Minimum heart rate and oxygen consumption rate had been reported at saddle height of 100% of trochanteric height (Nordeen-Snyder, 1977; Price and Donne, 1997). Therefore, the saddle height for this experiment was set equal to the trochanteric height of the subject. The crank length was kept standard (178.5 mm) as supplied with the ergometer. After taking 5 min data of physiological responses during resting the subject was asked to start pedalling work on the bicycle ergometer (Fig. 1) at a pre-set pedalling rate. The metronome for pedalling rate was set as per the requirement for that trial. The workload was increased to the level required for the trial within first 30 s using the load increase button of the monitor provided on the ergometer.

The subject worked on the ergometer at the set pedalling rate and workload for a duration of 15 min. At the end of 15 min trial he was asked to stop pedalling work, get down from the ergometer and have rest while sitting on a chair placed by the side of the ergometer. The data on physiological responses were transferred to an excel sheet for further analysis.

2.4. Data analysis

Work output during any physical activity is better expressed in terms of percentage of aerobic capacity or maximum oxygen consumption rate (VO_{2max}) of workers. Keeping this point in view the aerobic capacities of agricultural workers were assessed by measuring oxygen consumption rate and heart rate at different sub-maximal workloads as per Naughton protocol while pedalling on computerised bicycle ergometer. The aerobic capacity of each subject was determined using the technique proposed by Maritz et al. (1961).

The mean values of physiological responses *i.e.* heart rate (HR), and oxygen consumption rate (OCR) for each trial with each subject were calculated by averaging the 10 min data from 6th to 15th minute. To have a meaningful comparison of physiological responses the delta (Δ) values (increase in physiological responses over rest) were calculated by subtracting the resting values of physiological responses from the mean value of physiological responses during pedalling work.

The data on delta values of physiological responses for each trial for 12 subjects were averaged to get the mean values of physiological responses at different pedalling rates and power outputs during pedalling work. These data were subjected to detailed statistical analysis by using statistical software (INDOSTAT) to know the effect of power output and pedalling rate on physiological and psychophysical responses.

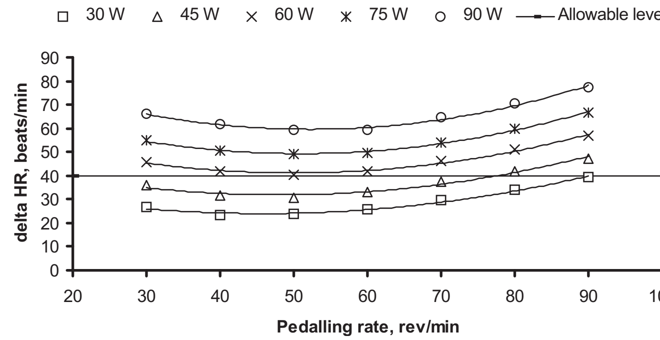

Fig. 2. Variation in ΔHR with pedalling rate at different power outputs.

3. Results

3.1. Physiological characteristics of the subjects

The mean age predicted maximum heart rate (HR_{max}) and maximum oxygen consumption rate (VO_{2max}) of the subjects estimated by the technique proposed by Maritz et al. (1961) were 192 ± 7.5 beats min^{-1} and 2.32 ± 0.26 l min^{-1}, respectively. Nag (1981) determined that maximum heart rate (HR_{max}) and oxygen consumption rate (VO_{2max}) of Indian agricultural workers in the age group of 20–29 years were 188 beats min^{-1} and 2.35 l min^{-1} for 50 kg body weight. The mean age and weight of subjects (agricultural workers) participated in the present study were 27.6 years and 58 ± 8.5 kg, respectively. Thus, the age predicted maximum heart rate value *i.e.* 192 beats min^{-1} and estimated value of maximum oxygen consumption rate (2.32 l min^{-1}) using sub-maximal tests in the present study are in close agreement with the values reported by Nag (1981).

The general equation for predicting the oxygen consumption rate of agricultural workers on the basis of heart rate responses of 12 subjects at sub-maximal workloads was observed as:

$$y = 0.00004x^2 + 0.0054x - 0.2021 \quad (1)$$

Where,
y = Oxygen consumption rate, l min^{-1} and
x = Heart rate, beats min^{-1}

3.2. Cardiac responses at various power outputs and pedalling rates

Variation in mean values of ΔHR with pedalling rate at different power outputs has been presented in Fig. 2, which shows that at a given power output the ΔHR during pedalling on bicycle ergometer decreased with increase in pedalling rate from 30 to 50 rev min^{-1} and then increased in a curvilinear fashion with increase in pedalling rate from 50 to 90 rev min^{-1}. Further, at a given pedalling rate the ΔHR has been always higher at higher power outputs.

From Fig. 2 it is also evident that for each level of power output there was an optimum pedalling rate for which the value of ΔHR was lowest and this optimum pedalling rate increased with increase in power output. The regression lines shown in Fig. 2 have been determined by the least squares method, and fit a general parabolic function of the form:

$$Y = ax^2 + bx + c \quad (2)$$

Where,
Y = heart rate, beats min^{-1},
x = pedalling rate, rev min^{-1}, and
a, b and c are constants.

Table 1
Regression coefficients and coefficient of determination of pedalling rate on ΔHR.

Power output, W	a	b	c	R^2	Optimal pedalling rate, rpm
30	81.17×10^{-4}	-74.3333×10^{-2}	41.012698	0.9848	46
45	92.76×10^{-4}	-89.1369×10^{-2}	53.298016	0.9779	48
60	102.61×10^{-4}	-102.8899×10^{-2}	66.960516	0.9887	50
75	116.85×10^{-4}	-119.1488×10^{-2}	79.698810	0.9927	51
90	129.43×10^{-4}	-135.1128×10^{-2}	94.8535	0.9887	52

The regression coefficients and coefficients of determination (R^2) at different power outputs have been computed by the least squares method for the curves showing the variation in ΔHR with pedalling rate and are given in Table 1. The computed R^2 values for the five regression lines ranged from a minimum of 0.98 at 45 W power output to a maximum of 0.99 at 75 W power output. The optimum pedalling rates for each power output (defined as that pedalling rate, which required the least ΔHR to maintain a given power output) has been calculated by setting the first derivative of each regression equation of pedalling rate on ΔHR to zero, and solving for the most efficient pedalling rate. The results indicated that the optimum pedalling rate increased from a minimum of 46 rev min^{-1} at 30 W to a maximum of 52 rev min^{-1} at 90 W (Table 1).

Considering the acceptable limit of 110 beats min^{-1} of heart rate for continuous work as proposed by Saha et al. (1979) and taking the value of resting heart rate as 70 beats min^{-1}, the acceptable limit of ΔHR for continuous work comes to 40 beats min^{-1}. A horizontal line corresponding to this allowable limit of ΔHR (40 beats min^{-1}) for continuous work has been superimposed on Fig. 2. It indicates that ΔHR at 30 W power output was well within the acceptable limit for continuous work even at the highest tested pedalling rate of 90 rev min^{-1}. At 45 W power output the ΔHR was within the acceptable limits as long as pedalling rate was below 80 rev min^{-1}. However, at the pedalling rate of 90 rev min^{-1} the value of ΔHR exceeded the allowable limit of 40 beats min^{-1} for continuous work.

At 60 W power output the pedalling rate at which the value of ΔHR (40 beats min^{-1}) was very close to the acceptable limit was about 50 rev min^{-1}. At pedalling rates lower or higher than 50 rev min^{-1}, the ΔHR value at 60 W power output was beyond the acceptable limit. At power output of 75 W and 90 W the ΔHR values were always higher than the acceptable limit.

Table 2 presents the ANOVA for the mean values of ΔHR at different power outputs and pedalling rates. It indicates that ΔHR was significantly affected ($p < 0.01$) by power output as well as pedalling rate. Effect of the interaction between power output and pedalling rate on ΔHR was also significant ($p < 0.01$). The values of ΔHR for different power outputs at 50 rev min^{-1} pedalling rate (24, 31, 40, 49 and 59 beats min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) were significantly lower ($p < 0.05$) than those at other speeds. On the other hand ΔHR at 40 rev min^{-1} (23, 32, 42, 50 and 62 beats min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) and 60 rev min^{-1} (26, 33, 42, 50 and 60 beats min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) were at par ($p < 0.05$) with each other and were significantly lower ($p < 0.05$) than those at 30 rev min^{-1} (27, 36, 46, 55 and 66 beats min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively), 70 rev min^{-1} (30, 37, 46, 54, and 65 beats min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively), 80 rev min^{-1} (34, 42, 51, 60 and 71 beats min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) and 90 rev min^{-1} (39, 47, 57, 67 and 77 beats min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively). Further, the values of ΔHR at 30 and 70 rev min^{-1} pedalling rates at different power outputs were at par with each other and were significantly lower ($p < 0.05$) than those at 80 and 90 rev min^{-1} pedalling rates.

Table 2
ANOVA for the effect of power output and pedalling rate on ΔHR.

Source of Variations	df	Sum of Squares	Mean Squares	F-ratio
Replications	11	41 849.70	3804.52	27.39[a]
Power outputs	4	70 296.58	17 574.14	126.53[a]
Error (A)	44	6111.47	138.90	
Pedalling rates	6	13 317.27	2219.55	505.66[a]
Power output × Pedalling rate	24	198.34	8.26	1.88[a]
Error (B)	330	1448.51	4.39	
Total	419	133 221.88	317.95	

CD for power output at $p < 0.05 = 3.67$ beats min^{-1}.
CD for pedalling rate at $p < 0.05 = 0.75$ beats min^{-1}.
[a] Significant at 1% level of significance.

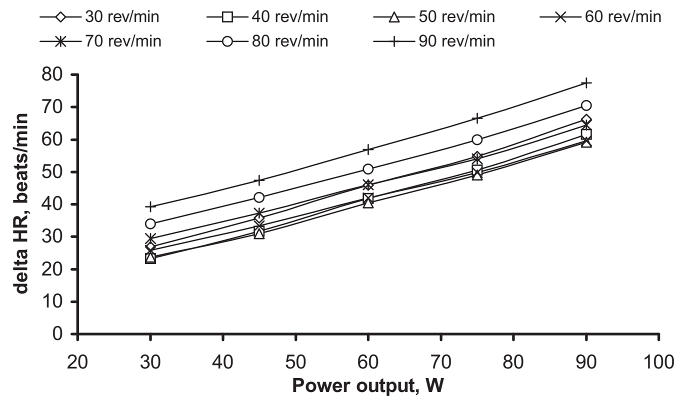

Fig. 3. Variation in ΔHR with power output at different pedalling rates.

Variation in mean values of ΔHR for 12 subjects with power output at different levels of pedalling rate is presented in Fig. 3, which shows that at a given pedalling rate the ΔHR increased linearly with power output. At higher pedalling rates from 70 to 90 rev min^{-1} the ΔHR was always higher than those at other pedalling rates at a given power output. The value of ΔHR at different power outputs at pedalling rate of 30 rev min^{-1} was higher than those at 40 to 60 rev min^{-1}.

3.3. Respiratory responses at various power outputs and pedalling rates

Variation in mean values of ΔOCR with pedalling rate at different levels of power output is presented in Fig. 4, which indicates that at a given power output the ΔOCR decreased with increase in the pedalling rate from 30 to 50 rev min^{-1} and then increased in a curvilinear fashion with increase in pedalling rate. At a given pedalling rate the value of ΔOCR was always higher at higher power outputs. Seabury et al. (1977) observed similar trend in variation of oxygen consumption (energy expenditure) with pedalling rate at different power outputs as those in the present study.

From Fig. 4 it is also evident that there was an optimum pedalling rate for which the value of ΔOCR was lowest and this optimum pedalling rate increased with increase in power output. The regression coefficients and coefficients of determination were computed by using the method described for ΔHR and are given in Table 3. The computed R^2 values for the five regression lines were 0.99. The optimum pedalling rates for each power output (based on least ΔOCR) have been calculated by method described for cardiac responses. The results (Table 3) indicate that the optimum pedalling rate increased from a minimum of 46 rev min^{-1} at 30 W to a maximum of 52 rev min^{-1} at 90 W. These findings are in close agreement with those of Wilson (1986) and Chen et al. (1999).

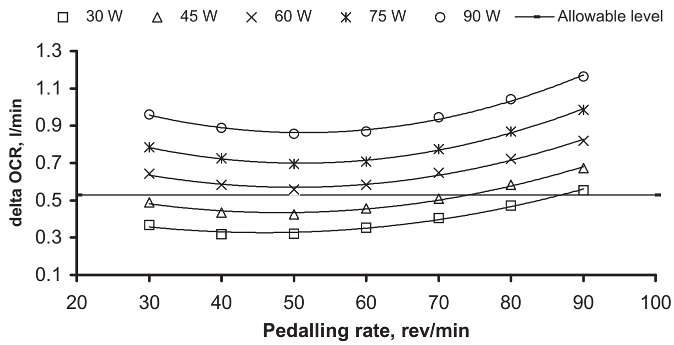

Fig. 4. Variation in ΔOCR with pedalling rate at different power outputs.

Saha et al. (1979) have suggested an acceptable workload for continuous work for Indian agricultural workers as 35% of VO_{2max}, which gives an acceptable limit of oxygen consumption rate as 0.81 l min^{-1} for the subjects participated in the present study. Taking the value of oxygen consumption rate during rest as 0.28 l min^{-1} (mean value of resting OCR of subjects participated in the present study), the acceptable limit of ΔOCR for continuous work comes to 0.53 l min^{-1}. A horizontal line corresponding to this allowable limit of 0.53 l min^{-1} of ΔOCR for continuous work has been superimposed on Fig. 4. It indicates that ΔOCR at 30 W power output was within the acceptable limit even at the highest tested pedalling rate of 90 rev min^{-1}. At 45 W power output the ΔOCR was within the acceptable limits as long as pedalling rate was below 70 rev min^{-1}. However, the pedalling rates higher than 70 rev min^{-1} required higher ΔOCR than the acceptable limit of 0.53 l min^{-1}. At 60, 75 and 90 W power outputs the values of ΔOCR at different pedalling rates were always higher than the acceptable limit of 0.53 l min^{-1}. However, the ΔOCR at pedalling rate of 50 rev min^{-1} at 60 W (0.56 l min^{-1}) was very close to the calculated acceptable limit of 0.53 l min^{-1} of oxygen consumption rate.

ANOVA (Table 4) for the data on ΔOCR of subjects during pedalling on bicycle ergometer at different power outputs and pedalling rates indicates that ΔOCR was significantly affected ($p < 0.01$) by power outputs as well as pedalling rates. Effect of the interaction between power output and pedalling rate on ΔOCR was also significant ($p < 0.05$). The values of ΔOCR at 50 rev min^{-1} (0.32, 0.43, 0.56, 0.69 and 0.86 l min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) were significantly lower ($p < 0.05$) than those at other pedalling rates. On the other hand ΔOCR at 40 rev min^{-1} (0.32, 0.44, 0.58, 0.72 and 0.86 l min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) and 60 rev min^{-1} (0.35, 0.46, 0.58, 0.71 and 0.87 l min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) were at par with each other and were significantly lower ($p < 0.05$) than those at 30, 70, 80 and 90 rev min^{-1} pedalling rates. The values of ΔOCR at 30 rev min^{-1} (0.37, 0.49, 0.64, 0.78, and 0.96 l min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) and 70 rev min^{-1} (0.40, 0.51, 0.65, 0.78 and 0.95 l min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) were at par with each other and were significantly lower ($p < 0.05$) than those at 80 rev min^{-1} (0.47, 0.58, 0.72, 0.87 and 1.04 l min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively) and 90 rev min^{-1} (0.55, 0.67, 0.82, 0.99 and 1.16 l min^{-1} at 30, 45, 60, 75 and 90 W power output, respectively).

Table 3
Regression coefficients and coefficient of determination of pedalling rate on ΔOCR.

Power output, W	a	b	c	R^2	Optimal pedalling rate, rpm
30	1.20×10^{-4}	-1.1064×10^{-2}	0.580782	0.9895	46
45	1.41×10^{-4}	-1.3646×10^{-2}	0.763997	0.9912	48
60	1.62×10^{-4}	-1.6199×10^{-2}	0.975975	0.9905	50
75	1.91×10^{-4}	-1.9458×10^{-2}	1.194677	0.9964	51
90	2.07×10^{-4}	-2.1301×10^{-2}	1.409797	0.9943	52

Table 4
ANOVA for the effect of power output and pedalling rate on ΔOCR.

Source of Variations	df	Sum of Squares	Mean Squares	F-ratio
Replications	11	11.5975	1.0543	30.79[a]
Power outputs	4	16.7009	4.1752	121.93[a]
Error (A)	44	1.5067	0.0342	
Pedalling rates	6	3.3181	0.5530	392.90[a]
Power output × Pedalling rate	24	0.0582	0.0024	1.72[b]
Error (B)	330	0.4645	0.0014	
Total	419	33.6459	0.0803	

CD for power output at $p < 0.05 = 0.058$ l min^{-1}.
CD for pedalling rate at $p < 0.05 = 0.013$ l min^{-1}.
[a] Significant at 1% level of significance.
[b] Significant at 5% level of significance.

Variation in ΔOCR with power output at different levels of pedalling rate is presented in Fig. 5. It shows that at a given pedalling rate the ΔOCR of agricultural workers during pedalling on bicycle ergometer increased linearly with power output. In a review on the effect of pedalling rate and work rate on energy expenditure and efficiency, Ettema and Lorås (2009) concluded that a linear relationship between work rate (power output) and energy expenditure (oxygen consumption) exists, irrespective of subject performance level. Similar to ΔHR, the ΔOCR at a given power output was higher at higher pedalling rates of 70–90 rev min^{-1}. The value of ΔOCR at different power outputs at 30 rev min^{-1} pedalling rate was higher than those at 40 to 60 rev min^{-1}.

4. Discussion

A number of investigators (Benedict and Cathcart, 1913; Dickinson, 1929; Garry and Wishart, 1931; Åstrand, 1953; Banister and Jackson, 1967; Pugh, 1974; Gaesser and Brooks, 1975; Seabury et al., 1977) have concluded that the optimal or 'most efficient', pedalling rate is approximately 50 rev min^{-1} throughout the moderate to high-power output range. Seabury et al. (1977) concluded from several experiments that a most economical pedalling rate existed for each power output and this most economical pedalling rate increased with increased power output. Together with the results from Banister and Jackson (1967), they reported in a heterogeneous group of subjects that at very low external workloads (0–80 W) the most economical pedalling rate was about 40 rev min^{-1}, increasing to about 60 rev min^{-1} at high workloads (200–230 W).

On the basis of above discussions it may be concluded that for each level of power output there existed an 'optimal pedalling rate'

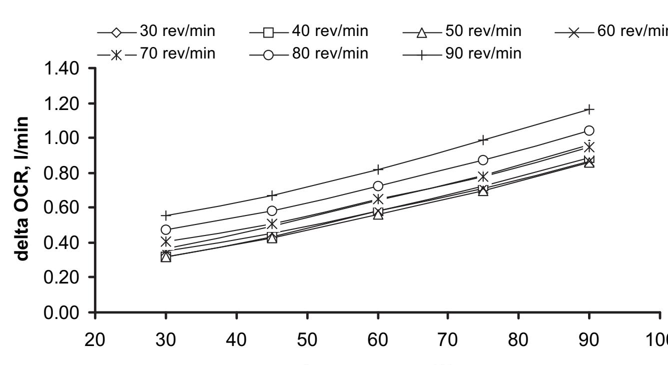

Fig. 5. Variation in ΔOCR with power output at different pedalling rates.

also called the 'most economical pedalling rate' or the 'most efficient pedalling rate' for which the physiological responses were minimum. Further, this optimal pedalling rate increased with increase in power output. These findings are in corroboration with several earlier studies for other occupational groups (Banister and Jackson, 1967; Gaesser and Brooks, 1975; Seabury et al., 1977; Coast and Welch, 1985; Åstrand and Rodahl, 1986; Macintosh et al., 2000; Hansen et al., 2002; Foss and Hallén, 2004).

Banister and Jackson (1967) reported that oxygen consumption rate increased linearly with power output at each pedal rate. They also observed that when the regression lines between oxygen consumption rate and power output at pedalling rates ranging from 40 to 120 rev min^{-1} were superimposed, the lines with pedal rates 40 to 80 rev min^{-1} overlap, whereas the 100 rev min^{-1} line was distinguishably higher and the 120 rev min^{-1} line was even higher. These findings are in close agreement with the results of the present study. Here also the oxygen consumption rate increased with power output at each pedalling rate and lines for 80 and 90 rev min^{-1} were distinguishably higher than those for low pedalling rates, which overlapped each other (Fig. 5).

For many decades, researchers have tried to find the optimal pedalling rate in cycling. The major focus has been on the effect of pedalling rate on efficiency (Gaesser and Brooks, 1975; Hagberg et al., 1981; Faria et al., 1982; Coast and Welch, 1985; Marsh et al., 2000; Hansen et al., 2002; Samozino et al., 2006; Cannon et al., 2007). Patterson and Moreno (1990) stated that the term "optimal pedalling rate" may differ depending on whether it refers to most economical, maximum power producing, less fatiguing or most comfortable pedalling rate. For a competitive cyclist, the optimal pedalling rate is the one that produces the best performance *i.e.* maximum average speed. On the other hand for an occupational activity the optimal pedalling rate is one, which requires minimal physiological workload and that too within the acceptable limits for daylong work and therefore, produces minimal fatigue.

An increase in pedalling rate causes significantly less effective application of forces to the crank arm and therefore, results in increased OCR at a given power output (Patterson et al., 1983; Lorås et al., 2009; Ettema et al., 2009). In the present study the increase in oxygen consumption rate when the pedalling rate at a given power output increased from 50 to 90 rev min^{-1} may be due to decrease in force effectiveness index as explained above. At a given power output, increased muscle contraction velocity at higher pedalling rate may be another reason for increased oxygen consumption rate.

Marsh and Martin (1997) observed that changes in power output had little effect on the most economical pedalling rate, which varied between 53.3 and 59.9 rev min^{-1} for variation in power output from 75 to 150 W. Recently, Hansen et al. (2002) reported that the most economical pedalling rate increased from 50 rev min^{-1} at 147 W to 66 rev min^{-1} at 258 W in a group of subjects with diverse training conditions. During prolong exercise the subjects choose a pedalling rate that is close to the energetically optimal pedalling rate (Brisswalter et al., 2000). A change of muscle fibre recruitment pattern with exercise duration and pedalling rate would explain the shift in energetically optimal rate towards a higher pedal rate observed at the end of exercise.

The physiological cost of moving the legs depends upon their movement in relation to gravitational forces and acceleration. The change in the leg's potential energy when vertically displaced a certain distance in a gravitational field is independent of the speed. The changes with respect to time should therefore, be proportional to contraction frequency. The kinetic energy of the legs, however, increases with velocity squared and the changes in kinetic energy should therefore, increase in a power function related to contraction frequency. Hence the total power from the legs at a constant external power increases in a curvilinear fashion with pedalling rate. Despite disagreement on exactly how to calculate internal work, there is no contradiction on this conclusion. Based on this phenomenon, oxygen consumption rate should increase with increasing pedalling rate at all workloads. Because this apparently is not the case, two explanations exist: either the difference in internal work between pedalling rates changes with increasing workload or the muscle efficiency changes differently between pedalling rate with increasing workload. The efficiency of the whole muscle could change in association with the recruitment pattern of motor units with different force-speed relationships. This has been discussed in a theoretical model by Sargeant (1994) and later tested experimentally with the use of electromyography (EMG) by Macintosh et al. (2000). This model assumes that a power–velocity relationship exists at each recruitment level of the skeletal muscles, with the hyperbolic shape being the same during both sub-maximal and maximal activation. This means that, in order to minimally activate the muscle, a unique cadence exists for all sub-maximal workloads. On the other hand Cannon et al. (2011) observed that muscle fatigue is requisite for the onset of VO_2 slow component, which reduces work efficiency during a constant work rate exercise above the lactate threshold. However, progressive muscle recruitment is not obligatory. Rather, a reduction in mechanical efficiency in fatigued fibres is implicated.

From experimental data it is known that maximal power output is achieved at a pedalling rate of about 120 rev min^{-1} during maximal activation of type I and II fibres (Sargeant et al., 1981; Sargeant, 1994). Based on this knowledge, Sargeant (1994) deduced that maximum power output would be attained at approximately 60 rev min^{-1} in type I fibres as the maximum power is attained at 60 rev min^{-1} in these fibres. At 120 rev min^{-1} as type I and type II fibres are combined, there may be a gradual increase in pedalling rate as workload increases, to sustain at the top of the power–velocity curve of each workload.

The shift to a higher pedalling rate for optimal velocity is dictated by the need to recruit additional fast-twitch motor units as workload increases. To sustain a certain power output would therefore require activation of a greater proportion of the muscles, with increased oxygen cost as the probable outcome. In support of this model, Ahlquist et al. (1992) found glycogen depletion to be greater in type II fibres at 50 rev min^{-1}, compared to 100 rev min^{-1} at high workloads. This indicates a greater activation of the muscle at 50 rev min^{-1} as opposed to 100 rev min^{-1}, illustrating the possible benefits of choosing a high pedalling rate at high workloads. Despite some disagreements in the literature and the simplifications carried out in the model, it reflects the finding that the most economical pedalling rate increases with increasing workload.

Since the findings of the present study are based on the experiments conducted on a bicycle ergometer under controlled laboratory conditions, the physiological responses may differ from those reported under actual field conditions. The physiological responses may also be different for female agricultural workers. However, the study gives a guideline for the design of any pedalling device to be operated by male agricultural workers throughout the whole working day. For such a device the power requirement should be limited to 60 W and the pedalling rate should be 50 rev min^{-1}. The findings of the study along with the findings of another study conducted for optimisation of saddle height and crank length have been utilised for the design of a dynapod. The designed dynapod can be used as an interface between human worker and any rotary type machine for efficient power utilisation from human muscles. The dynapod had been tried with a rotary maize sheller with 59% increase in its shelling capacity and 67% reduction in ΔHR in comparison to hand cranking mode. Evaluation of dynapod with other rotary type machines such as grain mill, cleaner grader *etc.* is in process.

5. Conclusions

Based on the study it was concluded that at a given power output the physiological responses during pedalling on bicycle ergometer, initially decreased with increase in the pedalling rate from 30 to 50 rev min^{-1} and later increased in a curvilinear fashion with increase in pedalling rate from 50 to 90 rev min^{-1}. On the other hand the physiological responses increased linearly with increase in power output. At each level of power output there existed an 'optimal pedalling rate' for which the physiological response were minimum. Further, this optimal pedalling rate increased with increase in power output. The optimum pedalling rate increased from a minimum of about 45 rev min^{-1} at 30 W to a maximum of 52 rev min^{-1} at 90 W. On the basis of physiological studies conducted at various power outputs and pedalling rates it was concluded that for Indian agricultural workers the muscular power output in pedalling mode, which could be sustained for long duration pedalling work is 60 W. At this power output the optimum pedalling rate is 50 rev min^{-1}.

Acknowledgements

The authors are grateful to Dr. S. D. Kulkarni, Project Director, APPD and Dr. Pitam Chandra, Director, Central Institute of Agricultural Engineering, Bhopal, for their help and encouragement during the study. Assistance received from Mr. R. J. Raina, AICRP on ESA is duly acknowledged. Thanks are also due to the subjects for their wholehearted cooperation during the experiments.

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