Design Analysis And Applications Of A Regenerative Bicycle Ergometer

Chukwuneke J. L., Ugwuegbu D. C., Sinebe J. E., Enyi L. C.

Abstract: Man needs to do some form of physical work in other to remain healthy, this work is similar to the work done by any machine or equipment and thus should be channeled to give useful output, but rather, it is usually dissipated into the environment in form of heat. The regenerative bicycle ergometer takes advantage of the greater power generated by the limbs and arms, thus conserves, converts and stores the energy dissipated by the rider with an ideal mechanical advantage of 7.6, it strategically uses simple mechanisms to magnify its work and then converts this mechanical energy into electrical energy by the use of a dynamo, with a speed ratio of 108.5 and a transmission efficiency of 89%, the rider pedals 27rpm to obtain the dynamo's rated input of 2600rpm, giving an output of 12.6volts. The regenerative bicycle ergometer is designed and constructed to perform all the core functions of a bicycle ergometer, having an allowable load of 116.5kg and a maximum resistance of 65.33N which is equivalent to a mass of 6.66kg. The energy converted is stored in a 12volts battery, making its use flexible, clean and meeting the energy demands of man.

Index Terms: Battery, Design, Dynamo, Electrical Energy, Human Body, Physical Exercise, Power Generation, Regenerative Bicycle Ergometer, Transmission.

1 INTRODUCTION

Physical exercise has proven to be a very useful medical tool in our lives; it enhances and maintains physical fitness, and overall health and wellness [1]. Frequent exercise boosts the immune system, and helps prevent the disease of affluence such as heart disease, type 2 diabetes and obesity [2]. It no doubt has so many advantages but has its basis in the fact that man needs to do some form of physical work in other to remain healthy. This physical work done by man however is similar to work done by any equipment and thus should be channeled to give useful work output [3]. Knowing that electricity has always been a major concern in Nigeria, this paper present the design analysis of a regenerative bicycle ergometer which converts the mechanical work done by the rider to Electrical energy and then stores the electrical energy in batteries, this will reduce the use of internal combustion engines to power low energy appliances. The use of stored electrical energy in batteries, as seen in inverters, has proven to be very cost efficient, environmentally friendly and noiseless. But the question of what generates the energy stored in the battery comes up. Energy is generated by internal combustion engines, solar panels, hydrodynamics, wind mills, human work, and bio gases and so on, but our interest in this work is in conversion of the work done during exercise on a bicycle ergometer to stored electrical energy (i.e. the conversion of human energy to electrical energy that could be stored in battery systems). A high power dynamo attached to the bicycle ergometer will convert this mechanical energy generated during the exercise to electrical energy [4], storing the energy in a battery such that its use is flexible.

- *Chukwuneke J. L. is currently a Lecturer in Mechanical Engineering Department, Nnamdi Azikiwe University, Awka, Nigeria, E-mail: jl.chukwuneke@unizik.edu.ng*
- *Ugwuegbu D. C. is currently a Lecturer in Mechanical Engineering Department, Federal Polytechnic, Nekede, Nigeria.*
- *Sinebe J. E. is currently a Lecturer in Mechanical Engineering Department, Delta State University, Oleh, Nigeria.*
- *Enyi L. C. is currently a Lecturer in Mechanical Engineering Department, Delta State Polytechnic, Ogwashi-uku, Nigeria.*

The rider's work done on the bicycle pedal will rotate the shaft of the dynamo with the use of belts. This work focused on the design and fabrication of mechanical parts and components of the regenerative bicycle ergometer. To achieve this project objective, some criteria such as the strength, ergonomic design and safety while designing the machine body structure, mechanical systems and the efficiency of the energy conversion system were considered. The human body dissipates energy during physical exercise into the surroundings, this energy is not any different from that of internal combustion energy and thus should not be wasted. This mechanical energy can be converted to electrical energy, stored and used flexibly at the users own time. The regenerative bicycle ergometer unlike a bicycle ergometer does not dissipate the energy of the human rider but instead stores such that it is available for use when needed. This stored energy can be used by the human when needed. The more physical exercise done on the bicycle the more energy is generated and also the more physical fitness of the rider. The regenerative bicycle ergometer charges its batteries from work already been done by the human in form of exercise. The aim of this work is to design and fabricate a regenerative bicycle ergometer, this will conserve, convert and store energy dissipated by the rider during physical exercise. The objectives are: to harvest sufficient electrical energy from the rider during cycling, to store energy harvested (dissipated during exercise) into a battery which will in turn power low energy appliances, to be very efficient in converting the mechanical work done to electrical energy by using significant gear ratios, to provide electrical energy for the basic needs of the user, such as powering up its electrical fan, bulbs and charging other low energy electrical devices, to have variable resistances for the cyclist during the exercise just as in a standard bicycle ergometer, to fit different riders ergonomically employing seat adjustments, to improve the health of the rider. This work is focused on the data collation of actual cycling rates of different riders while exercising on a bicycle ergometer, analysis of data to ascertain the cycling rate of the rider considering various cases. Regenerative bicycle ergometer with variable resistances equipped with belt and pulley that produce the turning input in the dynamo and storage of the electrical energy generated into batteries were design and fabricated. The regenerative bicycle ergometer performs all functions of a basic bicycle ergometer but goes further to store the energy dissipated during the course of exercising. The stored energy when in use is noiseless and clean because it does not have any effect on the surroundings. This work will be very useful in generating energy for low energy appliances such as fans, energy saving bulbs, recharging of electronic gadgets. The energy stored will be directly related to the rate at which the bicycle ergometer is used. These stationary bicycles will find use in homes, gyms and fitness centers and hospitals, etc. This work is very viable because it conserves converts and stores energy which man dissipates during physical exercise without disturbing the rider's physical exercise and makes it available for the user when needed.

2 MATERIALS AND METHODS

2.1 Regenerative Bicycle ergometer Material Selection and Analysis

When carrying out this analysis; materials and processes, economic and aesthetic ergonomic decisions which are required before the product is designed as well as considering a possible mechanical and electrical requirement were considered. The factors considered for the selection of materials for this work; machinability, rigidity, availability, strength and cost of the materials. The materials selected for different components and the reasons for their selection are listed in the table 1.

TABLE 1
MATERIAL SELECTION

S/N	Component	Material selected	Reason(s) for Selection
1	Frame	Mild steel	High wear resistant, high strength, good rigidity.
2	Shaft	Carbon steel	High strength, good machinability, good heat treatment properties, high wear resistant properties.
3	Bearing	Stainless steel	High resistance corrosion.
4	Bearing sitting	Stainless steel	High resistance to corrosion.
5	sprocket	Medium carbon steel	Strong with good wear properties and low cost,
6	Transmission	Bush Roller chain	High axial stiffness, low bending stiffness, high efficiency and low cost
		Belt	Relatively low cost, high efficiency
7	DC motor (dynamo)	300 Watts	Generates electrical energy from rotational force that the pulley gives.
8	Pedal	Plastic	Low cost and light weight
10	Flywheel	Aluminium	Low cost and low weight.
11	Battery	Deep cycle	Can power electronics for a long time, and can be deeply discharged and charged many times.

Selection of a Dynamo: The dynamos used in the bicycle energy harvesting are low wattage dynamos such that the energy developed was sufficient to illuminate the bicycle head and tail lamps when the rider cycles and not necessarily for long periods or storage, to power external appliances. Since the average cyclist pedals for about 70rpm and an athlete 100rpm [4], the dynamo input revolution had to be in range with the speed developed by the rider. Since this work aimed at harvesting sufficient energy from the rider during the cycling duration, the basis for dynamo selection was made with respect to the power output of the dynamo

TABLE 2
COMPARISON OF THE SELECTED DYNAMO AND THE COMMONLY USED BICYCLE LIGHTNING DYNAMO

Specifications	Commonly used Bicycle Dynamos	DC Power Dynamo
Max power output	6 Watt	300 Watt
Rated output voltage	12 Volts	12 Volts
Input rpm for max power	70 – 100 rpm	2600 rpm
Weight	140g – 280g	3629g
Dimensions	9.5cm x 3cm x 4.5cm	13cm x 7cm x 8cm
Price range	X	3X

Selection of Transmission System: Chain and belt drives are a means of transmitting power like gears and shafts. Chain and belt drives are characterised as shown in table 3.

TABLE 3
PERFORMANCE OF THE CONSIDERED TRANSMISSION TYPES

	Belt	Chain
Required alignment accuracy	Medium	Medium
Positive drive	No (except toothed)	Yes
Efficiency	Medium	High
Stiffness	Low	High
Strength	Low-medium	High
Ability to span large distances	Medium	Medium
Maintenance	Medium	High
Cost	Low	Low

Selection of Bicycle Ergometer Body Parts: The body parts of the regenerative bicycle ergometer are majorly made up of steel based on the carbon content; Mild and low carbon steel: It is the most common form of steel because its price is relatively low and is easy to shape making it easy to handle [5], while it provides material properties that are acceptable for many applications. It contains 0.05-0.25% carbon and 0.4% manganese, Medium carbon steel: It has 0.29-0.54% carbon and 0.6 – 1.65% manganese content. It is ductile and strong with good wear properties, Higher carbon steel: Carbon steel which can successfully undergo heat treatment has carbon content in the range of 0.55-0.95% and 0.3-0.9% manganese. It is very strong and holds shape memory and therefore is suitable for springs and wire [6], Ultra high carbon steel: This contains approximately 0.96-2.1% carbon content. It is an extremely strong material though it is brittle and requires special handling.

Shafts: The shaft material is made of Stainless steel. Stainless steel is an alloy with a minimum of 10.5% chromium content by mass. Stainless steel does readily corrode. It is used where both the properties of steel and resistance to corrosion are required. It differs from carbon steel by the amount of chromium present.

Sprockets: A sprocket is a profiled wheel with teeth or cogs that mesh with a chain, track or other perforated or indented material [6].

It is different from a gear in the sense that they do not mesh together directly and also different from a pulley in the sense that pulleys are smooth and sprockets are rough. The sprockets are made of medium carbon steel and have good wear properties.

Bicycle ergometer Frame and Base: The frame and base of the regenerative bicycle are circular and rectangular pipes made from mild steel, these mild steel pipes carry the weight of the rider and also keep the bicycle in an upright position.

Selection of Battery: There several types of batteries ranging from their chemical composition to their application, such as a deep cycle battery and a starting battery. A deep cycle battery has the ability to be deeply discharged and charged many times during its service life, deep cycle batteries are designed for power electrical equipment for a long period of time. Since the aim of the work is to store energy to powered electronics, a deep cycle battery is used for storage of electricity in the regenerative bicycle ergometer.

2.2 Design Modification

Bicycle ergometer is equipment in human factor engineering for measuring muscle work. In friction-type bicycle ergometer, the subject is made to work against friction created on ergometer flywheel by a brake belt mechanism. As the subject pedals the bicycle, the flywheel rotates against the brake belt around its rim. The brake belt is tensioned by the addition of weights on one end while the other end is attached to a spring balance [7]. The regenerative bicycle ergometer is a modification of the typical bicycle ergometer. The regenerative bicycle ergometer goes further to conserve, convert and store the energy dissipated during the exercise, such that its use is made flexible. The usual bicycle ergometer is hereby transformed to an electricity generator.

3 DESIGN ANALYSIS, RESULTS AND DISCUSSION

3.1 Non Structural Components

Velocity Ratio: The dynamo is a D.C motor working in reverse; it is an electrical generator that produces direct current from mechanical rotational energy. Dynamos were the first electrical generators capable of delivering power for industry, and the foundation upon which many other later electric-power conversion devices were based, including the electric motor, the alternating-current alternator, and the rotary converter. Today, the simpler alternator dominates large scale power generation, for efficiency, reliability and cost reasons. A dynamo is simply a DC motor working in reverse. For this work, MNS 300 watt air cooled DC generator was used. The MNS 300 specification: Model number - E63M0056TL, Output voltage – 15 volts DC, Nominal current – 15Amps, Peak current – 20Amps, Max RPM – 2600, Pulley diameter - 5.08 cm (was replaced with a 2cm pulley for a higher velocity ratio). The dynamo is connected to the bicycle pedal crank by means of belts and pulleys. Optimal pedaling frequency for most subjects is 50-75 revolutions per minute. This is the range of RPMs in which most subjects have their greatest mechanical efficiency. On the other hand, trained cyclists may prefer pedaling closer to 90 or 100 revolutions per minute [4]. Following the statement that an average cyclist can pedal to about 70 revolution per minute (70RPM), it is obvious that it ordinarily cannot deliver enough revolutions to run the dynamo whose rated rpm 2600 for maximum output power. Hence, complex but drive was introduce to boost the dynamo pulley RPM.

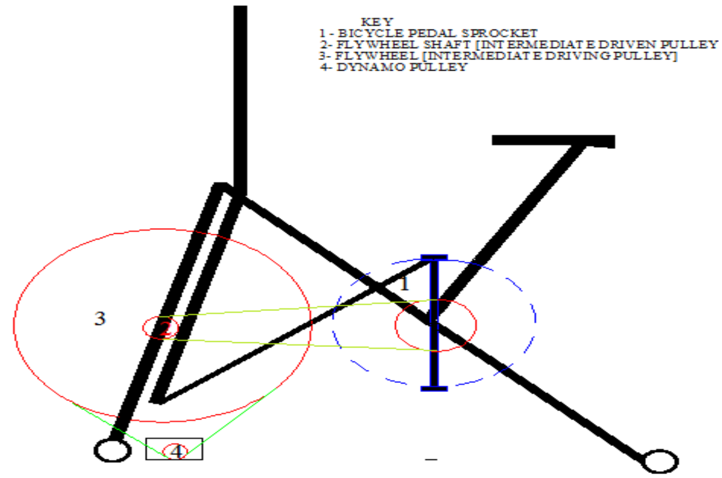

Fig. 1. *Pulley Arrangements*

In designing the belt drives, the following where considered; High velocity ratio to the dynamo, and compact pulley arrangement considering the length of the bicycle and thus reducing the distance between their centers. The crank diameter of a standard cycle bicycle is 34cm, the pulley of the dynamo is 4.5cm, the flywheel shaft [intermediate driven pulley] is of diameter 1.5cm, the flywheel [intermediate driving pulley] is of diameter 43cm.

Velocity ratio: $$\frac{n4}{n1} = \frac{D1 \times D3}{D2 \times D4} \quad (1)$$

Where; n_4 – number of revolutions per minute of dynamo pulley, n_1– number of revolutions per minute of bicycle pedal crank, D_1– diameter of bicycle pedal crank = 34cm, D_4 – diameter of dynamo pulley = 4.5cm, D_2 - The flywheel shaft =3cm, D_3 - The flywheel = 43cm. N_4 should be greater or equal to 2600rpm for the dynamo to operate properly to give an output of 300watts.

$$\text{Hence; } n_4 = n_1 \left[\frac{34 \ X \ 43}{4.5 \ X \ 3}\right] \geq 2600\text{rpm}; \ n_1 \geq 24\text{rpm}$$

Therefore the dynamo will operate at its maximum output if the rider can maintain a cadence (cycle per minute) equal or greater than 24 revolutions per minute. This is a very obtainable speed for any rider. To ensure that the pulley diameter selection and corresponding minimum input rpm is attainable by riders of different ages and sex an experiment was conducted.

Length of Chain and Center Distance: Chain must contain even integer number of links and hence cannot pick an arbitrary centre distance and chain pitch. Nearest chain lengths (in pitches) for a contemplated centre distance, CC, are calculated by empirical formulae like (for a two sprocket system). The result of which should be rounded up to the next even number to calculate the actual centre separation, C_A

$$L = \frac{N_1 + N_2}{2} + \frac{2C_C}{P} + \frac{P(N_1 - N_2)^2}{4C_C\pi^2} \quad (2)$$

where; N_1 and N_2 are the numbers of teeth on the sprockets = 66 and 20 respectively, p is the chain pitch = 0.8cm, C_c is the contemplated center = 38cm. Hence; L = 140.032cm.

Therefore, rounding up to the next even number, L = 142cm

Then, the actual center distance;

$$C_A = \frac{P}{8}\left[2L - (N_1 + N_2) + \sqrt{[2L - (N_1 + N_2)]^2 - \frac{\pi}{3.88}(N_1 - N_2)^2}\right] \quad (3)$$

Hence; C_A = 38.796cm

Length of Belt: The length of the belt joining the flywheel (intermediate driving) to the dynamo pulley is calculated as shown;

$$\text{Length of belt (3-4)} = \pi(D_3 + D_4) + 2X_3 + \frac{(D_3 - D_4)^2}{4X_3} \quad (4)$$

Where; X_3 = centre distance from flywheel (intermediate driver) shaft to dynamo pulley = 29cm

Hence; Length of belt (3-4) = 220cm

Metering: A voltmeter attached to the output terminals of the dynamo is used to evaluate the output voltage. The output voltage is directly proportional to the input cadence of the rider. The output voltage can thus be related directly to the input rpm with the equation below;

$$\text{Cadence} \propto \text{Voltage} \quad (5)$$

$$\text{Rpm} = K\,V \quad (6)$$

Where; K is the grace regenerative constant, V is output voltage and Rpm is the input cadence of the rider.

Rope Brake Tension: The resistance on the bicycle pedal is provided by friction. The variable resistance of the bicycle ergometer is controlled by a rope brake system, with its maximum resistance of 6kg, thus an equivalent weight of 58.86N.

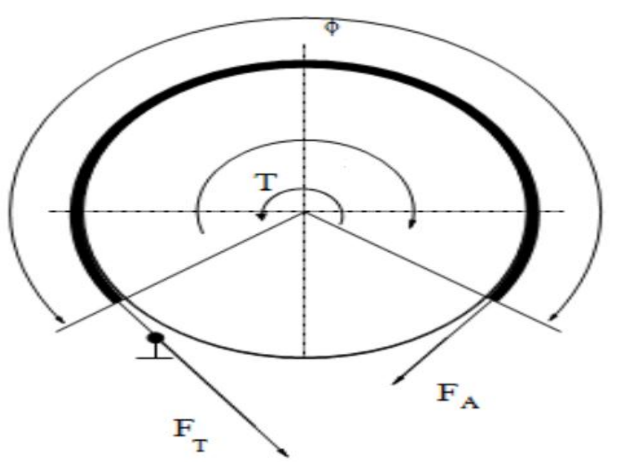

Fig. 2. *Forces acting on the tension drum*

The following equation provides the braking torque as a function of the external brake force that tightens the belt;

$$T = (F_T - F_A) \times R_D \quad (7)$$

Where; T = Braking torque, F_T = force acting on the tight side, 58.86N (at maximum tension), F_A = force acting on the loose side, R_D = radius of the drum

The forces F_T and F_A are related; $\frac{F_T}{FA} = e^{\mu\emptyset}$ (8)

Where; μ = dynamic coefficient of friction between leather and metal, 0.25, Ø = angle of contact, 250 deg = 4.36rad, F_A = 20N. Hence; T= 8.35Nm.

Charging Circuit: The **c**harging system regulates the output voltage fluctuations for maximum output voltage of 15volts. The charging system consists of Diode; Capacitor; and Integrated circuit; serves as a variable input voltage regulator, the LM 317 IC regulates voltage from 3 – 35 voltage

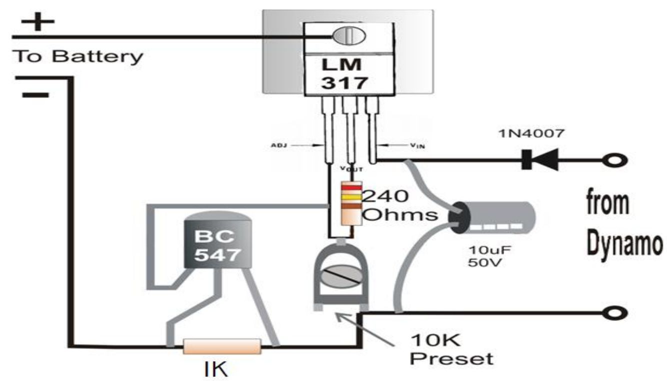

Fig. 3. *Battery charging circuit diagram*

3.2 Bicycle Structural Components

The maximum loads on the bicycle structure are calculated as shown.

I. Bicycle Seat Support

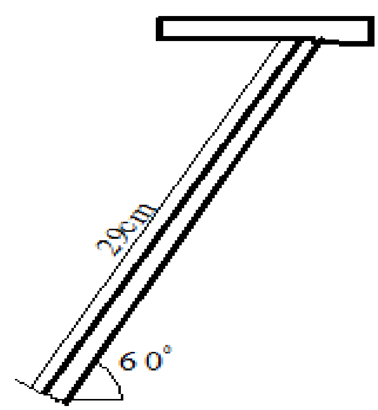

Fig. 4. *Bicycle seat support*

The material used for the bicycle sit support is mild steel with the following specification; Diameter 35mm, Hollow with 2mm thickness, Young's modulus of 210GN/m^2. According to Euler formula used for calculating critical load for a column or strut, considering that one end is fixed and the other free;

$$\text{Buckling load (BL)} = \frac{\pi^2 EI}{4L^2} \quad (9)$$

Where; E = young's modulus, L = length of the strut, I = moment of inertia of inertia of cross sectional area of the pipe;

$I = \frac{\pi}{64}\,(D_o^2 - d_i^2)$ (for circular pipe) (10)

Where; D_o = outer diameter of pipe, d_i = inner diameter of pipe.

Hence; I = 1.3 X 10^{-5} m^2 and BL = 80MN

Using a factor of safety of 4 since it involves human well being;

$\text{Safe load} = \frac{buckling\ load}{factor\ of\ safety}$ (11)

Hence; Safe load = 20MN

Considering the angle of inclination the strut will buckle at a load of L = 20sin60^o MN.

Therefore, considering inclination Safe load (L) = 17MN.

II. Bicycle Seat Beam

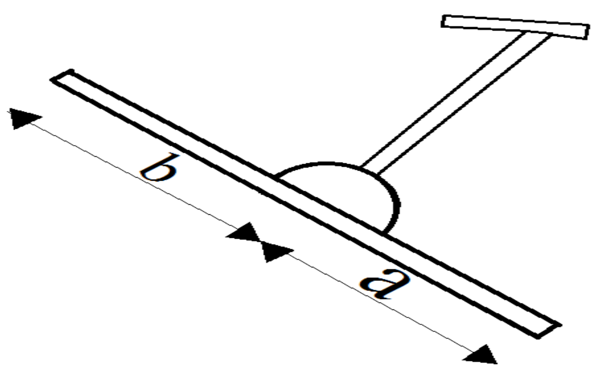

Fig. 5. *Bicycle seat beam*

The maximum allowable load on the bicycle seat (F);

$\sigma = \frac{YFL}{4I}$. (12)

Where; σ = maximum stress = 400MPa, 100MPa (n = 4) was employed, Y = perpendicular distance from neutral axis to outermost fiber = 0.0175m, L = length of the beam = 1m, I = moment of inertia = 5 x 10^{-8} m^4. Hence; F = 1143N.

Therefore, maximum load = 116.5kg.

Bending moment on the beam:

$M = \frac{Fab}{L}$ (13)

Hence; M = 285Nm, $V_1 = \frac{Fb}{L}$ = 594.36N and $V_2 = \frac{Fa}{L}$ = 548.64N

Maximum deflection on beam

$\delta = \frac{F a^2 b^2}{3EIL}$ (14)

Where; E = modulus of elasticity = 210GPa

Hence; $\delta = 2.3 \times 10^{-3}$m

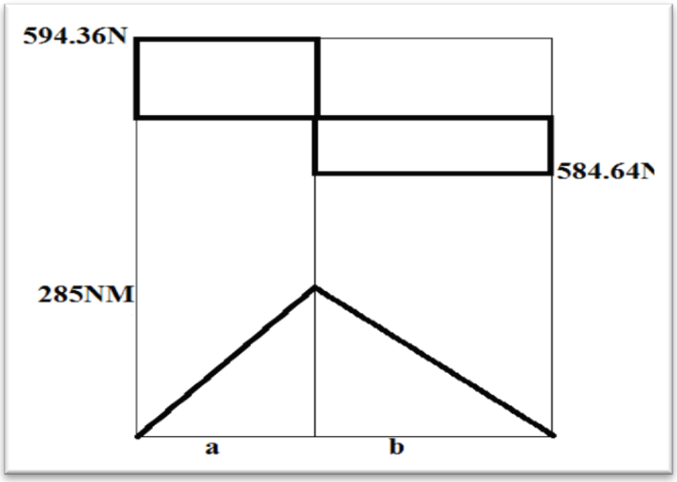

Fig. 6. *Bending moment diagram*

3.3 Required Torque and Resistance Generated by Dynamo

The pulley force required to rotate the pulley will surely add to the resistance force required to cycle the bicycle ergometer, the torque required to rotate the dynamo at an average cadence of 70rpm, is derived as shown;

Torque (T) = $\frac{60\,P}{2\pi N}$ (15)

Where; T is the dynamo shaft torque, N is the number of revolutions per minute, P is the output power of the dynamo. The rated rpm of the dynamo is 2600, power is 300W.

Hence; T = 1.1Nm

Therefore the resistance on the pedal crank:

$R = \frac{2T}{d}$ (16)

Where; d = diameter of the pedal crank pulley, R = resistance added to the pedal by dynamo = 6.47N and Equivalent mass = 0.66kg.

Therefore at maximum tension, the rider supplies a torque of 9.45Nm and thus overcomes a resistance of 65.33N which is equivalent to a mass of 6.66kg

3.4 Mechanical Advantage

Mechanical advantage is a measure of the force amplification achieved by using a tool, ideally the device preserves the input power and simply trades off forces against movement to obtain a desired amplification in the output force [8]. The ideal mechanical advantage (i.e. without considering losses due to friction and belt slip) is calculated as shown;

The ideal mechanical advantage (IMA) = $\frac{\text{load}}{\text{effort}}$ (17)

Where; Load = 48.89N; Effort = $\frac{\text{torque}}{\text{bicycle pedal radius}}$ = 6.47N

Therefore, the ideal mechanical advantage (IMA) = 7.6

3.5 Bicycle Ergometer Experiment

Healthy males and females of age between 15 – 60 years were used. The tension belt on the ergometer flywheel is tightened to the fullest and the rider is to cycle uninterrupted for 30minutes on the bicycle ergometer, the stopwatch is set to countdown from 60 seconds continuously for the cycle period of 30minutes. The cycling rate is counted by the instructor and recorded. The lowest rpm attained by the rider during the 30minutes exercise is obtained and then noted.

Table 4
Test results

Category			`Male	Female
S/N	Age (years)	Cycle Period (minutes)	Lowest Cadence (rpm)	Lowest Cadence (rpm)
1	15 – 20	10	50	40
2	21 – 25	10	55	40
3	26 – 30	10	56	43
4	31 -35	10	52	36
5	36 – 40	10	47	30
6	41 – 45	10	43	26
7	46 – 50	10	37	26
8	51 – 55	10	30	22
9	56 – 60	10	18	20

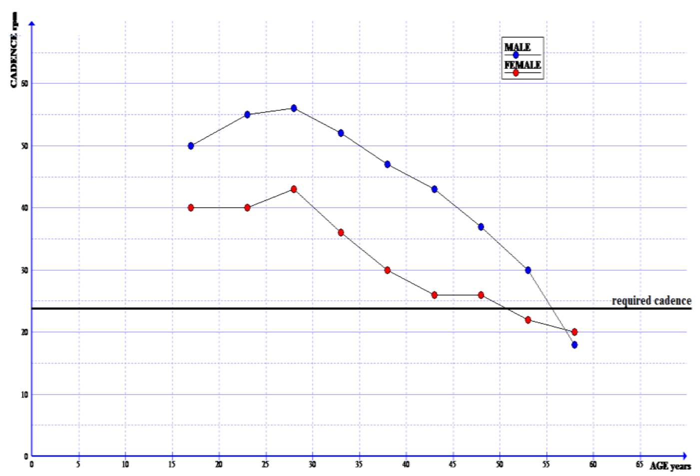

Fig. 7. *A plot showing the lowest cadence against the respective age groups*

Fig. 7 shows that the lowest cadence of majority of the age groups during the cycle period of 10minutes is well above the required cadence. The pulley selection gives a healthy velocity ratio and thus the dynamo pulley will rotate at a speed higher than its rated input and therefore the dynamo will deliver sufficient output most times when the regenerative bicycle ergometer is in use by various riders. The velocity ratio is thus 108.5

3.6 Transmission Efficiency

The regenerative bicycle ergometer converts mechanical energy to electrical energy, the machine was test run and the following was deduced.

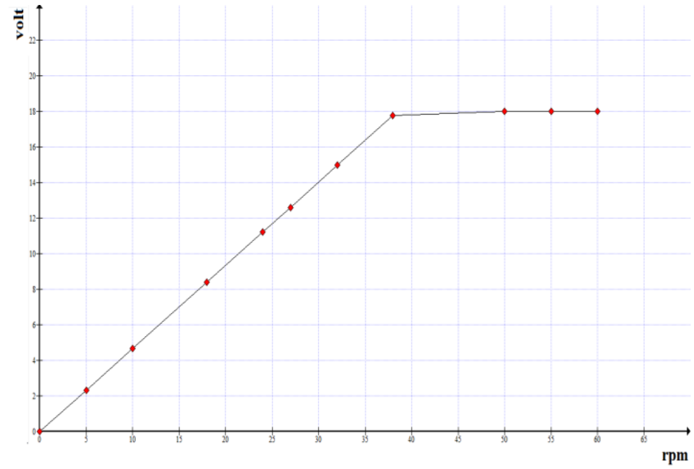

Fig. 8. *Voltage against rpm.*

From the specification, the required dynamo revolution required to produce 12.6 volts is 2600 rpm on the dynamo pulley. In the design, the cadence required to give an output of 2600 rpm on the dynamo pulley is 24rpm. After fabrication, the cadence producing the output of 2600 is 27rpm. This increment in the required cadence is as a result of losses due to slip. The fabricated regenerative bicycle ergometer has a transmission efficiency of 89%. From fig. 8 and referring to Eq. (6); 27rpm = K 12.6V. Hence, K = 2.14 which is the Grace Regeneration Factor

3.7 Regenerated Energy

It has been established that as long as the rider cycles at a cadence greater than 27rpm, the dynamo will give off sufficient voltage; on that note the power generated in by a cyclist in 30 minutes was calculated. For 30minutes of exercise with a cadence above 27rpm: 150W.h of power was generated or expended. When the cyclist generates 150W.h, it means that a single 15Watt energy saving bulb can be run for 10hours for 30minutes cycle with this regenerative bicycle ergometer. In a gym where the bicycle ergometer is used for an average of 5hours a day by different cyclists, it will yield 1.5 KW.h. This can power ten (10) 15Watt energy saving bulbs for 10 hours which will adequately lighten the gym hall or make do for security lights run overnight. 1.5KW.h can also power up a 100Watt industrial fan for 15hours. This energy is very substantial and should be conserved in the most efficient ways.

4 CONCLUSION

The designed and fabricated bicycle ergometer met all aims and objectives, as it performs the function of the bicycle ergometer and a clean power generating plant. The work done by the rider was successfully conserved, converted and stored. The uses of the regenerative bicycle ergometer are; Generation of clean electrical energy, Physical fitness development evaluation, to enhance weight loss, to counter cardiovascular, sports training, and physical therapy and functional movement testing. After the design and fabrication of this regenerative bicycle ergometer, attachments of digital system to increase the core functionality and user friendliness of the machine and installation of inverters so that the end product is alternating current are recommended.

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