Effect of thresher drive linkage design on human physiological workload of a pedal operated thresher

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Abstract: Pedal operated paddy threshers are widely used in the rice growing countries such as India, Bangladesh, Bhutan, Korea and some African countries. Thresher-drive linkage plays a vital role in human-machine interaction and workload on the human operator. The four-bar linkage design used in pedal operated paddy thresher was replaced with four alternative designs of thresher drive-linkages to assess the load application pattern and physiological work load while operating the pedal operated paddy thresher. The machine was tested with five operators for physiological workload estimation. The linkage combinations were found to have significant effects at 1% level on the work pulse rate and workload to operators. Considering the force-displacement relationships and physiological workload on the operators, linkage three was found to be the most promising design with lowest work pulse rate of 45.90 beats min^{-1} and change in energy expenditure rate of 214.5 W (12.87 kJ min^{-1}).

Keywords: pedal operated thresher, thresher, thresher drive linkage, physiological workload

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1 Introduction

India is the second largest rice-producing nation in the world. During the year 2008-09, the rice was grown in 45.54 million hectare area and total rice production was 99.18 million tons. However, at global level it ranks only fifty-fourth in terms of productivity. There is also a need to increase the production to 128 million tons by year 2011-12 (Tewari, 2003) in order to meet the demand of a growing population, which stands over a billion at present. Cultivable land available per family in various districts in the State of Meghalaya is in the range of 0.4 to 2.5 ha. More than 80% of the land holding in Meghalaya is below two ha (Anon, 2002). It is made of small patches on slopes and valleys of hills. Plots are small compared to those in other parts of the country. The small plot size has forced the majority of the farmers to turn to small implements and machinery. In order to improve mechanization in Meghalaya it is required to emphasize on small implements and machinery (Anon, 2001).

Power operated threshers are popular in States such as Haryana, Punjab and Uttar Pradesh which have developed well in agriculture while manually operated hold-on type pedal threshers are popular in traditional rice growing areas of eastern and southern India. Current population of pedal threshers in India is estimated to be one million. This type of threshers is also used in many other developing countries such as Bangladesh, Bhutan, Korea and some African countries.

Pedal operated paddy (POP) threshers are hold-on type (Anon, 1982). It seems to have originated in Japan and is specific to rice crop. Having been adopted in many rice growing regions of the world mainly in Asian countries, its design and construction features have

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undergone many changes at different locations. Figure 1 illustrates one model prevalent in many parts of India. Prakash (1979) designed and developed a manually operated multi-crop thresher. He reported that threshing efficiency has a close correlation with peripheral velocity of the threshing elements and the clearance between the threshing element and concave. He found that a cylinder peripheral speed of 12.5 m s^{-1} gave a threshing efficiency of 87-94%. Saeed et al (1995) evaluated a hold-on type power operated Korean thresher with Basmati-385 rice variety. The thresher gave a maximum grain output of 537 kg h^{-1} with a threshing efficiency of 99.2% at a cylinder speed of 500 r m^{-1} (peripheral speed 17.3 m s^{-1}) and crop feed rate of 1,300 kg h^{-1}.

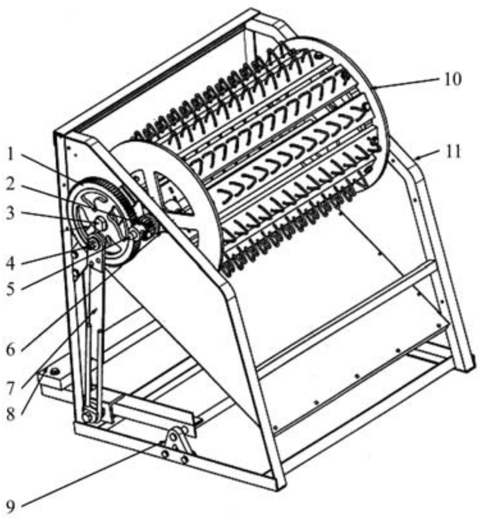

Figure 1 Pedal operated paddy (POP) thresher (Agrawal, 2008)

Body dimensions play an important role in accessing the controls and applying force on the machine members (Kroemer, 1997). The population of Meghalaya differs from the population of eastern and southern parts of India in many anthropological aspects. Therefore, a research work was carried out for design modification of the thresher for use in Meghalaya. In terms of workload classification threshing operation with POP thresher is considered to be a moderately heavy to heavy work involving more than the average physiological load to operator (Satapathy and Mohanty, 2005). Effect of different cylinder drive linkage mechanisms on the pedal force requirement and human physiological workload are reported in this paper. Physiological cost during thresher operation was determined. Various research workers have measured heart rate, oxygen consumption rate, blood pressure and concentration of lactic acid in blood in order to estimate the physiological load of human body. Heart rate and oxygen consumption rate are used as indicators of physiological energy expenditure rate in the present work. After operating the thresher for a long time different body parts feel pain or discomfort. The body part loaded to the maximum feel more pain or more discomfort. Subjective scores such as body part discomfort score (BPD score) and visual analogue discomfort score were also determined.

Torque required to operate the threshing cylinder is derived from the force applied on the pedal through the leg of operator. Pedal is attached on a long lever pivoted on the frame of the thresher (Figure 2). It oscillates during operation. It forms extension of follower link in a planar four bar linkage mechanism. In the mechanism crank, which is a driven link, can make full rotation. Rotation of crank is transferred to the threshing cylinder through a pair of gears, which increases the speed of rotation by a factor varying from 1:3 to 1:5. During operation, an operator lifts and holds a bundle of the crop against the cylinder. He/she operates the pedal by one leg keeping the other leg on the ground in a standing posture (Figure 3). After threshing, the bundle is thrown away and a new bundle is collected. At the end of work, grains spread over the ground are collected by sweeping the floor.

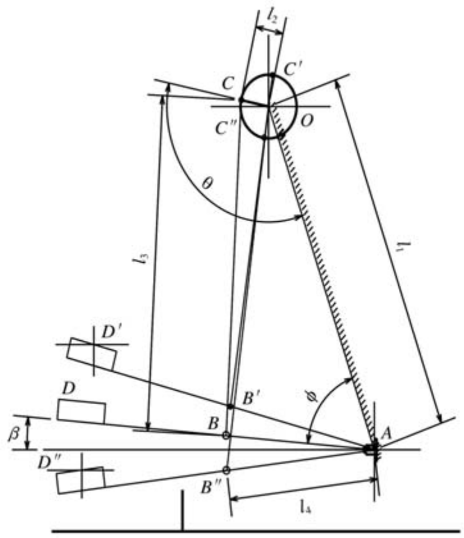

Figure 2 Four bar linkage of the pedal operated paddy thresher (Agrawal, 2008)

a b c

Figure 3 Various steps in pedal operated paddy threshing

2 Methodology

2.1 Modification of thresher-drive linkage

Force and motion characteristics of four bar linkage depend upon the link lengths. Human beings may show preference to some force-displacement characteristics of a pedal. Accordingly, the cylinder drive linkage may be modified and alternative designs may then be compared on the basis of human preference. In order to evolve alternative designs of the linkage few functions relating to the pedal angle and crank angle were assumed. These functions were used for a synthesis procedure based on Freudenstein's Equation. In the synthesis procedure the first step is to generate three points through which linkage system passes and loop remains closed. Freudenstein's Equation (Equation (1)) for a four bar linkage is given as

$$K_3 + K_1 \cos\theta + K_2 \cos\varphi = -\cos(\theta - \varphi) \tag{1}$$

where, K_1, K_2 and K_3 are three independent algebraic expressions in terms of link lengths which are unknown. These three link length expressions can be given as

$$K_1 = \frac{l_1}{l_4} \qquad K_2 = -\frac{l_2}{l_4} \qquad K_3 = \frac{l_3^2 - l_1^2 - l_2^2 - l_4^2}{2l_2 l_4}$$

To solve Equation (1), a relationship between crank angle θ and angle ϕ was assumed and three values of angle ϕ were taken. Solution of Equation (1) gave the values of K_1, K_2 and K_3. Link length l_1 (Figure 4) was assumed and other three link lengths l_2, l_3 and l_4 were obtained through the equations given above. Later the synthesized linkage was tested for its complete range of operation through 360° movement of crank angle θ at angular intervals of 5° and especially at critical change over points. Only those link lengths were selected which were possible to be adopted within the existing frame height of the thresher and for which pedal displacement remained within reasonable leg height range keeping the operator body in a vertical posture on the ground. Operator remained parallel to the thresher frame. The thresher was to be kept within a reasonable distance range from operator's body. The distance should not exceed the fore arm length of 5th percentile female worker while it should not be less than 95th percentile buttock-knee length of 95th percentile male. This was to minimize possibility of causing knee injury in such work activities. Selected linkage designs are given in Table 1. The linkage 5 shown in Table 1 exists already in the threshers.

Table 1 Link lengths and configuration of synthesized linkages

S. N.	Linkage configuration	Link length /cm					ϕ_0
		l_1	l_2	l_3	l_4	Follower /extension BD	
1	I	14.5	4.1	28.0	22.0	22.0+extension 7.5 cm at 150°, l_5=19.7, l_6=19.7	88.5
2	II	44.5	3.3	48.2	17.2	Extension 17.5 cm rotated at 161°	141.8
3	III	44.5	6.0	40.1	21.6	18.7 cm	78.1
4	IV	21.0	4.0	35.0	18.1	23.0 rotated at 138°and 7.5 cm at 87°	171.3
5	V*	44.5	3.9	38.4	18.0	Extension 20 cm	55.6

Note: * Existing mechanism. ** l_1 = OA= length of fixed link, l_2 = OC=crank length, l_3 = CB= length of connecting rod, l_4 = AB= length of follower link, l_5, l_6 = length of additional link, ϕ_0 = angle of pedal with fixed link when crank angle θ = 0°.

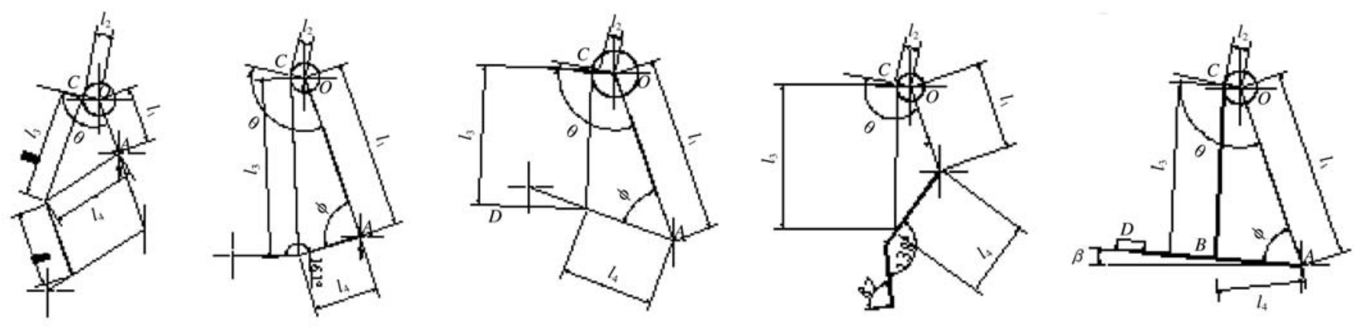

Figure 4 Kinematic link lengths of thresher drive linkage designs

2.1.1 Mounting linkage on the thresher

It can be seen that link lengths vary quite widely. Also the fixed link needs to have different orientations in different designs, pedal is mounted on follower extension. Parallel linkages were added in one design to bring the pedal at a convenient location for human operation. Kinematic link lengths of the five designs are illustrated in Figure 4. The link lengths in these designs vary appreciably. The following arrangements were made and some adjustments were incorporated in the test set-ups in order to mount the linkages:

a) Crank lengths were 4.1, 3.3, 6.0, 4.0 and 3.9 cm for the five different designs. Five gears were made in which crank of suitable length were obtained;

b) In linkage designs 1, the pivot point of the pedal was at a large height (39.5 cm) from the ground since length of fixed link is small. This resulted in the pedal remaining too high. Therefore parallel linkages were added;

c) Pedal pivot point could be located at different locations on the thresher frame;

d) In two linkage designs the pedal beam was bent for convenience;

e) In linkage 4 the follower link was extended and bent.

Frames were made with 30 ×30 ×3 mm MS angle iron. Width of the frame was 340 mm. Angular velocity and acceleration of the pedal in the linkage designs above were calculated for constant crank speeds using mathematical relationships. Displacement, velocity and acceleration values were plotted against crank angle as shown in Figure 5 (a) to (e). It can be seen from the figures that the acceleration values as well as their variations are different in different linkages. This shows that different motion and force characteristics can be expected at the pedal.

2.1.2 Selection of linkages and development of test setups

Energy requirement for operation of thresher had been determined separately (Agrawal, 2008). Power requirement at a peripheral speed of 6.2 m s^{-1} was found to be 35.2 W. At a grain feed rate of 45.1 kg h^{-1}, specific energy requirement for threshing was 0.78 Wh kg^{-1}. In order to test the linkages the cylinder assembly was removed and a torque equivalent to the torque consumed at the cylinder was applied through a friction brake. The friction brake consisted of a flat belt run over a flat brake drum of 10 cm diameter and 5 cm width. The tight end of the belt was fixed rigidly with the frame through a 490 N load cell while a weight was hanged on the slack side. The wrap angle was 160°. In order to apply the required torque a weight was hanged on the slack side. Tension on the tight side was measured using the load cell. Value of dead weight at which the required torque is obtained was estimated. The following relationship Equation (2) was used for calculation of torque applied.

$$T_{av}=(F_1-F_2)r \quad (2)$$

where, T_{av} = Average torque applied; F_1 = Belt tension in tight side; F_2 = Belt tension in slack side; and r = Effective radius of the brake drum.

To simulate the threshing condition where 35.2 W power was consumed the weight required to be used on the slack side of the belt passing over the 100 mm diameter pulley used as brake drum was calculated to be

2.05 kg. In order to provide the necessary moment of inertia, two discs were prepared having a total moment of inertia 0.354 kg m^2. These discs were mounted on the extension of the cylinder shaft.

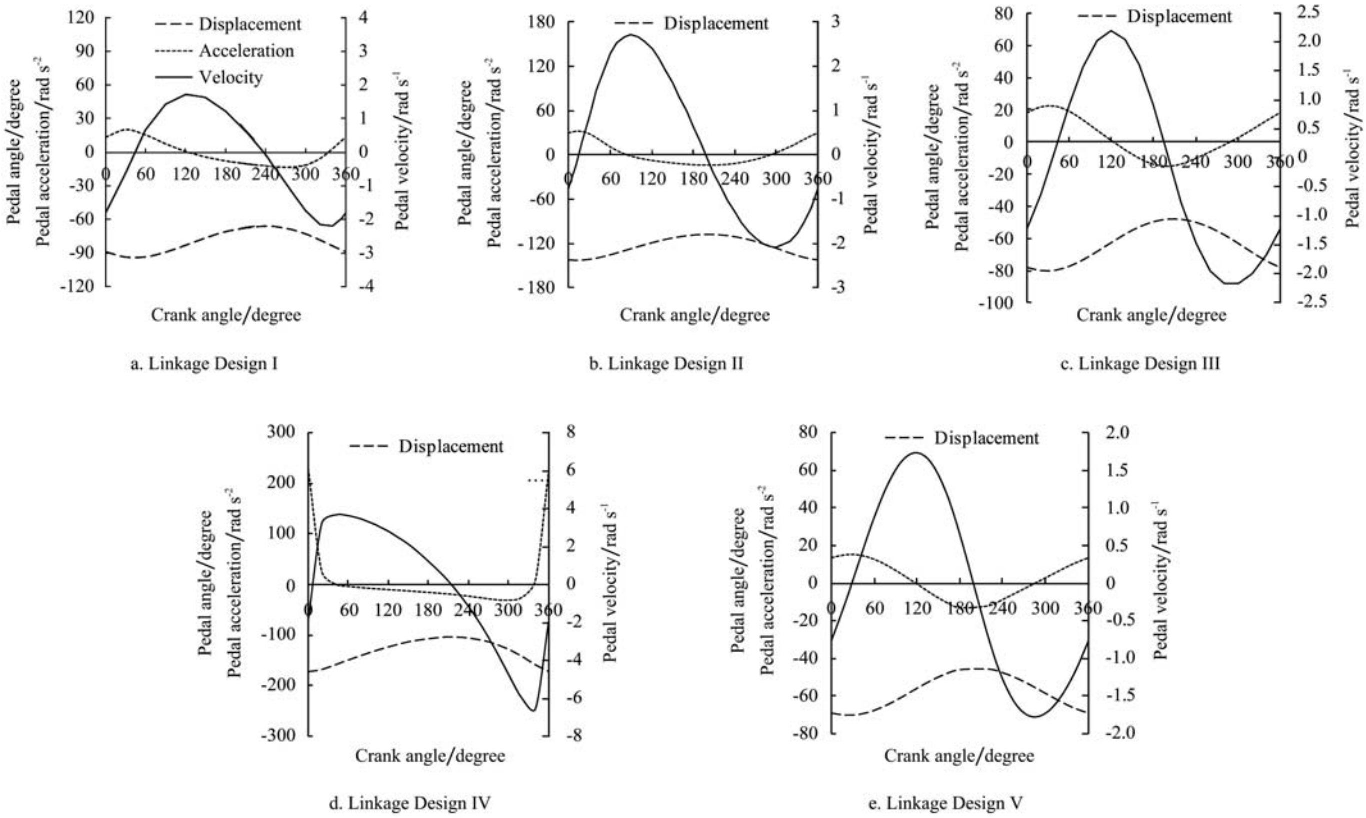

Figure 5 Displacement, velocity and acceleration of pedal against crank angle in thresher drive linkage designs

2.1.3 Measurement of force applied on the pedal

Force is applied on the pedal by leg. Magnitude of the force varies with the pedal position. It may be noted that the leg applies force on the pedal while it goes downwards. After attaining momentum, as the threshing cylinder continues to rotate, the pedal will start rising and during this period the leg experiences an upward force. Thus, during the downward motion energy is supplied by the human operator to the machine while small amount of energy is spent by the machine when the pedal as well as the leg moved up. Difference in the energy in the two cases is the energy consumed by the machine. Force applied on the pedal is measured using a force transducer while angular position of the pedal is measured using a potentiometer. A 490 N capacity Novatech load cell was used as transducer for recording the force. It was fixed on the pedal so that the line of application of force coincided with centre point of the pedal. Mounting of the force transducer is illustrated in Figure 6. The output of the load cell was fed to a data acquisition system Model Data Taker 800. The load cell was calibrated using dead weights. Force and displacement values were sampled at a rate of 32 samples s^{-1}. An operator was asked to operate the pedal maintaining a speed of 300 r m^{-1} (at the threshing cylinder). Potentiometer output and strain gauge output were sampled for few cycles after attaining steady operation. Graph was prepared between force applied on the pedal and pedal position.

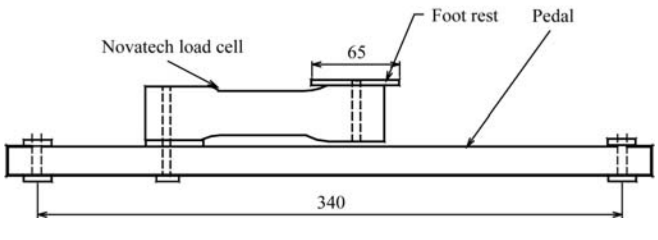

Figure 6 Mounting of load cell for measurement of pedal force

2.2 Measurement of physiological cost

i. Selection of subjects

Subjects were randomly selected after ascertaining their previous experience in thresher operation and their health status and past records. A structured proforma was utilized to collect data with regards to health status and past records. Five subjects were selected for the study. Details of the subjects are given in Table 2. Subjects having past record of respiratory ailments or chronic diseases such high blood pressure, diabetes, etc. were avoided. Subjects were explained the work to be performed and measurement procedures in detail and only volunteer subjects for the work were selected.

Table 2 Basic details of the selected subjects

Subject	Age in years	Previous experience in threshing	Health status	Stature /mm	Weight /kg
1	32	Yes	Ok	1641	58.5
2	29	Yes	Ok	1587	64.2
3	45	Yes	Ok	1635	68.3
4	25	Yes	Ok	1687	61.8
5	34	Yes	Ok	1524	59.8

In order to determine the physiological workload, subjects were first prepared and calibrated. Before exercise they were allowed to take rest on a chair for 30 minutes. Resting heart rate and oxygen consumption rate were recorded using heart rate monitor and Oxylog II, respectively. Calibration of the subjects was carried out using bicycle ergometer. Their heart rate and oxygen consumption rate were recorded during the exercise. The linkage test setups were prepared. Appropriate weight (2.05 kg) was placed on the slack side of the belt in order to apply required braking torque. They operated the test setups and the physiological energy expenditure rate was calculated from oxygen consumption rate using Equation (3):

$$EER = 20.88 \times OCR \quad (3)$$

where, EER = Energy expenditure rate, kJ min^{-1}; and OCR = Oxygen consumption rate, L min^{-1}.

The subject was asked to pedal. After the rest, each trial was carried out with a subject for duration of 15 minutes. Threshing cylinder speed was maintained at 300 r m^{-1} while two pedal speeds, 60 and 75 cycles min^{-1}, were used based on observation of Geetha (2003), who reported that pedaling speed lower than 50 cycles min^{-1} affects the work output of POP threshers and pedaling speed more than 75 cycles min^{-1} is strenuous especially for women workers. Before changing the pedal speed the gear at the cylinder was changed. Average values of heart rate and oxygen consumption rate for one minute were recorded during the 6th to 15th minute. A minimum of two hours of time gap was allowed for the subjects between two consecutive trials. Five subjects were employed for this study. A split-plot design was adopted for the experiment. The experimental layout is given in Table 3. Heart rate of the subjects is influenced by ambient temperature and humidity. Calibration as well as test setup operation were carried out in laboratory condition where these parameters did not vary much. Ambient temperature and humidity were recorded during the trials.

Table 3 Experimental layout for measurement of physiological cost of operation of thresher with linkage setups

Subject 1		Subject 2		Subject 3		Subject 4		Subject 5	
N1	N2	N1	N2	N2	N1	N1	N2	N2	N1
L5	L2	L3	L1	L2	L1	L2	L1	L3	L1
L3	L3	L1	L3	L5	L3	L3	L3	L5	L2
L2	L4	L2	L4	L1	L4	L5	L2	L1	L4
L4	L1	L5	L2	L4	L5	L4	L4	L2	L3
L1	L5	L4	L5	L5	L2	L1	L5	L4	L5

Note: N1 = 60 cycles min^{-1} and N2= 75 cycles min^{-1}, L1, L2, L3, L4 and L5 are synthesized linkage designs.

3 Results and discussion

3.1 Effect of thresher drive linkage on force –displacement pattern

Force applied by the operator on all five-linkage combinations was recorded and the results are indicated in Figure 7 (a) to (e). It can be seen that in each linkage combination, the force applied at different height of the pedal is different although all the linkages transmitted nearly the same amount of work in a cycle. In the linkage 1, the operator has to apply a considerably large force of about 230 N for pedal movement from 150 to 50 mm and later it reduced to almost zero when the pedal reached its lowest point. Since the operator has no time to lift his leg the force applied by the threshing cylinder played a major role in lifting his leg. In case of linkage 2 (Figure 7 (b)), the operator is able to exert a large force in lower pedal height and it began to stop quickly. However, during the return motion the force applied on the leg remains more or less constant. In case of linkage 3, the force applied increases very rapidly in first half of the pedal movement from top to down. At this height pedal position is such that operator can utilize his maximum leg strength, as it had been established in a separate experiment earlier, the operator could apply his maximum force at a height of about 0.16 × S (where S = stature). At pedal's topmost position (235 mm above ground) the pedal height is about (0.15 × S) to (0.16 × S) for most of the operators. As the pedal moves down the magnitude of force applied was found to be decerased and it reached to almost zero when the pedal touched resting point. However, again during return motion, the leg is lifted back and a small force is experienced in lifting the leg. In case of linkage 4, the force applied was large in the first half of the pedal movement from top to the bottom, but in this case very high force was applied during this process to impart sufficient amount of energy at the pedal. The pedal moves very fast during the last part of its movement due to high acceleration. It returns quickly resulting in a quick hit back on the operator's leg leaving no time to lift his leg. This results in a large amount of work done on the leg which was a loss to the thresher. To compensate this loss of energy, the operator was required to apply more force during the downward travel of pedal. It was the cause of too large magnitude of force needed at the downward stroke. In case of linkage 5, force applied during the downward travel is large. At the same time, during return motion, the link applies also comparatively large amount of force on the leg, which is the cause for requirement of large amount of force during the downward travel. Considering the force versus displacement relationships, linkage 3 appears to be the most promising design.

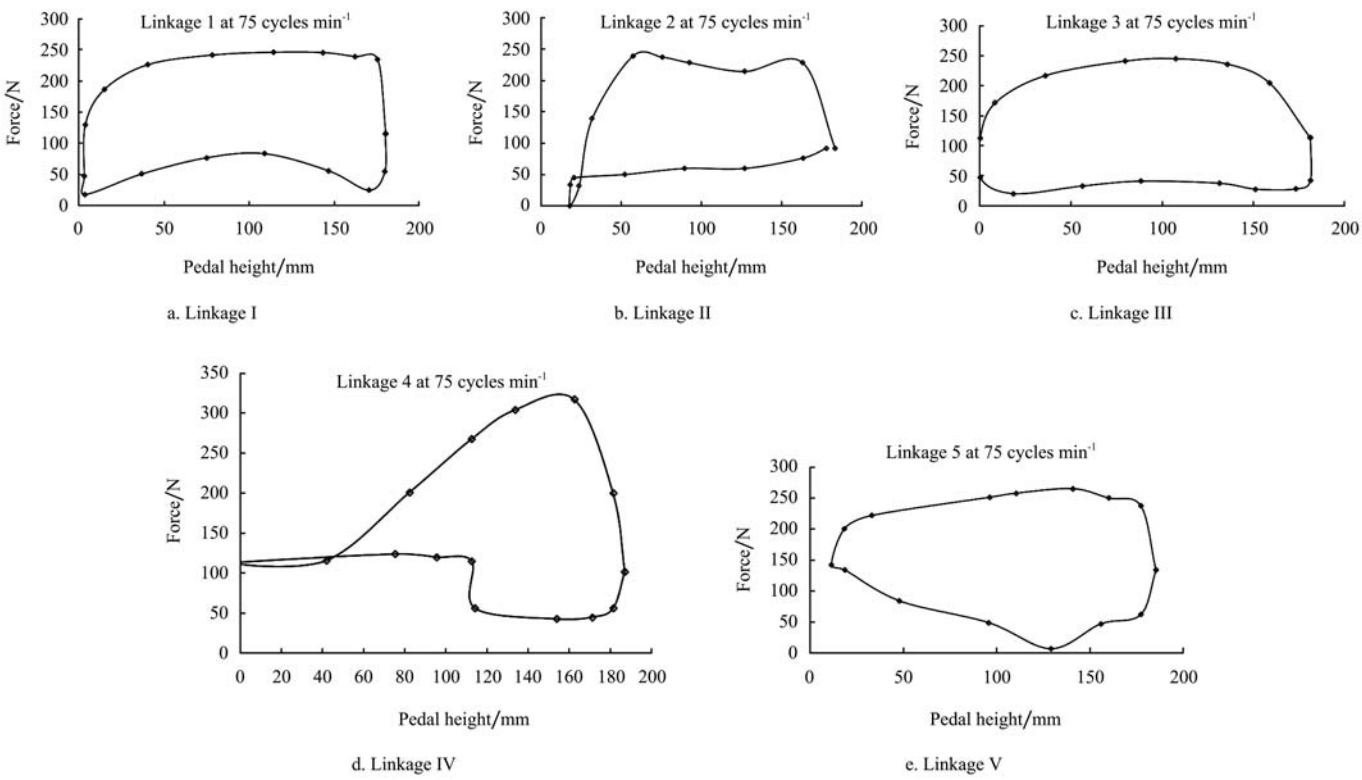

Figure 7 Pedal force versus pedal position graph for different linkage designs (Measured values)

3.2 Effect of thresher drive linkage on physiological cost

Change in heart rate and change in oxygen consumption rate of the five subjects were measured operating the five linkage designs. For each subject the heart rate correlated well with the oxygen consumption rate with linear relationship, which showed that their physiological energy expenditure rate is well correlated with these measured parameters. Change in heart rate (work pulse rate) and change in oxygen consumption rate (work load) were found to be reducing with the decrease in cyclic speed from 75 to 60 strokes min^{-1}. But analysis of variance presented in Table 4 suggested that the cyclic speed has no significant effect on work pulse rate (change in heart rate) and workload (change in oxygen consumption rate). The linkage combinations have significant effect at 1% level on the work pulse rate and workload. It can be seen from Table 5 that the lowest work pulse rate of 45.90 beats min^{-1} was recorded for linkage 3 followed by linkage 5, linkage 2, linkage 1 and linkage 4. Similar trend was observed in change in oxygen consumption rate also. Linkage 3 was found to be having lowest changes in oxygen consumption rate and in heart rate at both cyclic speeds. It has the lowest energy expenditure rate as shown in Figure 8. This suggests that linkage 3 among the five tested linkages gave the lowest physiological workload to the operators. This agrees with the finding on force versus displacement characteristics shown in Figure 7 (a) to (e). It may also be noted that keeping thresher speed as the same the pedaling speed can be reduced from 75 to 60 cycles min^{-1}.

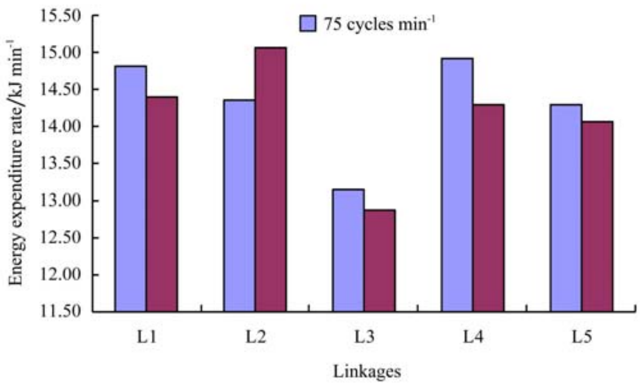

Figure 8 Physiological energy expenditure rate during operation of thresher with different drive linkages

Table 4 ANOVA of linkage designs and speed of operation

S. N.	Variable	df	Δ*HR*		Δ*OCR*	
			MSS	F-value	MSS	F-value
1	Replication (Subject)	4	42.66	6.49**	1.7×10^{-2}	37.75**
2	Pedaling speed (A)	1	0.32	0.05	9.0×10^{-4}	1.98
3	Error (a)	4	6.57		4.6×10^{-4}	
4	Linkage design (B)	4	47.17	4.38**	1.1×10^{-2}	8.72**
5	A×B	4	6.36	0.67	1.4×10^{-3}	1.12
6	Error (b)	32	10.77		1.3×10^{-3}	
	Total	49				

Note: ** Significant at 1 % level.

Table 5 Change in heart rate and change in oxygen consumption rate at different linkages and two cycling speeds of pedal

S. N.	Linkage design	Cycling speed, cycles per minute					
		75			60		
		Δ*HR*, beats min^{-1}	Δ*OCR*/L min^{-1}	Δ*EER*/kJ min^{-1}	Δ*HR*, beats min^{-1}	Δ*OCR*/L min^{-1}	Δ*EER*/kJ min^{-1}
1	L1	51.66	0.71	14.82	51.02	0.69	14.40
2	L2	49.70	0.69	14.37	51.74	0.72	15.06
3	L3	45.90	0.63	13.15	46.68	0.61	12.87
4	L4	52.00	0.71	14.92	49.92	0.68	14.30
5	L5	48.70	0.68	14.31	47.80	0.67	14.06

3.3 Power requirement under different linkage system

The total work done and the net work done were estimated for each representative cycle at two different cycling speeds, i.e. 75 and 60 cycles min^{-1}. The net work done was estimated by deducting the work done during the return stroke of the cycle when the work was done by the pedal on human leg under influence of moment of inertia. The physiological power input was estimated using the data collected for energy expenditure rate. The total power input, net power input and physiological power input by operators are presented in Table 6. It was found that for total input power of about 44.3 to 51.6 W the physiological power input by operator were in the range of 219 to 251 W. The physiological power input for Linkage 3 was the lowest at both cycling speeds.

Table 6 Power input and physiological power input at different pedaling rate and linkage designs

Linkage Design	Total power input/W	75 cycles min^{-1}			Total power input/W	60 cycles min^{-1}		
		Net power /W	*EER* /kJ min^{-1}	Physiological power input by operator /W		Net power /W	*EER* /kJ min^{-1}	Physiological power input by operator /W
L1	50.51	37.70	14.82	247.00	46.7	35.8	14.40	240.00
L2	48.76	36.41	14.37	239.50	45.7	34.9	15.06	251.00
L3	48.19	41.14	13.15	219.17	44.3	38.9	12.87	214.50
L4	48.78	27.31	14.92	248.67	45.6	29.7	14.30	238.33
L5	51.64	36.38	14.31	238.50	45.6	36.4	14.06	234.33

4 Conclusions

Pedal operated paddy threshers are in use and adopted by the farmers of many States of India. Small-scale fabricators manufacture these threshers commercially. Thresher drive linkage plays a vital role in utilizing the human energy for producing effective mechanical power output. Therefore, four alternate designs of four-bar linkages were designed and developed to ascertain the effect of motion characteristics (displacement, velocity and acceleration) on human interaction and physiological workload. It was found that changed motion characteristics have significant effect on force-displacement pattern and physiological workload on the operators. Among the five tested linkage systems, linkage combination 3 (with fixed link length l_1= 44.5 cm, crank length l_2 = 6.0 cm, connecting rod length l_3 = 40.1 cm and follower length l_4 = 21.6 cm) was found to have the lowest physiological workload and was preferred by the operators among the five designs tested.

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