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Development of a dynapod for female agricultural workers on the basis of ergonomic studies

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■ **ABSTRACT :** Dynapod is a portable pedal operated power device that consists of a stand, saddle, handlebar, chain and sprockets, cranks and pedals. A person can generate four times more power by pedaling than by hand cranking. However, continuous pedaling at this rate could be done for only short periods (about 10 min). Pedaling at about half this power (90 W) could be sustained for around 60 min. Most people engaged in delivering power continuously for an hour or more would be most efficient when pedaling in the range of 50 to 70 rpm. In respect to the objective of the study, the design parameters for dynapod and the development of dynapod, a postural dynamometer for foot operated rotary power generation was designed and developed. Experiment was conducted for optimization of flywheel, pedaling rate, power output, saddle height and crank. Heart rate, oxygen consumption rate (OCR), blood pressure (BP), pulse oxygen saturation extent, rate of perceived exertion (RPE) were taken as dependent variables. The flywheel of diameter 550 mm was found to be suitable for dynapod. The optimum pedaling rate increased from minimum of about 45 rpm at 30 W to a maximum of 52 rpm at 90 W. The rate of perceived exertion (RPE) increased with increase in pedalling rate at given power output. Crank length of 180 mm and saddle height of 0.96 trochanteric height gave the minimum physiological responses. The dynapod can be successfully used as an interface between the human worker and a hand operated stationary farm equipment in pedalling mode for getting more output from the machine with less effort and fatigue.

■ **KEY WORDS :** Anthropometry, Ergonomics, Pedaling, Dynapod, Fatigue, Oxygen consumption rate (OCR), Rate of perceived exertion (RPE)

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Dynapod is a portable pedal operated power device that consists of a stand, saddle, handlebar, chain and sprockets, cranks and pedals and a flywheel is also used to get uniform speed of operation. The word dynapod has been derived from two Greek words, 'dyna' means power and 'pod' means leg. Wilson (1986) reported that a person could generate four times more power (185 W) by pedaling than by hand cranking. However, continuous pedaling at this rate could be done for only short periods (about 10 min). Pedaling at about half this power (90 W) could be sustained for around 60 min. Most people engaged in delivering power continuously for an hour or more would be most efficient when pedaling in the range of 50 to 70 rpm. Sharma and

Singh (1970) identified nine operations in which women actively participate; those were seed storage, winnowing, care of animals, harvesting, weeding, soak pit, sowing, transplanting, and applying manure in the field using implements, respectively. They further found that women participate in large proportions in four farm operations, *viz.*, seed storage (75%), winnowing (75%), care of animals (74%) and harvesting (71%) in comparison to others. It was examined and found that the oxygen consumption and heart rate kinetics during arm cranking and leg cycling at work rates above the anaerobic threshold. Oxygen consumption and heart rate values were significantly ($p< 0.001$) lower in arm cranking than in leg cycling (Schneider *et al.*, 2002). Singh *et al.* (2008) studied in detail about the aerobic capacity of women and following regression equations were obtained and suggested for estimating oxygen consumption (y) at their known heart rate (x) during agricultural operations, $y = 0.0119\,x - 0.7665$ (for 25 to 35 years of age), $y = 0.0106\,x - 0.5501$ (for 36 to 45 years of age), $y = 0.0114\,x - 0.68$ (General equation). The gross efficiency, heart rate and perceived exertion were minimum at 60 to 80 rpm. (Coast *et al.*, 1986). To use pedal power for occupational work such as stationary farm operations considering all the physiological responses that define about the status and condition of the worker's body involved in agricultural operations, and keeping in mind the large participation of women in agricultural operations but less study on it, this study was planned which particularly concentrates on the female agricultural workers of Jabalpur region with following objectives :

– To optimize the design parameters for dynapod.

– To develop the dynapod on the basis of anthropometric data and physiological responses of the female agricultural workers.

■ METHODOLOGY

A postural dynamometer for rotary power generation was designed and developed with a provision of foot operated flywheel by pedaling. It was made out of cycle's rim, pedal, chain and frame to involve minimal cost as shown in Fig. A. Rim was used as flywheel. Another arrangement with spring balance, threaded bolt and rope was also made for loading the flywheel as an aid to calculate power requirement. Whole arrangement was made so that at a particular load, number of revolutions of the flywheel was noted while the pedaling was done, to calculate the power requirement by following formula

$$P = \frac{2\pi NT}{4500} \qquad (1)$$

here, P = Power, hp

N = Number of revolutions, rpm

T =Torque = Load x Distance between flywheel centre and centre of spring balance.

Experiment was conducted for optimization of flywheel by selecting four different diameters and eighteen load levels with pedaling rate, linear speed and power as the dependent variables. In order to determine the optimum power output for long duration pedaling work and optimum pedaling rate corresponding to that power output, one experiment for the measurement of physiological responses at different power outputs and pedaling rates was conducted on the conceptually designed postural dynamometer. There were 315 trials for the entire experiment with nine subjects, asymmetrical factorial CRD experimental design was used with pedaling rates (seven levels) and power outputs (five levels) as independent variables and heart rate, oxygen consumption rate (OCR), blood pressure (BP), pulse oxygen saturation extent, rate of perceived exertion (RPE) as dependent variables. In order to optimize the saddle height and crank length for dynapod another experiment was conducted with 42 trials and seven subjects, asymmetrical factorial CRD was used with saddle height (three levels) and crank lengths (two levels) as independent variables and heart rate, oxygen consumption rate (OCR), blood pressure (BP), pulse oxygen saturation extent, rate of perceived exertion (RPE) as dependent variables. Heart rate was measured using stethoscope. Pulse oxygen saturation extent and blood pressure was measured with the pulse oximeter and sphygmomanometer, respectively. Maximum heart rate (HR_{max}) was determined using the equation "$HR_{max} = 220 - age$, wherein age of subjects were known (Shephard, 1980). The aerobic capacity of the subject was determined using the equation $VO_2 = 0.01667\,HR - 0.8$. Following regression equation was used for estimating oxygen consumption (y) at their known heart rate (x) during agricultural operations. (Singh *et al.*, 2008) $y = 0.0114\,x - 0.68$. RPE scale that runs from 0 – 10 was used to measure the intensity of exertion to body while pedaling. The body part discomfort score (BPDS) was then assessed using the Corlett and Bishop (1976) technique.

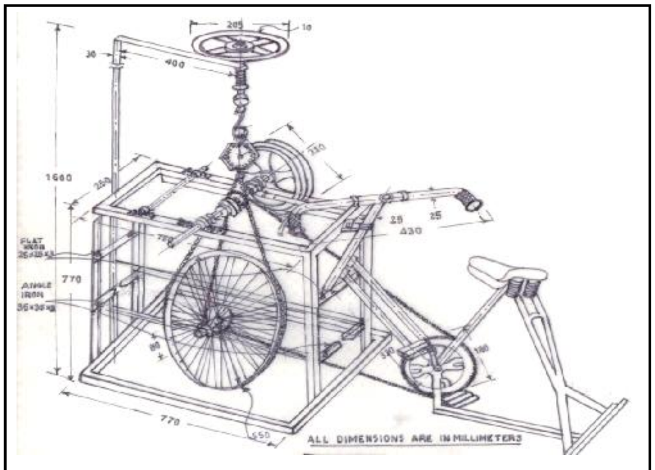

Fig. A : Postural dynamometer

RESULTS AND DISCUSSION

In the first experiment for wheel diameter optimization, flywheel of diameter 550mm could be pedaled with regular trend upto maximum load level as apparent from the graph in Fig. 1. As shown in graph (Fig. 2), at any given load, the power output increased with decreasing diameters of the flywheel. The line in graph for flywheel of diameter 510 mm, showed almost a constant trend from load of 1.4 kgf to load of 2.4 kgf at power level ranging between 50 – 60 W, thus it was selected for the dynapod. As the size of flywheel increased, the capacity to pedal decreased at any given load. Table 1 shows the mean value of changes in heart rate, oxygen consumption ratio, blood pressure and SpO2 percentage during pedalling at different power outputs and pedalling rates. To show case the effect on body's physiology and fatigue level. In case of with the flywheel of maximum diameter, the capacity to pedal got limited at a load of 1.8 kgf as apparent from the readings in Table 1. The ANOVA (Table 2 to 5) results showed that HR, ΔHR, OCR and ΔOCR were significantly affected by power outputs as well as pedalling rates but blood pressure and SpO2 was not significantly affected but the readings showed recovery of blood pressure rise after experiment.

ANOVA results (Table 6) on body part discomfort score (BPDS) showed that it was significantly affected by the power output and pedalling rates showcasing the effect on psychological health of the subject.

The optimum pedalling rate for each power output (defined as that pedalling rate, which required the least heart rate to maintain a given power output) was calculated by setting the first derivative of each regression equation of pedalling rate on heart rate to zero, and solving for the most efficient pedalling rate. The results indicated that the optimum pedalling rate increased from a minimum of 46.9 rpm at 30 W to a maximum of 51.4 rpm at 90 W. Likewise was done for OCR, blood pressure and RPE and result was almost in the above range.

In second experiment of cranklength and saddle height optimisation, effect on physiological responses HR, ΔHR, OCR, ΔOCR, blood pressure, SpO2 and RPE are shown in Table 7. As the crank length increased from 180 to 200m, all of the above variables increased. And at one crank length, with increase in saddle height, physiological responses increased and then decreased.

Stattistical analysis (ANOVA) showed that both saddle height and crank length affected the ΔHR significantly ($p < 0.01$) while effect of interaction of saddle height and crank length on ΔHR was found to be

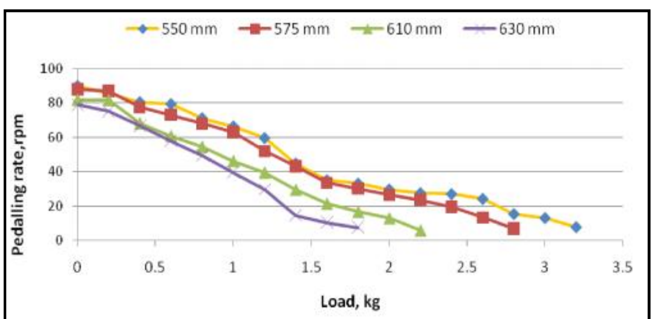

Fig. 1 : Variation in pedalling rate with load for different diameters of flywheels

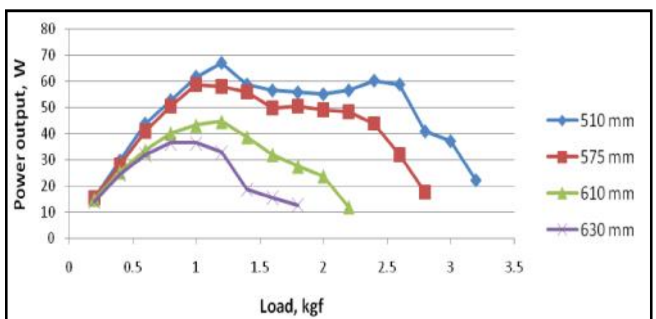

Fig. 2 : Variation in power output with load for different diameters of flywheels

Table 1 : Mean values (n=9) of physiological responses during pedalling at different power outputs and pedalling rates

Power output, W	Pedalling rate, rpm	Heart rate, beats min^{-1}	ΔHR beats min^{-1}	OCR, l/min	ΔOCR, l/min	Blood pressure, mm of hg	SpO_2, per cent	Rate of perceived exertion
	30	95.00	24.3	0.41	0.279	122/72	97	1.5
	40	94.25	23.0	0.39	0.265	117/72	97	1.5
30	50	92.60	23.5	0.37	0.245	114/72	98	1.0
	60	95.60	24.0	0.40	0.277	119/72	99	1.0
	70	98.90	27.4	0.43	0.31	124/72	98	1.5
	80	102.5	31.1	0.48	0.35	127/71	97	3.0
	90	106.80	35.3	0.52	0.40	129/71	96	3.0
	30	104.1	33.5	0.50	0.38	126/72	96	2.0
	40	102.4	31.5	0.48	0.35	123/72	96	2.0
	50	101.5	28.6	0.47	0.32	120/72	97	1.5
45	60	103.6	31.6	0.49	0.36	125/72	98	1.5
	70	106.5	35.0	0.52	0.39	128/71	97	2.0
	80	110.6	38.0	0.55	0.43	132/71	96	3.0
	90	114.6	41.0	0.59	0.46	135/70	95	3.0
	30	112.3	41.6	0.60	0.47	130/71	96	2.0
	40	110.6	39.6	0.57	0.45	128/71	96	2.0
	50	108.9	37.6	0.55	0.42	125/71	97	1.5
60	60	111.2	40.6	0.58	0.46	129/71	97	2.0
	70	115.1	44.6	0.63	0.50	133/70	96	2.5
	80	118.0	48	0.67	0.55	135/70	95	3.0
	90	122.9	52.1	0.72	0.59	139/69	94	3.5
	30	121.3	50.5	0.70	0.57	139/71	95	2.5
	40	119.6	48.5	0.67	0.55	134/71	94	2.5
	50	117.4	46.4	0.65	0.52	132/71	95	3.0
75	60	120.7	49.5	0.68	0.56	135/71	96	3.0
	70	124.9	53.4	0.73	0.61	141/69	94	3.5
	80	128.5	57.2	0.78	0.65	143/68	93	4.5
	90	134.6	63.0	0.84	0.72	147/68	92	5.0
	30	133.9	66.5	0.83	0.71	142/69	94	2.5
	40	131.0	61.4	0.81	0.68	140/69	93	2.5
	50	128.6	58.3	0.78	0.65	137/69	94	3.0
90	60	130.8	59.3	0.80	0.67	141/69	95	4.0
	70	134.6	64.3	0.84	0.72	146/66	93	4.5
	80	139.5	70.3	0.90	0.78	151/65	92	5.0
	90	145.9	75.3	0.97	0.84	147/64	91	5.5

Table 2 : ANOVA for the effect of power output and pedalling rate on heart rate (HR)

Sources of variation	df	Sum of squares	Mean squares	F-ratio
Power outputs	4	54008.84	13502.21	61.46**
Pedalling rates	6	7328.88	1221.48	5.56**
Power output x pedalling rate	24	174.36	7.265	0.03^{NS}
Error	280	61514.75	219.69	
Total	314	123026.83	391.80	

** indicates significance of value at P=0.01 NS=Non-significant insignificant (Table 8 and 9).

Similar to heart rate the OCR and ΔOCR increased from 180 to 200 mm. On the other hand, at a given crank length the OCR and ΔOCR decreased with increase in saddle height from 0.92 to 0.96 trochanteric height and then increased with increase in saddle height from 0.96 to 1.00 trochanteric height.

On the basis of above readings and statistical

Table 3 : ANOVA for the effect of power output and pedalling rate on aHR

Sources of variation	df	Sum of squares	Mean squares	F-ratio
Power outputs	4	55460.92	13865.23	54.46**
Pedalling rates	6	7308.74	1218.12	4.78**
Power output x pedalling rate	24	153.93	6.41	0.03^{NS}
Error	280	71276.59	254.55	
Total	314	134200.18	427.38	

** indicates significance of value at P=0.01 NS=Non-significant

Table 4 : ANOVA for the effect of power output and pedalling rate on OCR

Sources of variation	df	Sum of squares	Mean squares	F-ratio
Power outputs	4	7.0119	1.7529	60.92**
Pedalling rates	6	1.622	0.2703	9.39**
Power output x pedalling rate	24	0.0481	0.002	0.069^{NS}
Error	280	8.056		
Total	314	134200.18	0.0287	

** indicates significance of value at P=0.01 NS=Non-significant

Table 5 : ANOVA for the effect of power output and pedalling rate on aOCR

Sources of variation	df	Sum of squares	Mean squares	F-ratio
Power outputs	4	7.027	1.75	59.41**
Pedalling rates	6	0.962	0.16	5.42**
Power output x pedalling rate	24	0.032	0.0013	0.045^{NS}
Error	280	8.28	0.0295	
Total	314	15.432	0.049	

** indicates significance of value at P=0.01 NS=Non-significant

Table 6 : ANOVA for the effect of power output and pedalling rate on BPDS

Sources of variation	df	Sum of squares	Mean squares	F-ratio
Power outputs	4	26612.59	6653	7.19**
Pedalling rates	6	3507.80	584.63	9.87**
Power output x pedalling rate	24	1429.37	59.56	1.01^{NS}
Error	280	19554.23	69.83	
Total	314	33503.99	106.70	

** indicates significance of value at P=0.01 NS=Non-significant

Table 7 : Mean values (n=7) of physiological responses during pedalling at different saddle heights and crank lengths

Saddle height, fraction of Trochanteric height	Crank length, mm	HR, beats min^{-1}	ΔHR, beats min^{-1}	OCR. l/min	ΔOCR, l/min	BP, mm of Hg	SpO_2 (%)	RPE
0.92 TH	180	111.42	40.92	0.59	0.46	129/71	96	2.0
	200	113.2	42.62	0.61	0.48	130/70	95	2.5
0.96 TH	180	109.0	38.42	0.56	0.43	125/71	96	1.5
	200	111.3	41.00	0.58	0.46	129/71	96	2.0
1.00 TH	180	110.0	39.42	0.57	0.44	128/71	96	1.5
	200	115.0	44.42	0.63	0.51	133/70	95	2.5

analysis (ANOVA), it was concluded that crank length of 180 mm which was very close to the standard crank length (178.5 mm) on adult bicycle gave minimum physiological responses. On basis of the results of the physiological and psychophysical studies, the optimal pedaling rate at 60 W power output was found to be 50 – 60 rpm. The flywheel of diameter 550 mm was found to be suitable and used for dynapod. The 5th and 95th percentile trochanteric heights (TH) of female agricultural workers of Jabalpur region were 650 and 792 mm and optimized saddle height was 0.96 of TH, thus the saddle heights was made adjustable varying from 620 – 785 mm. The seat-tube angle for the design of the dynapod was taken as 80^0 from the horizontal on the basis of the recommendations of Price and Donne (1997). The longitudinal support bar that is found in bicycle was removed and an inclined bar was provided to comfort the female workers. The height of pedal from the ground surface when the pedal is at its lowest position should be such that the toes should not strike the ground even when the foot is in fully flexed position. The 95th percentile foot length for female agricultural workers of Jabalpur region was 200 mm, therefore the clearance was taken as 100 mm.

The number of teeth on big sprocket was taken as 60 on the basis of sprockets being used on bicycles and being easily available in the market. The chain pitch was taken as 12.7 mm. the pitch circle diameter of big sprocket was thus calculated using equation :

Using the equation, $$D_P = \frac{P}{\sin\left(\frac{180}{n}\right)} \quad (2)$$

Dp = 12.7/[sin (180/60)] = 242.66 mm

And found to be 242.66mm.Same equation 4.3 was used to calculate pitch circle diameter of small sprocket and sprocket on output shaft. They were 73.1mm and 194.1 mm, respectively. Thus power transmission system consisted of a series of chain and sprockets where small sprocket was given drive through pedalling, through chain the power was transmitted to big sprocket. Same shaft ob which big sprocket was mounted, an eccentric wheel was mounted. A reciprocation bar connected to eccentric knob of eccentric wheel was connectable to any hand operated agricultural machine like ground decorticator or Sheller as shown in Fig. 3. Thus the fabrication enabled

Fig. 3 : Dynapod attached to groundnut decorticator

Table 8 : ANOVA for the effect of saddle height and crank length on aHR

Sources of variation	df	Sum of squares	Mean squares	F-ratio
Power outputs	2	42.88	21.44	3.38**
Pedalling rates	1	100.29	100.29	15.81**
Power output x pedalling rate	2	20.46	10.23	1.61^{NS}
Error	38	241.04	6.34	
Total	43	404.67	9.41	

** indicates significance of value at P=0.01 NS=Non-significant

Table 9 : ANOVA for the effect of saddle height and crank length on aOCR

Sources of variation	df	Sum of squares	Mean squares	F-ratio
Power outputs	2	0.015535	0.007768	4.19**
Pedalling rates	1	0.021518	0.021518	13.62**
Power output x pedalling rate	2	0.004	0.002	1.26^{NS}
Error	38	0.06	0.001579	
Total	43	0.101053	0.032864	

** indicates significance of value at P=0.01 NS=Non-significant any hand operated machine to be operated by pedalling.

Conclusion :

Pedalling enables cranking at same rate as that by hand but with far less effort and fatigue involved. Instead it increases the rate of doing work. The objective of optimization of parameters (physiological responses and bpds score) for design of dynapod indicated flywheel of diameter 550 mm and pedalling rate from minimum of about 45 rpm at 30 W to a maximum of 52 rpm at 90 W were found to be optimum for dynapod. The rate of perceived exertion (RPE) was found to increase with increase in pedalling rate at given power output. Also with the increase in power level, the rate of perceived exertion of subjects increased. On the basis of the results of the physiological responses at different saddle heights and crank lengths, it was concluded that crank length of 180 mm and saddle height of 0.96 trochanteric heights gave the minimum physiological responses. This pedal operated dynapod can be successfully used in place of hand operated stationary farm equipments for better efficiency and with less fatigue, as a person can generate four times more power by pedaling than by hand cranking

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