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Improving Bicycle Design by Adopting Advanced Methods of Force or Torque Conversion And Ergonomics Principles

Mohanraj Karuppusamy

PG student, Department of Mechanical Engineering, College of Engineering, Guindy,
Anna University, Chennai, India.
e-mail:mohanraj2ker@gmail.com

***Abstract* — This paper discusses about the difficulty with the design of the bicycles commercially available with normal wheel base for regular commute. The current design of the bicycles employs conventional circular pedalling mechanism which has an inherent problem of sinusoidal variation of the force required to be imparted by the legs. And the shorter wheel base leads to the operation of the pedal with knee angles varying from 65° to145°. Applying foot force on pedal at a knee angle at 90° or less leads to pain in human knee joints especially when run for a longer duration. This paper proposes an alternate design concept with a rack and gear drive mechanism which is positioned ergonomically to improve the comfort of riding by reducing the power/energy consumed and the fatigue, so that the riders can avail the benefit of riding for longer duration.**

***Index Terms* —HPV, Bicycle, Ergonomics, gear, rack, knee pain**

I. INTRODUCTION

Bicycle was the first human means of transport for the individuals. Though gasoline & battery powered vehicles have been developed in the past and current centuries, the bicycle is still being used by economically poor people for their transport. They use bicycle for distances of 2-3 kilometers, though the speed of travel is less in the range of 15 to 20 km/h. Other than that, people use bicycle for physical exercise. With growing concern on cities flooded with motor vehicles, traffic problems, release of green house gases, it is highly recommended to use bicycles for short distance travels.

This study has aimed at finding a suitable method to enable efficient conversion of the force applied on the pedals by human foot into torque. The solution has to be arrived by using the principles of Ergonomics, cycling mechanics and better engineered drive system to reduce the fatigue which can enable to increase the possibility of using the bicycle for a longer duration or to reduce travel time by riding at higher speeds. Thus it can be made possible to increase the usage of bicycle instead of using IC engine based two wheelers.

II. PROBLEM STATEMENT

The design of bicycles commercially available even nowadays does not provide a convenient posture and a mechanism with which a human being can apply higher force over the pedals and efficient conversion of force into torque so that the bicycles can be operated with less fatigue for a longer duration. Though the modern cycles with multiple sprocket and clutch has provision to get higher torque or speed at wheels, they may have a problem of improper / wrong engagement of chain leading to malfunction and reduced life of drive system components.

III. LITERATURE REVIEW

There are various designs available commercially and developed for the bicycle or human powered vehicle competitions by the engineers and the cyclists in the following ranges. Refer the figures III.A to III.F

- from classical pedal operated bicycle to battery operated / solar powered e-bike or pneumatic/hydraulic cylinder operated bicycle
- from upright sitting bicycle to ergonomically well designed recumbent bicycles
- bicycles with different sprocket sets from single speed ratio to 30 speed ratios with Derailleur change system
- two wheel (bicycle) and three wheel (tricycle-Tad pole and Delta designs)
- from over seat steering to under seat steering
- from normal wheel base (approximately 43”) to long wheel base
- from central pedal drive (crank kept in between front and rear wheels) to outside the wheels pedal drive (crank kept in-front of the handle bar)
- pedal operated, hand operated, combination of both
- from conventional bicycle to human powered vehicle (HPV) with aerodynamic fairing

In recumbent or semi-recumbent version bicycles, the rider can exert a greater pedalling force than it is possible with a conventional bicycle. The backward inclined posture of the rider reduces the area of human body projected on the vertical

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plane against the wind, thus helps to reduce the air drag. Also this posture may provide better comfort for the riders.

All the above mentioned designs show that there are studies going on even now and there is a scope for improvement and it can be investigated.

Fig.III.A. A classical bicycle with rear wheel drive – single ratio (Source:https://www.fixedgearfrenzy.com/products/state-bicycle-co-city-shoreline-deluxe)

Fig.III.B. Modern city bike with Derailleur drive (Source: http://www.colourbike.com/Life_Bike/tongqinche.html)

Fig.III.C. A recumbent bicycle with midway pedal (Source: Aleah Pavlicek, Brandon Walker and Xingyu Chen, Terence Staples, Quamrul Mazumder, Design and Improvement of a Human Powered Vehicle (HPV))

Fig.III.D. Short wheel base recumbent bicycle with crank in front of the front wheel (Source: http://www.lightningbikes.com/p38/)

Fig. III.E. A recumbent bike - front wheel drive with U joint (Source: Benjamin Knaus, Philip Basmadjian, Nick Supat, ASME Human Powered Vehicle, A thesis submitted to the faculty of the Mechanical Engineering, California Polytechnic State University, (2010))

Fig.III.F. Full body bike (can be operated by both hands and legs at the same time and separately) (Source: https://energonplus.ru/aGFuZCBwZWRhbCAgYmlrZQ/)

IV. OPPORTUNITIES FOR IMPROVEMENT

(a). Angle of knee

Design of the classical and modern city bicycles have a situation in which the knee angle is approximately 90° or even less when applying maximum force on the pedal (front most position) while it varies from 65° to 145° approximately for the complete rotation of the crank. The figure IV.A gives the range of knee angle when riding a modern bicycle.

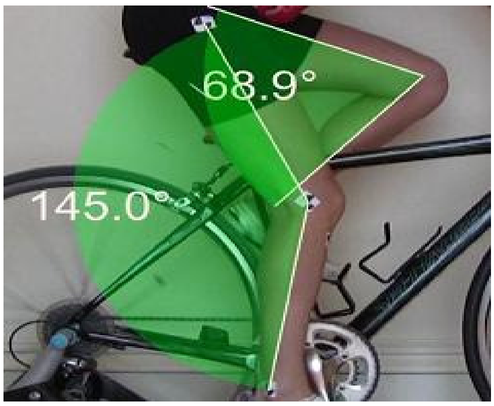

Fig. IV.A. Knee angle variation during cycling

(Source: www.bikedynamics.co.uk)

Operating bicycle with shorter angle leads to excessive rubbing force between the Articular cartilage and Meniscus (Refer the figure IV.B), especially for a longer time will lead to wear and pain. In long run, it may lead to knee failure for the people who ride bicycle with additional load frequently.

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If the knee angle is maintained between 135° to 180°, it will be better to apply a higher force and operate conveniently for a longer duration with the same force applied at present and the wear or pain of knee joint can be reduced.

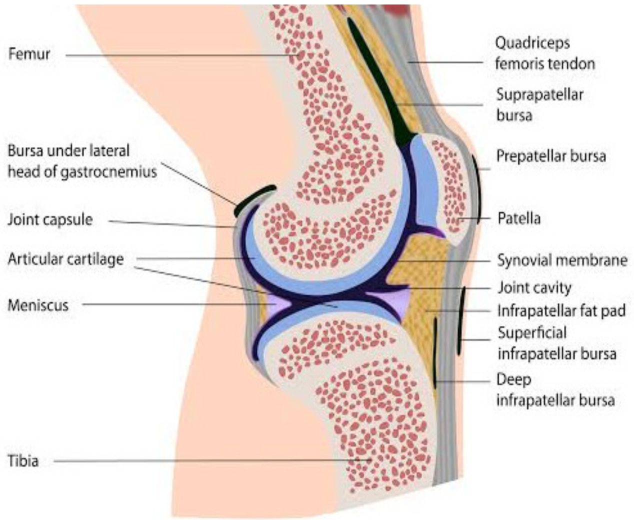

Fig. IV.B. Anatomy of human knee joint
(Source: www.daviddarlinginfo.com)

Though it is better to maintain the knee angle as above and to have back support (as in recumbent bicycles) to apply a higher force, there are few disadvantages like large wheel base and difficulty in balancing the bicycle. Since the full recumbent version has these difficulties, it may be suitable to make the proposed concept as a "Semi recumbent" design.

(b). Variation of the force demand

From the figure IV.C given below, it is understandable that the circular pedalling mechanism of the current design of the bicycles has an inherent problem of variation foot force required on the pedals for a constant torque with rotation angle of the crank (i.e. line of action of force is not always tangential with the crank leading to sinusoidal variation) and due to the change in the angle of the leg with respect to the crank.

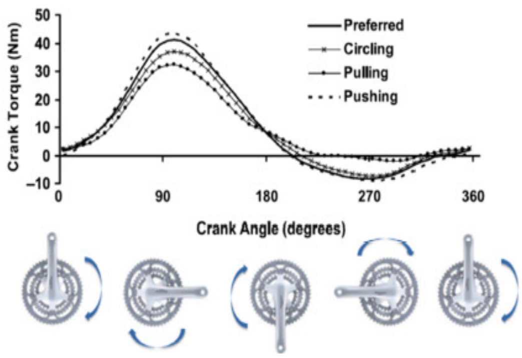

Fig.IV.C.Bicycle crank torque at various angles in current design (Source: Quintana-Duque, J.-C., Dahmen, T., Saupe, D. Estimation of Torque Variation from Pedal Motion in cycling)

It is desirable, if a mechanism can be developed to apply a constant force or force in a narrow range throughout the foot operation cycle for a particular speed.

V. REQUIREMENTS EXPECTED TO BE FULFILLED

The following are the important requirements set and expected to be fulfilled by the proposed design.

- Shall allow to use a correct posture which leads to less fatigue even for 1 hour drive
- Shall give a provision to apply maximum force
- Shall be able to ride at maximum speed of 50 km/h
- Shall be operable by 90 % of Indian adults (5th percentile female to 95th percentile male)
- Shall be operable by an average Indian male continuously for a period of half an hour at a speed of 40 km/h on a plain road
- The space required to store the bicycle shall not be much higher than current classic design, especially the length i.e. the wheel base
- Shall be safe to operate
- Shall be maintained and serviced easily

VI. ALTERNATE CONCEPT FOR FOOT FORCE CONVERSION

Few concepts have been generated considering the opportunities for improvement, compared the pros & cons, scored them and selected one of the two concepts with high score based on cost factor.

The picture Fig VI.A gives the concept of the proposed drive system which has to be used in addition to the current single speed drive system which contains a big crank wheel fixed on the bottom bracket axle (centre axle) except crank and a small free wheel sprocket. In the proposed design, there are two pairs of rack and gear, each one pair for both left and right hand side which are mounted over a drive shaft through an one way bearing.

There are two sprockets of equal diameter, one on drive shaft and the other one on centre axle at the left hand side of the bicycle and connected by using a chain of suitable length. Only in the forward direction of rotation, the force from the rack will be taken to the wheels through the shafts, sprockets and chains.

The top ends of both the racks are connected by using a rope which runs over a pulley. The length of the rope is designed in such a way that both the racks stand in the middle position of the stroke, when the rope extension lengths are kept equal on both the sides. And the axle of the pedal provided at the bottom of the rack acts as a stopper and limits the extension of the rack on the other side.

Both the racks contribute equally for the rotation of the drive shaft to make a complete cycle. And the number of rotations of the gear and shaft depends on the stroke length

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which is in turn dependent on anthropometric measures of individuals i.e thigh and leg lengths.

Both the racks are guided by using linear bearing guide to ensure a free movement of the pedal. Linear guide has to be selected of sufficient load and moment capacity to withstand the radial load at gear mesh and bending moments exerted due to the difference between the leg and rack axis respectively.

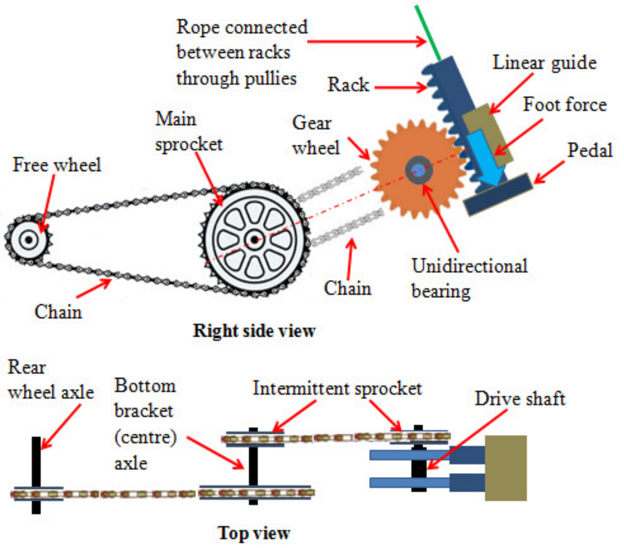

Fig.VI.A. Free return rack and gear mechanism for converting reciprocation of foot into rotary motion of gear box input shaft

VII. OPTIMISATION BETWEEN CONFLICTING REQUIREMENTS

From the requirements listed, the following have been found to be conflicting each other.

- Shorter wheel base Vs Maximum foot force (Parameter – Projected length of extended leg in horizontal direction)
- Maximum pedalling frequency – 120 cycles/minute for a wheel speed of 50 km/h Vs Maximum drive torque at drive shaft.
- Different anthropometric dimensions Vs Fixed position of drive mechanism
  These conflicts have been taken for further study.

(a) Wheel base, force and speed optimisation

One of the parameter which affects the wheel base of the bicycle is the posture of the body, especially the angle of thigh and leg. Since there is a contradiction exists between the requirements on wheel base and foot force, it was necessary to study different combinations of thigh and leg angles of the human beings. The anthropometric data of Indian population covering the 5^{th}, 50^{th} and 95^{th} percentile lengths of males and females have been collected and studied.

The conventional bicycle has a crank directly coupled to the sprocket and since the leg operates the crank directly, it is possible to achieve a maximum speed of 120 RPM at the main sprocket with the safe maximum pedalling frequency generally considered as 120 cycles per minute.

Hence, it is required for the new design also to consider 120 cycles per minute as the maximum speed of pedal operation. To limit this speed at the max speed of the bicycle, it is necessary to optimise the number of turns of the gear wheel per stroke of the rack which in turn demands optimised stroke length.

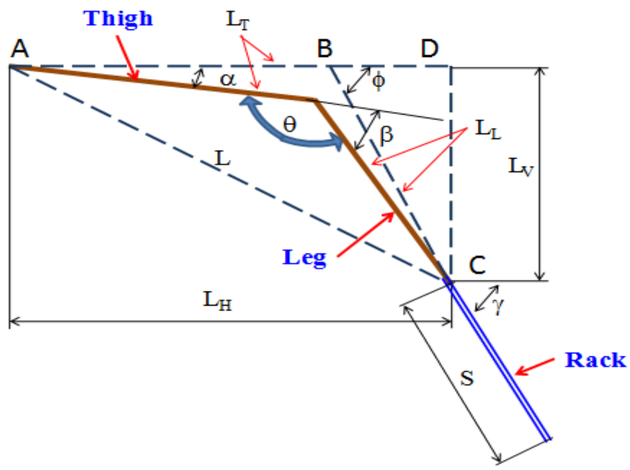

Fig.VII.A. Line diagram of thigh and leg length, angle between them and relationship with rack orientation

L_T – Length of thigh

L_L – Length of leg

L – Combined length of thigh and leg in extended condition

L_H - Combined length of thigh and leg in extended condition projected on horizontal plane

L_V - Combined length of thigh and leg in extended condition projected on vertical plane

α - Angle of thigh with respect to the horizontal plane

β - Angle of leg with respect to the axis of thigh

ϕ - Angle of leg with respect to the horizontal plane

θ - Knee angle i.e. the included angle between thigh and leg axes

γ - Angle of orientation of the rack with respect to the horizontal plane.

There is an interrelation between the thigh and leg angles and it varies with respect to the foot position. The value of β, ϕ, θ at any particular position are dependent on the lengths of thigh and leg, position of rack pedal from seat centre, angle of orientation of the rack.

With the help of a computer aided design (CAD) 2D sketching with appropriate constraints, the relationships between angles and following details have been studied.

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1. Values of β at various values of α and γ
2. End position of foot at various α values
3. Maximum value of α
4. Maximum stroke possible
5. Range of knee angle (θ) = 180 - β ; (ϕ = α + β)
6. Orientation of the rack (γ)

Based on the study findings, it has been decided to use the angles of thigh and leg as given below.

Range of α - from 0° at the start to 50° at the end of the stroke
Range of β - from 90° at the start to 0° at the end of the stroke
Range of ϕ – based on the combination of angles α & β
Range of θ - from 90° at start to 180° at the end of the stroke.

Refer table VII.A and VII.B for the recorded values.

At the end of the stroke, thigh and leg are in line and makes an angle with the horizontal plane varying from 45° to 49° based on rider's anthropometric percentile.

An optimum position of the rack with respect to the seat centre and orientation of the rack (67.5°) also has been found.

(b) Modification of seat tube angle

The current design of the bicycles have a seat tube angle higher than 65° (Refer VII.B). When the saddle or seat is raised to match crotch height and / or thigh and leg lengths of the individual, the seat height increases in a different ratio than the ratio between thigh and leg lengths. This difference leads to a situation of wrong angle of leg with the pedal.

The ratio of thigh and leg lengths between 5th percentile female to 95th percentile male of Indian population is close to constant value and the angle between them is close to 43°. Refer the figure VII.B and table VII.C.

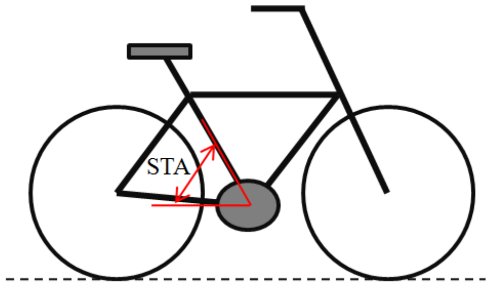

Fig. VII.A. Seat tube angle of a bicycle

TABLE.VII.A

POSITION, ORIENTATION OF THE RACK AND STROKE LENGTH ACHIEVABLE FOR 5TH PERCENTILE FEMALE RIDER

Top position of pedal in X direction (mm)	Top position of pedal in Y direction (mm)	Angle of rack operation path, γ (degrees)	Seat tube extension (mm)	Start angle of thigh, α (degrees)	End angle of thigh, α (degrees)	Start position of rack (mm)	End position of rack (mm)	Stroke length of the rack, S (mm)
480	395	45	0	0		4		199
					40.8		203	
		60	0	0		3.4		209.1
					44.6		212.5	
		75	0	0		3.2		231.5
					49		234.7	

TABLE VII.B

POSITION, ORIENTATION OF THE RACK AND STROKE LENGTH ACHIEVABLE FOR 95TH PERCENTILE MALE RIDER

Top position of pedal in X direction (mm)	Top position of pedal in Y direction (mm)	Angle of rack operation path, γ (degrees)	Seat tube extension (mm)	Start angle of thigh, α (degrees)	End angle of thigh, α (degrees)	Start position of rack (mm)	End position of rack (mm)	Stroke length of the rack, S (mm)
480	395	60	150	0		23.5		
					45		324.6	301.1
		67.5	150	0		22.2		
					47		337.3	315.1
		75	150	0		21.5		
					49		354.9	333.4

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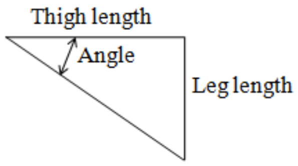

Fig. VII.B. Angle between thigh and leg

By using this constant ratio as an advantage, the position of the rack and gear drive mechanism has been fixed at a particular distance with respect to the seat centre, so that when there is an adjustment of the seat according to an individual's thigh and leg dimensions, there will be only a very little effect on the angle of leg with the rack.

TABLE.VII.C

ANGLE BETWEEN THIGH AND LEG

Rider category	Thigh length (mm)	Leg length (mm)	Angle (degrees)	Nominal angle (degrees)
5th percentile	421.5	402.5	43.67	43
50th percentile	500	464	42.86	
95th percentile	563.5	519	42.65	

VIII. ESTIMATION OF POWER AND FORCE DEMAND

(a). Assumptions for the calculations

- The mass of the rider is equal to 75 kg.
- The mass of the bicycle is 20 kg
- The bicycle is run on good road
- The bicycle is run on a level road i.e. zero gradient; hence change in potential energy is zero.
- Rolling resistance co-efficient for the drive components is equal to 0.008
- Maximum cadence (Number of pedalling cycles/minute) is 120 cycles for each leg and pedal operation provides power for half of the cycle i.e. downward or propulsive force through 180° on both pedals with a phase difference of 180°.
- The kinetic energy stored in wheels is negligible since the mass and moment of inertia are very less than those characteristics of the rider.
- The bicycle is brand new and maximum frictional loss is about 5% & 10% for current and proposed designs respectively.
- The head wind (opposing riding direction) velocity is negligible and the air drag is proportional to the vehicle speed alone.
- The frontal area of the rider is 0.6 m^2 and the effect due to clothing on air drag is negligible.

(b) Force / Power requirement calculations

Considering the assumptions given above, the speed of the bicycle, rear wheel, power and pedal force requirements for the cadence levels 10 to 150 cycles/minute have been calculated.

The equations from (1) to (9) are applicable for both conventional bicycle transmission with single speed ratio and the proposed design.

Total power required at a constant speed of the bicycle, P

$P = (P_{RR} + P_{AD}) \div E$ (1)

Where,

P_{RR} is the power required to overcome rolling resistance (W)

P_{AD} is the power required to overcome the air drag (W)

E is the approximate efficiency of the bicycle equal to 95% for the current design and 90% for the proposed design.

P_{RR} = Gross weight (Bicycle + Rider(s)) × V × Rolling resistance co-efficient (2)

$P_{AD} = 0.5\ \rho\ C_d\ A_f\ V^3$ (3)

$= 0.5 \times 1.225 \times 1 \times 0.6 \times V^3$

Where,

ρ - Air density (kg/m^3) = 1.225

C_d – Air drag co-efficient = 1

A_f - Frontal area of rider = 0.6 m^2

V is the speed of the bicycle in m/s

Bicycle speed V (m/s) = Speed in km/h × 1000 ÷ 3600 (4)

Laden wheel diameter, $D_{wl} = D_w - 0.2$ m (5)

$D_{wl} = 0.65 - 0.2 = 0.63$ m

Speed of the wheel, N_w (RPM) = $V \times 60 \div (\pi D_{wl})$ (6)

Torque required at the wheel at constant speed T_w (N-m)

$T_w = P \times 60 \div (2\ \pi\ N_w)$ (7)

Speed ratio between the sprockets, I_s = No of teeth in main sprocket ÷ No of teeth in freewheel = 44 ÷ 18 = 2.44

Speed of the main sprocket or crank $N_c = N_w \div I_s$ (8)

Torque required at the main sprocket, T_m (N-m)

$T_m = T_w \times I_s$ (9)

Equation (10) is applicable only for the conventional design.

Tangential force required at the crank, F_c (N)

$F_c = T_m \div r_c$ (10)

Where "r_c" is the radius of the crank = 165 mm = 0.165m

The tangential force required at the pedal for single rider load using the above equations for different cadence levels from 10 to 120 cycles/minute has been calculated.

Tangential force $F_t = F_c$

In general, the design of the conventional bicycles is that the angle of leg with the crank is 90° (i.e. tangential) when the crank is at 3'O clock position when viewed from right hand side and it enables that the entire push force is applied in the

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tangential direction with the crank. At the positions above and below this, some portion of the force applied is getting converted into a radial component.

At the crank angles (φ) close to the vertical, most of the force applied on the pedal is converted into a radial force component and to achieve required tangential force can be achieved by applying more force. The fig.VIII.A graphically explains this.

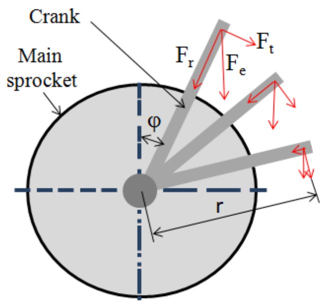

Fig. VIII.A. Sinusoidal variation force demand in conventional design

The force experienced (F_e) by the leg considering that it is applied in vertical direction for simplicity of the calculation can be given as

$F_e = F_t \div \sin\varphi$ (11)

Where φ is the angle of the crank with the vertical.

The mean power $P_m = F_{e\text{ - mean}} \times V_c$ (12)

Where, $F_{e\text{–mean}}$ is the arithmetic mean of the force experienced at different crank angles (N)

V_c is the velocity of the crank

$= (2\pi\, r_c\, N_c) \div 60$, m/s (13)

Based on the tangential force values calculated, the force experienced by the leg at various angles of the crank with respect to the vertical axis have been calculated and given in table VIII.A And the same table gives the arithmetic mean of the force experienced at six different angles of the crank and the mean power demand.

The equations (14) and (15) are applicable for the proposed design. Since the diameters of both the driver and driven sprockets mounted over the drive shaft and centre axle respectively are equal,

Torque required at the drive shaft $T_d = T_m$

Speed of the drive shaft $N_d = N_c$

Force required to drive the gear wheel F_d (N)

$F_d = T_d \div r_g$ (14)

Where r_g is the radius of the gear wheel (m)

Frequency of operation of rack N_r (cycles / minute)

$N_r = (\pi \times D_g \times N_d) \div (2 \times S)$ (15)

It is found that the maximum deviation of the axis of leg with respect to the axis of rack as 21° which accounts to 7% increase in the force required at the maximum. The average increase in force requirement over the complete cycle has been estimated to be about 4%.

The values calculated for single rider load using the above equations for different cadence levels from 10 to 120 cycles/minute have been given in the table VIII.B & VIII.C

TABLE VIII.A

FORCE AND POWER DEMAND AT VARIOUS CADENCE LEVELS FOR CONVENTIONAL BICYCLE WITH SINGLE SPEED RATIO

Pedal operating frequency (Cycles per minute)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
Bicycle speed (km/h)	**3**	**6**	**9**	**12**	**15**	**18**	**21**	**24**	**27**	**29**	**32**	**35**
Theoretical force required at pedal @ 95% efficiency (N)	**38**	**41**	**47**	**55**	**66**	**79**	**94**	**112**	**132**	**154**	**179**	**205**
Force experienced at 15 deg of the crank (N)	146	160	182	214	255	305	363	431	508	595	690	794
Force experienced at 30 deg of the crank (N)	76	83	94	111	132	158	188	223	263	308	357	411
Force experienced at 45 deg of the crank (N)	53	58	67	78	93	111	133	158	186	218	252	291
Force experienced at 60 deg of the crank (N)	44	48	54	64	76	91	109	129	152	178	206	237
Force experienced at 75 deg of the crank (N)	39	43	49	57	68	82	97	116	136	159	185	213
Force experienced at 90 deg of the crank (N)	38	41	47	55	66	79	94	112	132	154	179	205
Arithmetic mean of the force experienced (N)	**66**	**72**	**82**	**97**	**115**	**138**	**164**	**195**	**230**	**268**	**311**	**358**
Mean power demand, P_m (W)	**11**	**25**	**43**	**67**	**99**	**143**	**199**	**269**	**357**	**464**	**592**	**743**

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TABLE VIII**Error! No text of specified style in document.**B
FORCE AND POWER DEMAND WITH PROPOSED DESIGN FOR 5TH PERCENTILE FEMALE RIDER

Pedal operating frequency (Cycles per minute)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
Bicycle speed (km/h)	3	6	9	12	14	17	20	23	26	29	32	35
Force required at pedal @ 90% efficiency (N)	99	109	124	146	173	207	247	293	346	404	469	540
Ideal power demand (W)	7	16	27	43	64	91	127	172	228	296	378	475
Mean power demand considering leg angle variation (W)	8	17	28	44	66	95	132	179	237	308	393	494
Percentage of energy saving	**33.6**											

TABLE VIII.C
FORCE, POWER DEMAND WITH PROPOSED DESIGN FOR 95TH PERCENTILE MALE RIDER

Pedal operating frequency (Cycles per minute)	**10**	**20**	**30**	**40**	**50**	**60**	**70**	**80**	**90**	**100**	**110**	**120**
Bicycle speed (km/h)	4	8	12	16	20	24	28	32	36	40	44	48
Force required at pedal @ 90% efficiency (N)	102	120	150	191	244	309	386	475	575	688	812	948
Ideal power demand (W)	10	24	46	78	124	189	275	386	527	699	908	1157
Mean power demand considering leg angle variation (W)	11	25	47	81	129	196	286	402	548	727	945	1203
Percentage of energy saving	**26**											

(*c) Comparison of the force & power*

When the force demand with the conventional and the proposed design are compared, it is apparent that there is more variation of the force experienced at different crank angles in the current design. Though the arithmetic mean of the force experienced at different angles of the crank with the current design seems to be less when compared to the force demand with the proposed design, the power demand with the current design is more. The highest force at shorter angles of the crank with vertical plane in the current design is about 140% of the force required with proposed design. In this calculation, the effect due to acute knee angle when the pedal is at top most position has not been considered. If that is also taken into account, there will be considerable increase in force/power demand which can be treated as the reason for knee pain and wear.

If the mean of sinusoidal variation i.e. 0.637 times the peak force is considered, then the mean force will be higher than the arithmetic mean which in turn will result in higher power demand.

When the power demand of both conventional design and proposed design are compared, it is evident that there is an energy saving potential with the proposed design.

The equation (16) gives the method to calculate percentage energy saving.

Percentage of energy saving at a particular speed by using the proposed design

= (Power demand in conventional bicycle drive – Power demand in proposed drive) × 100 ÷ Power demand in conventional bicycle drive. (16)

Power demand values have been highlighted in the tables VIII.A,VIII.B & VIII.C for the same speed considered for the comparison.

IX. PICTURES OF 3D MODEL OF THE PROPOSED DESIGN FOR REFERENCE

The figure IX.A & IX.B gives the concept 3D model of the bicycle with proposed drive design and the important parts.

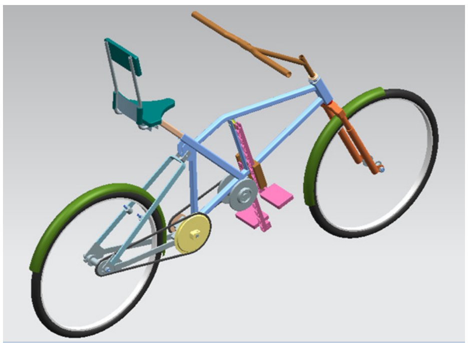

Fig. IX.A.3D model of proposed design-without safety cover

The proposed design has a seat with back rest to enable application more force on the pedals.

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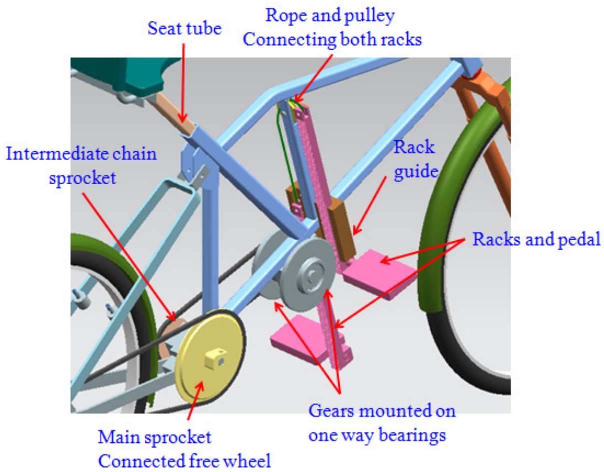

Fig. IX.B. Important parts of proposed design

X. CONCLUSION

In the proposed design, though there is a variation of angle of the leg with axis of the rack during operation, the force demand will increase only by 7% at the maximum. And it has been ensured that the knee angle will not be less than 90° in any position of the pedal for all the riders ranging from 5th percentile female to 95th percentile male. The theoretical calculation of energy saving gives an indication that there will be 26% to 33.6% energy saving with the proposed design. Considering all the above points and calculated values for both conventional and the proposed design, it can be concluded that there will be a definite advantage of less knee pain or wear or fatigue when compared to the bicycles of current design, though there is an increase in number of components and the manufacturing cost / sales price of the bicycles.

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Mohanraj Karuppusamy, Author born in Pollachi, Tamilnadu, India in 1979. He received the B.E. degree in mechanical engineering from Anjalai Ammal Mahalingam Engg. College, which was affiliated to Bharathidasan Universtiy, Tiruchirappalli, Tamilnadu, India, in 2000 and currently pursuing M.E degree in mechanical engineering with specilisation in product design and development at College of engineering, Guindy (CEG), Chennai, India.

From 2000 to 2017, he has worked in various private manufacturing sector companies of which importantly worked as Assitant engineer- Tool planning in Lakshmi Automatic loom works limited, Coimbatore, India and as Assistant manager-Product development in Rieter India pvt. Ltd, Satara district, Maharashtra, India. He is currently working with HCL technologies Ltd., Chennai, India as Senior technical lead.

His research interest includes Robust design, Integrated product design and development, low cost automation, improving design of the machines for sustainable economy & environment, industrial design, Ergonomics and research and development of machines/methods for agricultural sector, tiny and small scale industries for improving quality and productivity.