Development and Performance Evaluation of a Leg and Arm Exercise Machine

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Abstract — *Elliptical cross trainer (leg and arm exercise machine) has become popular for cardio respiratory fitness training. They are found in almost every gym house, recreation centre and hotels in Nigeria, all of which are imported as new products or fairly used. The use and maintenance of these machines have been problematic due to abuse, poor maintenance, sophisticated technology, lack of spare parts which have declined the patronage of these products. Therefore this report describes the process of developing a prototype design of a leg and arm exercising machine which solves all the problems mentioned above without jeopardizing functionality and efficiency. This design is also a weight based resistance machine thereby reducing the cost, size, and weight of the machine. A performance evaluation was carried out to evaluate, rate the performance and efficiency of the machine. Results obtained shows this prototype machine can be rated better.*

Key Words — Leg, arm, elliptical, exercising machine.

I. INTRODUCTION

Exercise is defined as activities that result in contraction of skeletal muscle. The term is usually used in reference to any activity that promotes physical fitness. Although muscle contraction is the common element of all forms of exercise, many other organs and systems are affected, for example, the heart and lungs. Many people also found that regular exercise enhances their sense of mental well- being along with their general physical health (Meyer, 2008)

Today there is an increasing emphasis on preventive medicine, or maintaining health, partly as a result of the increasing costs of health care and greater awareness of the effects of lifestyle on health and longevity. While public interest in exercise and fitness has increased during the past 20 to 30 years, according to the United States National Centre for Health Statistics, in 1990 only 41 percent of adults 18 to 64 years of age reported that they exercised regularly, and only 32 percent of those over 65 years of age reported regular exercise or participation in physical sports. Over one- quarter of Americans (three-quarters by some standards) are significantly overweight and are at risk for a wide variety of health problems (Encarta, 2009).

Elliptical cross training is the newest and most popularexercise found in the finest health clubs in the world (www.buzzle.com, 2004). Elliptical trainers combine the natural stride of the treadmill and the simplicity of a stair climber. On an elliptical trainer, you stand comfortably in an upright position while holding onto the machine`s handrails and striding in either a forward or reverse motion.What makes an elliptical trainer unique is the ability to offer a weight bearing workout that puts minimal stress on the joints. Your feet never leave the pedals of an elliptical trainer, thereby eliminating any impact in your workout. Whether you go forward or reverse, and regardless of the level of resistance, there is a reduced risk of injury from overusing any one-muscles group.For individuals trying to burn calories and trim down, the weight- bearing arm/leg exercise optimizes energy expenditure during self- selected exercise of moderate intensity in overweight subjects. In recent studies it was concluded that energy expenditure among overweight subjects was higher on the elliptical machine than a treadmill, or leg cycles with and without upper body motion. For overweight individuals who are initiating a regular exercise program to decrease excess body fat, they will find that elliptical treadmills optimize energy expenditure.

II. LITERATURE REVIEW

Elliptical trainers first entered the market in the 1990s. A more compact elliptical trainer was invented by Larry D. Miller for precor and was patented in 2004. Miller created the idea for the machine by filming his daughter running alongside a car, while watching the motion of her legs. His idea was to take that exact motion and put it into a machine that puts less strain on the joints (www.buzzle.com, 2006).

Elliptical machines are relatively new to the exercise machine scene, but they have surged in popularity as more and people discover the benefits of elliptical workouts. Since they first appeared in the 1990s elliptical exercise machines have been studied carefully for safety and fitness effectiveness, and found to be a great way to get a total body workout without the need for multiple fitness machines. (www.patentstorm.us, 2004)

An elliptical trainer (also sometimes called a cross- trainer) is a stationary exercise machine used to simulate stair climbing, walking, or running without causing excessive pressure to the joints, hence decreasing the risk of impact injuries. For this reason, people with some injuries are able to use an elliptical to stay fit, as the low impact affects them little. Elliptical trainers offer a non- impact cardiovascular workout that can vary from light to high intensity based on the resistance preference set by the user. (www.buzzle.com, 2006)

Treadmills of Fig.1a and b are favourite exercising equipment of most gym lovers as they are easy to use. Many people who wish to lose weight can take the help of a treadmill. Treadmills are usually meant for walking, jogging and running (Altena, 2002).

Fig. 1a. Manual Treadmill

Fig. 1b. Powered Treadmill
Source: (www.fitnessequimentsite.com)

ELLIPTICAL MACHINES

The first elliptical machines to come on the market were quickly embraced by fitness enthusiasts all over. These early models worked the lower body quite thoroughly, but the upper body stayed stationary to handlebars that did not move. Before too long, exercise buffs began asking for upper body action as well, and the manufacturers of elliptical exercise machines responded (Pierson, 2008)

Now most elliptical trainers come with both lower body and upper body motions as a standard feature, with some offering handlebar motions and resistance that can help you get a truly intense upper body workout.

Most elliptical trainers work the user's upper and lower body (although some models do not have moving upper body components). Though elliptical trainers are considered to be minimal impact, they are an example of weight- bearing form of exercise. They can be self- powered by user- generated motion or need to be plugged in for adjustment of motion and/or supplying their electronic consoles and resistance systems (Pierson, 2008).

There are three types of elliptical trainers, categorized by the motor or "drive" location. The oldest elliptical design is the "rear drive" type. The "front- drive" elliptical was the second generation design. The latest technology is the "centre-drive".

On some models, the incline of sloping roller ramps beneath the pedal- links can be adjusted to produce varying pedal motion paths. The result of such adjustment changes the burdens on various muscle groups in the legs. Some models can vary the incline, resistance and stride length over the course of a workout according to a preset program. Some trainers can be driven in a reverse as well as in a forward direction. Elliptical trainers are primarily driven via the legs, and most are combination designs having handle- levers attached to each pedal- link for the purpose of enabling a burden on the arms to provide a secondary source of driving power. The user grips the handles below shoulder height and pushes/pulls them while shuffling the feet back and forth within their elliptically shaped paths. Thus the oscillating handle motions are dependently coordinated with the constrained pedal motions. Poorly designed machines are too dependent on the user's leg power, producing excessive handle speeds as a result of mechanical ratios that do not provide enough advantage to the handle- levers. Consequently such machines feel to the user as if his or her arms are simply going along for the ride, rather than sharing in the work. The better models offer a harmonious combination of arm and leg exercise in the correct ratios (www.buzzle.com, 2006).

FEATURES OF ELLIPTICAL MACHINES

The basic features of elliptical machines include the drive system, the resistance system and the stride length. Let's take a look at each of these separately.

i. Drive system

The two types of drive systems are front drive and rear drive. Front drive systems tend to be used on low- end elliptical exercise machines and can produce a motion that is somewhat rough and awkward. Rear drive systems are far superior, providing much smoother motion and greater user comfort. Rear drive can be found on elliptical trainers from the mid- range on up to the very high end of the market.

ii. Resistance system

There are three (3) main types of resistance systems used on elliptical machines today. Low- end machines typically have a manual system that the user adjusts by hand, but some low-end and most mid- range machines use a motorized brake system. High- end machines use an eddy current brake system, which is extremely reliable and smooth. (www.wikipedia.org)

iii. Stride length

The stride length on low-end elliptical exercise machines is typically set at the factory and is not adjustable by the user. Mid- range and high- end machines, however, typically offer an adjustable stride length adjustment system that provides maximum flexibility and customization options for the user (www.wikipedia.org).

ADVANCED FEATURES OF ELLIPTICAL MACHINES

There is an almost endless list of advanced features that can be found on elliptical exercise machines. The more expensive the model, the more sophisticated the features.Rhonda and Antony(2008) talk a bit about some of the most common panel advanced features and how they might vary from machine to machine.

i. Control panel

The control panel can be very simple and straightforward or it can provide the user with a wide variety of input, feedback, monitoring and guidance. They are typically electronic and run on batteries, which need to be replaced periodically.

ii. Programmability

Most elliptical machines are programmable in some way. They may be programmable for individual users and their preferences; they may come with standard pre- programmed workouts, or some combination of both options.

iii. Heart rate monitors

More and more machines today include some form of heart rate monitoring to help you stay in your optimum aerobic zone during your workout. Some monitor your pulse via special handgrips, while others use small clips that attach to your ear or wrist and connect back to the elliptical machine with a small wire or, increasingly, with a wireless connection (Browder and Dolny, 2002)

iv. Adjustable incline

Many elliptical machines feature an adjustable incline to help trainer workout more or less intense. Some adjust manually, while others adjust remotely via a small motor.

v. Adjustable stride length

A step up from the standard stride length is the adjustable stride length found on some mid- range and nearly all high-end elliptical machines. The adjustment of stride length is generally done manually (Wikipedia, 2007).

III. METHODOLOGY

A. Design Considerations

In order to achieve the aim objectives of this project, research was carried out on existing machine from which adoptable ideas, principles and mechanism were adopted and upgraded where possible. Autodesk applications such as Autodesk inventor and other necessary CAD applications were used for preliminary sketch of the various parts designed.Standard information such as anthropometric data as well as knowledge of human posture and repetitive motion were considered in order to achieve an optimized ergonomic design of the final product.

Principles of design for manufacture was employed at the design stage to safe cost and time and help simplify the fabrication procedure which was carried out at the central workshop of school of engineering and engineering technology, the federal university of technology, Akure, Ondo State, Nigeria using standard tool and techniques to ensure quality output.

Performance evaluation of the developed machine was carried out using a number of participants of various weights and taking their systolic blood pressures at regular intervals of using the machine. Results are tabulated and discussed in this report. Conformity to ergonomic standard was ensured by checking the safe use of the developed machine by different category of people.

The anthropometric information used for this design was centered on the body segment masses analysis of Fig. 2 and Table 1 by Huston, (2009)

B. Design Analysis and Calculations

Basically the leg and arm exercise machine consist of main frame, crank engine, leg rails, handle bars and foot pedals. The isometric and part list drawings of the arm and leg exercising machine are as shown in Fig. 3 and 4 respectively.

Generally the functionality and running condition of the machine depends on the following design components: Stride length; Crank radius; Strength and rigidity of the leg rails; Length and diameter of the hand bars; and the main frame.

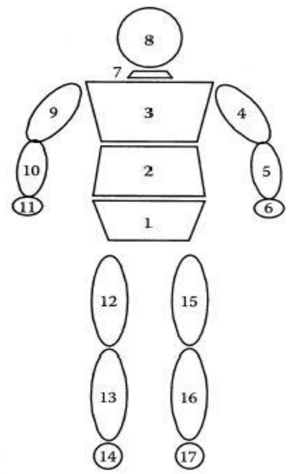


Fig. 2. Body Segment masses

TABLE I
BODY SEGMENT MASSES IN KILOGRAMS

	Body	Male			Female		
Name	segment	5th%	50th%	95th%	5th%	50th%	95th%
Lower torso (pelvis)	1	8.24	10.00	11.99	8.27	10.00	12.11
Middle torso (lumbar)	2	9.01	10.95	13.13	5.45	6.59	7.98
Upper torso (chest)	3	15.30	18.58	22.28	7.69	9.30	11.25
Upper arm	4, 9	1.84	2.23	2.67	1.41	1.71	2.07
Lower arm	5, 10	1.14	1.39	1.66	0.84	1.02	1.24
Hand	6, 11	0.43	0.52	0.63	0.34	0.42	0.50
Neck	7	1.48	1.80	2.16	1.20	1.45	1.76
Head	8	4.07	4.95	5.93	3.31	4.01	4.85
Upper leg	12, 15	6.96	8.45	10.13	6.22	7.53	9.11
Lower leg	13, 16	2.84	3.45	4.14	2.24	2.71	3.28
Foot	14, 17	0.85	1.03	1.23	0.71	0.86	1.04
Total		66.22	80.41	96.41	49.44	59.85	72.43

Fig. 3. Assembly drawing of leg and arm exercise machine.

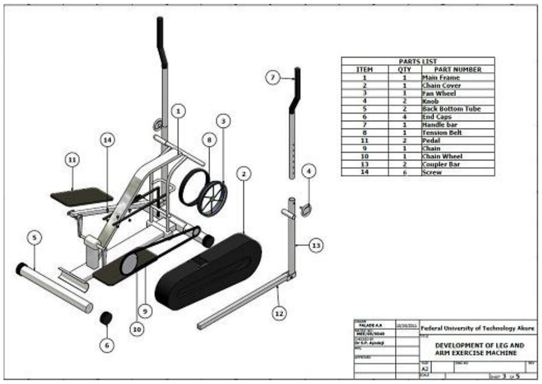


Fig. 4. Assembly drawing of leg and arm exercise machine.

LOWER LIMB STRIDE LENGTH DETERMINATION

Cochrane and Stannard (2005) concluded that stride length for manual force exertion should not be more than 550mm. A stride length of 500mm was chosen for this design in order to allow reasonable force exertion by hand simultaneously.

DETERMINATION OF THE CRANK RADIUS

In order to achieve a stride length of 500mm, the crank radius is calculated as follows;

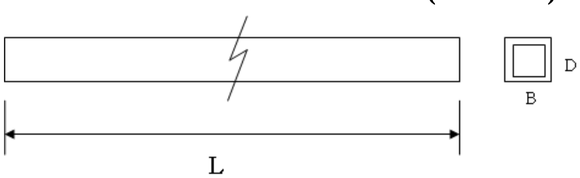
$\pi D = 2 \times 500$mm

Where D is the crank diameter, and

$D = 318.31\ mm$

Crank radius, R= 159.15mm≈ 160mm.

STRESS ANALYSIS OF THE BEAM (LEG RAIL)



Moment of Inertia,

$$I = \frac{BD^3}{12} - \frac{bd^3}{12} \qquad (1)$$

(Khurmiand Gupta, 2006)

I =5148.16mm^4

Maximum stress,

$$\sigma = {YFL}/{4I} \qquad (2)$$

(Khurmiand Gupta, 2006)

Where σ = maximum stress (N/mm^2)

Y = perpendicular distance from neutral axis(mm)

F = load (N)

L = length of beam (mm)

I = moment of inertia (mm^4)

$\sigma = \frac{12.7\times965\times760}{4\times5148.16}$ = 452.31 N/mm^2

Maximum deflection,

$$\delta = {FL^3}/{48EI} \qquad (3)$$

(Khurmiand Gupta, 2006)

Where δ = maximum deflection

F = load (N)

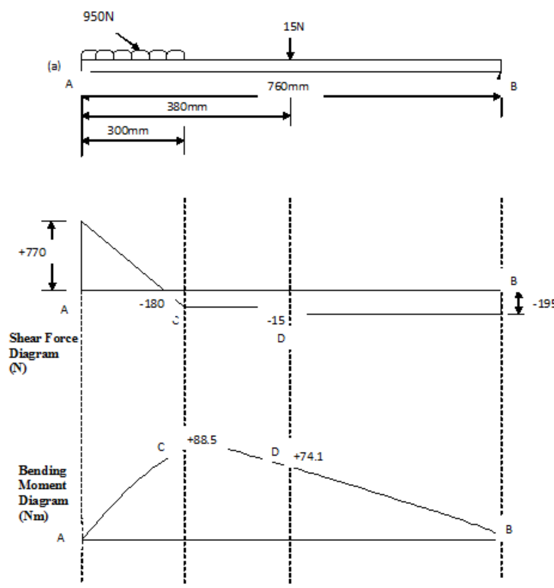
L = length of beam (mm)

I = moment of inertia (mm^4)

E = modulus of elasticity (N/mm^2)

$\delta = \frac{(965\times760^3)}{(48\times200000\times5148.16)}$= 8.57mm

SHEAR FORCE AND BENDING MOMENT DIAGRAM OF THE LEG RAILS



Determination of the reactions R_a and $R_{b;}$

$\Sigma fy = 0$ (4)

$R_a + R_b = 950 + 15$

$R_a + R_b = 965N$ (5)

$\Sigma M_b = 0$ (6)

$760R_a - 950\times610 - 15\times380 = 0$

$R_a = 770$ N

Using Equation (5)

R_b= 195N

Determination of shear force values

F_A = 770N

$F_C = 770 - 950 = -180N$

$F_D = -180 - 15 = -195N$

$F_B = -195 + 195 = 0N$

Determination of the bending moment values

M_A = 0 Nmm

$M_C = 770\times300 - 950\times150 = 88500$ Nmm (88.5Nm)

$M_D = 770\times380 - 950\times230 = 74100$ Nmm (74.1Nm)

$M_B = 770\times760 - 950\times650 - 15\times380$

$M_B = 585200 - 579500 - 5700 = 0$ Nmm (0Nm)

DETERMINATION OF HANDLE BAR DIAMETER

Huston (2009) compared literature sources and concluded that a handle for manual materials handling should be at least 115mm long, be 25 to 38mm in diameter and have a hand clearance of 30 to 50mm. Handles with diameters of 10, 30, 50 and 70mm were tested for torque differences in a gripping and turning action. The optimal handle size was found to be 50mm for both male and female subjects. Handle diameters in the range 30 – 50mm were found to be better than "too small or too large ones". For grip force, Wakker (1994) investigated handles with diameters ranging from 25 to 51mm and found that a cylinder with a diameter of 32mm enables the largest force exertion.

DETERMINATION OF CHAIN'S PITCH

Sprocket parameters are:
Radius of driving sprocket, r_1 = 100mm
Radius of driven sprocket, r_2 = 40mm
Number of teeth on the driving sprocket, T_1 = 36
Number of teeth on the driven sprocket, T_2 = 18

$$r_1 = \frac{p}{2} cosec \left[\frac{180}{T2}\right] \quad (6)$$

(Gupta, 2007)

$$0.1 = \frac{p}{2} cosec \left[\frac{180}{18}\right]$$

p = 0.0347m = 35mm

LENGTH OF CHAIN

L = $p \times$ k
Where $p =$ pitch of the chain = 35mm
K = multiplier factor which is defined by Gupta, (2007) as:

$$= \frac{T1+T2}{2} + 2m + \left[\frac{cosec\left[\frac{180}{T1}\right] - cosec\left[\frac{180}{T2}\right]}{4m}\right]^2 \quad (7)$$

m = $\frac{X}{p}$ where x = centre to centre distance between the two sprocket = 510mm
∴m= 14.57 and K ≈ 56.15
Therefore the length of the chain,
L = 1965.25mm ≈ 2m

VELOCITY RATIO OF THE CHAIN DRIVE

The velocity ratio of a chain drive is given by Khurmi and Gupta (2006) as:

$$V.R. = \frac{N1}{N2} = \frac{T2}{T1} \quad (8)$$

Where; N_1 = speed of rotation of the smaller sprocket (rpm); N_2 = speed of rotation of the larger sprocket (rpm); T_1 = number of teeth on the driving sprocket; and T_2 = number of teeth on the driven sprocket.

∴V.R. =2

FABRICATION

The stepwise process taken in the development of the leg and arm exercising machine are;marking out, cutting, machining, joining and fastening, welding, grinding and painting.The assembly of the components followed the under listed pattern:

i. cutting of the longitudinal bar to the designed dimension on which the whole body of the leg and arm exercise machine will stand.
ii. weldment of the two transverse tubes to the end of the longitudinal bar which forms the base section for the design work through the use of an electric arc welding machine.
iii. the structural strong main support bar which runs the base longitudinal bar is reinforced with two bent galvanized steel pipe and welded to the base frame to form the pivot for the handle bars.
iv. galvanised steel pipes of ¾ inch were cut and bent to form the handle bars and coupler bars.
v. an inch square pipe was cut, drilled and machined to form the leg rails.
vi. the bicycle crank engine waswelded to the main frame.
vii. cutting and weldment of metal sheet to form the desired cover case.
viii. grinding and painting were done to give the work a good finishing.

Pictures showing the developmental stages of the fabrication of the leg and arm exercise machine and testing are displayed in the appendix column.

PERFORMANCE EVALUATION OF THE MACHINE

The performance evaluation is carried out to know the functionality of the machine by investigating the heart rates and energy expenditure of participants who used the machine.

Ten (10) randomly picked male participants between the age of 25 and 40 were invited to take part in this study. The health status of each participant was ascertained by the physical activity readiness interview carried out by community health worker who assisted in this study. Full consent of participants was received prior to the test.

The participants were instructed not to engage in strenuous exercise for 24 hours before testing, to refrain from big meal within 2 hours of testing section, and to wear comfortable clothing and sports shoes for testing. Before the test, subject's body weight, height, BMI and resting heart rate were measured. The target heart rate was then calculated. Two (2) minutes warm up was providedduring which instruction on how the test was going to be carried out were explained to the participant and it was also time for them to experience the machine.

When the test started, subjects' age, height, weight and resting heart rates were entered into the data collection form for the estimation of Body Mass Index(BMI) and target heart rates. Heart rates were measured and recorded every six (6) minutes throughout the thirty (30) minutes main exercise duration, while energy expenditures were calculated along side.

RESULTS AND ANALYSIS

Table 2 gave a clue on the physical characteristics of the participants used in carrying out the performance evaluation while Table 3 displays the reading results got during the exercise undergone by the ten (10) participants.

TABLE 2
PHYSICAL CHARACTERISTICS OF PARTICIPANTS

s/no	Age (yrs)	Height (m)	Weight (kg)	BMI	Resting HR (bpm)	Target HR zone
1	26	1.70	80	27.7	69	130 - 175
2	32	1.72	82	27.7	71	130 - 170
3	35	1.69	70	24.5	72	130 - 170
4	29	1.64	68	25.3	74	135 - 175
5	30	1.75	85	27.8	70	130 - 170
6	35	1.73	82	27.4	72	130 - 165
7	40	1.73	78	26.1	72	125 - 165
8	26	1.66	64	23.2	73	135 - 175
9	25	1.71	66	22.6	71	135 - 175
10	33	1.74	86	28.4	70	130 -170

TABLE 3
COLLECTED READINGS DURING EXERCISE

Participants	HR Readings At Time Intervals (Bpm)							Average	EEE
s/no	(RHR)	2 min	8 min	14min	20 min	26 min	32min	HR(bpm)	(Calories)
1	69	92	103	128	140	149	139	131.80	290.60
2	71	89	98	131	145	152	148	134.80	314.14
3	72	92	104	138	145	159	155	140.20	335.14
4	74	90	100	129	138	147	150	132.80	291.69
5	70	96	103	145	143	147	148	137.20	324.05
6	72	97	110	142	140	148	148	137.60	331.15
7	72	93	105	151	150	150	148	140.80	350.26
8	73	88	95	120	161	155	154	137.00	303.76
9	71	89	110	155	155	158	156	146.80	347.94
10	70	90	102	138	141	142	141	132.80	309.13
	70.4	91.6	103	137.7	145.8	150.7	148.7	------	------

Key: HR – Heart Rate; RHR- Resting Heart Rate; bpm – Beats per minute; EEE – Estimated Energy Expenditure

After which, the estimated energy expenditure was calculated using Equation 9 (Allan, 2011) and the time for heart rate during the exercise are shown in Fig 5.

$$EEE_{male} = (0.2017A + 0.1992W + 0.6309H - 55.0969) \times \frac{T}{4.184} \quad (9)$$

Where, A = age (yrs)
W = weight (kg)
H = average heart rate (bpm)
T = time (min)

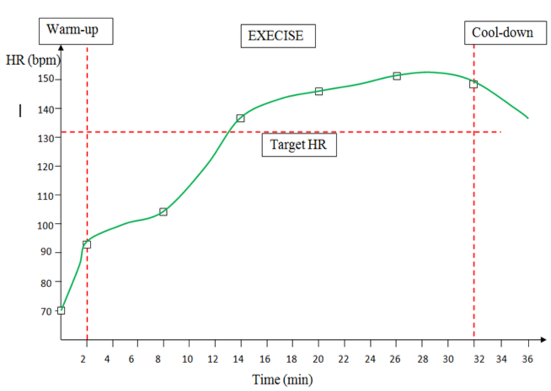


Fig. 5. Time course of heart rate (HR) during the exercise sessions.

From Fig. 5, vertical dashed lines show how each session was organized: *warm-up* (2 min), *exercise* (30 min), *cool-down* (4 min).

And results show that all the participants were able to attain the target heart rate zone, which implies that maximal energy expenditure was achieved during the work out. Participants who are familiar with exercise and elliptical trainer were able to reach target rates within the first 12minutes and were able to achieve maximal stride rates.

IV. COST OF PRODUCTION

Cost accounting is simply the collection of the cost of individual components (cost of material, manufacturing and cost of labor) are put together in order to determine the overall total cost of the product. The cost accounting for this project is outlined in Table 4 to 7 and the total cost of production including the other variable cost (vis-a-viz: transportation and miscellaneous) amounted to $40, thus making the cost of production of the machine to be $268 (US dollar).

TABLE 4
COST OF BOUGHT-OUT COMPONENTS (A)

S/N	Name	Specification	Quantity	Unit cost ($)	Total cost ($)
1	Chain	Bush roller chain	1	3.5	3.5
2	Complete crank engine	Adult	1	40	40
3	Rolling contact bearing	2mm diameter	50	0.5	2.5
4	Foot pedal	Adult	2	1	2
5	Smaller sprocket with wheel	20 teeth non reverse	1	4	4
				Total	52

TABLE 5
COST OF MATERIALS (B)

S/N	Name	Specification	Quantity	Unit cost ($)	Total cost ($)
1	Galvanised steel pipe	¾ inch	1	6	6
2	Mild steel rectangular pipe	Adult	1	15	15
3	Mild steel plate	1mm	1	20	20
4	Electrode	E13	1	9	9
5	Cutting disc	-	1	3	3
6	Grinding disc	-	1	3	3
7	Bolts, nuts and washers	Varies	-	2	2
8	Paint	Aerosol	-	18	18
				Total	76

TABLE 6
COST OF MACHINING JOBS (C)

S/N	Material	Type of machining	Machine used	Cost ($)
	Angle bar, cover case and galvanized steel pipe	Drilling	Hand Drilling Machine	3
			Total	3

TABLE 7
COST OF MACHINING JOBS (D)

S/N	Job	Machine used	Cost ($)
1	Welding	Arc welding machine	17
2	Labour	Manpower	80
		Total	97

V. CONCLUSION

Conclusively, this leg and arm exercise machine can be rated like any other (imported) elliptical cross trainer. The design has solved problems of difficulty of maintenance and repair of the leg and arm exercise machine in Nigeria, without jeopardizing functionality and efficiency. This design can be used as a prototype for designing/developing other leg and arm exercising machine which could serve as a source of income for intending producers of the machine. For further design, I recommend that subsequent design should include a tachometer to count the number of revolution and a heart rate monitor to display the user’s heart beat rate while exercising.

APPENDIX

Pictures Showing the Developmental Stages of the Fabrication of the Leg and Arm Exercise Machine and Testing.

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BIOGRAPHIES

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