DEVELOPMENT OF AN EXERCISE EQUIPMENT BASED UPON COMPLIANT CONSTANT FORCE MECHANISM TECHNOLOGY

The present health challenges in our community such as diabetes and high blood pressure could be prevented by regular exercise. Lack of regular exercise and unavailability of exercise equipments lead to ill health problem. There is a need to design exercise equipment that reduces fatigue in our body. The development of exercise equipment with lesser weight and low assembly cost and time will help in reducing the health challenges. The equipment is designed with application of Compliant Constant Force Mechanism (CCFM) technology and fabricated using local available material. CCFM technology helps in reducing assembly time and cost. The design principle involves elasticity of the flexible element “spring steel” which produces a constant force with set of defined principle such as kinematic, lagrangian and strain-energy analysis. The study requires design of muscle load ranges between 5 to 15kg which are classified as pennate and non-pennate muscle. It was observed that pennate muscle produces high constant force. However, the muscle group for both pennate and non-pennate within the range of 1-5kg are appropriate load for the designed equipment because of better equipment efficiency when applying the load. The velocity ratio between muscle load and CCFM element was 1.3:1. The maximum compliant constant force was 9045 N. The minimum possible compliant force was 13.24N with minimum stored potential energy of 2.46J. The equipment’s efficiency was determined to be 61%. The equipment is required to be used for muscle below 6kg within 10 to 18 cm of muscle length. The use of the equipment will improve health-condition of a normal body.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

The process for designing equipment is by engineering planning approach for meeting a specific purpose in a given society. The initial stage of designing engineering function is through planning and also through identification of a need. Synthesis (mechanism), analysis of forces, material selection, and design of elements, modification, detailed drawing and production of the designed elements is steps for fabricating equipment based on defined function (Khurmi and Gupta, 2003).

There is necessity in different homes in Nigeria to have exercises/strengthening or training equipment for having a good health. Hence, there is important need for developing such strengthening training equipment and this present study support development. According to Brown (1996), daily strength training or exercising of about an hour is necessary to improve overall health and quality of life and also to elongate human life span. Exercising activities may include aerobic activity like biking, walking etc. To train using this type of equipment is far from improving strength but also to gain good health. Therefore, daily training of exercise will minimise ailment such blood pressure and some other diseases. Exercising also causes fat reduction through using strengthening equipment. The reduction of calories is which also called burning of calories will be experienced. This leads to increase in temperature and rate of metabolism in our body. The exercising is also help to strengthen bone and production of glucose. There should be time for exercise in different in Nigeria because most people do not consider training or exercise as very important. Therefore, physical body fitness are required for staying strong and healthy (Wescott, 1996).

In the present study the need for exercising equipment arise to combat the effect of health hazards caused by lack of exercising in our community. However, the design mechanism adopted in the study for fabricating the exercise equipment iscompliant constant force mechanism (CCFM). The compliant constant force mechanism (CCFM)is based on modified elements configuration technologydevelopment and Design for No Assembly(DNA).The advantage of compliant mechanisms(CM) is the reduction in the total number ofparts required to accomplish a certain task. CMhelps in reducing manufacturing and assembly time, cost and it may be used to fabricate the designed product as one piece. This kind of design has been given a new name recently, which is “Design for No Assembly” (DNA). DNA is a design principle in which different machine component are used to perform motion function based on CM (Ugwuoke, 2011, Howell, 2001, Kotar and Sridhar, 2005).

1.2 Statement of the Problem

Quitea number of individuals die every month due to lack of exercise in our society. It is as a result of bad attitude and negligence towards strength training. Government’s effort to achieve an excellent reward in health sector through ministry of health in Nigeria during the past years is weakening. Different localities faces different environmental hazards in Nigeria and it is because variance in economic and social growth within each localities. The environmental health hazards are due lack of low financial strength in each home, poor shelter conditions, bad sanitation services habit and lack of good water. As a result there will be increases of different kind of illness which causes untimely death in our society. Increase in number of industry and agricultural sectors have sharply increased the exposure of industrial workersand large segments of the population to these risks of health hazards in our society. The society faces health hazardsthat are being associated with lack of good environmental sanitation services. This has endangers the society and poses threat such as malaria and typhoid and this resulted from poor personal hygiene. There is malnutrition due to excessive intake of unhealthy foods, leading to physical harm. Poor sanitation services especially in Nigeria homes have affected aged people, infants and lactating/pregnant mothers. There will be loss of lower muscle strength in the aged due to lack of exercising. Therefore, strength training is an important contributing factor in physical health of elderly people (Benjamin, 2005). Solving health related hazards in society due to lack of exercising requires affordable exercise facilities. However, there are none sophisticated strengthening equipment provided by government of Nigeria for the poor due to economy growth and therefore solving issues of health by individual gives room for personal hygiene development. Designand development of exercise equipmentwhich could be used at homewould relatively solve health relating hazards in the society.

1.3 Significance of the Study

Therefore there is the need for developing exercise equipmentthat reduces equipmentdesign factor such as wearing,backlash and total mass in kilogramme, production time and cost with better maintenance programme. Improving on design factor will help in producing exercise equipment with aesthetic design that meet people desire. Therefore production cost would be reduced because of reduction in total weight of the produced equipment. With the use of this type of exercise equipment for regular strength training, vulnerable disease would be prevented from erupting in our society. The vulnerable disease like diabetes, high blood pressure, strokes etc could be prevented by regular exercise. Diabetes contributes excess weight through production of cells that more resistive to body insulin. The strength training or exercising helps in prevent any kind of symptoms that will lead body breakdown or sickness. Lack of strength training may lead to high blood pressure or hypertension. The hypertension resulted to stroke or various related diseases because blood pressure increases with age in human or sometimes body weight gained. Risk of lining in uterus or cancer increases infertility in woman, joint problems; back pains are well known in Nigerian adults. Strokes are common in Nigerian aged people. Most strokes are caused byreduction of arteries passage and this lead to heart diseases. Day to day exercise reduces the effect of the vulnerable disease to minimal. Regular exercise would motivate and inspire the society as an effective tool for engaging and empowering individuals and communities for improving and funding health facilities. Sporting is a powerful means of mobilising more resources in the global fight against disease, but this as a potential just beginning to be realised. To prevent obesity, heart disease, blood pressure, cancer, depression, panics attack etc; exercising equipmentis one of the sporting tools required. Thus, it is important to increase initiative for developinglocal made exercise equipments. The equipment is designed with CCFM technology and it is cheaper to fabricate. The equipment would help to reducehealth hazards in our rural and urban area. The study tends to design and fabricate an exercise equipment to curtail health hazards in our locality.

1.4 Aim and Objectives of the Study

The aim of the study is to develop exerciseequipment that makes use of CCFM technology. The objective of the study is as follows:

i. designing of the exercise equipment

ii. fabrication of the equipment

iii. testing of the equipment

1.5 Scope of the Study

The scope of the study is to design, fabricate and test exercise equipment which based upon compliant constant force mechanism (CCFM) technology. The synthesis involves analysis of forces. The principle is capable of generating designs from well defined sets of constraints and boundary condition using strain energy analysis. The elasticity of the flexible segment is determined energy theory.

CHAPTER TWO

2.0 REVIEW OF THE LITERATURE

2.1 Role of Design and Manufacturing in Nigeria Economy

The design and manufacturing industry has contributed greatly to economic development and growth in the developed world. Therefore, design and manufacturing must see as developing tool for economic development in developing world such as Nigeria. To achieve special development in relation to design and manufacturing sector there must be plan and a process to activate the plan. However, development of exercise equipment is a need that is activated by plan and this will contribute to national development. Exercise equipment is a private facilitythat it is being used for residential purpose (Moavenzadeh and Rossow, 1976).

Exercise equipment will help as a catalyst towards developing our nation through physical fitness and development of its technology. However, development of exercise equipment is a technology that will help in growing our technology as a nation. This type of technology will support others local technology in industrial and agricultural sectors (Aderoba, 2000). As an innovation in local technology development, exercise machine will help to reduce importation of foreign exercise machine.

Technology has a wide range of definitions; nevertheless, it is a term traceable to “techne” which means activities by which man seeks to adapt to his environment. Technology is a scientific knowledge, used in practical ways, especially in the designing of new equipments. Science and technology is needed power to instrument changing for booming development of economic, social, and culture for standard living, better health services and educational facilities. Technology is transformation of a theoretical idea to a practical skill in order to produce the objects of one's need.

Engineering development of a country depends on some of the following factor (Aderoba, 2000):

i. standard of industrial output or exportation of local technology such as machines both residential and non-residential type
ii. standard of energy production in Mega Watt (MW) because this will lead to high turning output of local production
iii. standard of transportation development such as railways, ports and vehicle roads
iv. standard of research and development because will contribute to innovation and invention of existing local technology
v. level of access to information technology which is access recent development in telecommunication
vi. Development of public facilities such as health facilities, recreational and sporting facilities. The facility may include stadium, sports equipment, theatres and tourism parks.

2.2 Compliant Mechanisms Technology

According to Shuib, Ridzwan and Kadarman(2007), rigid-body mechanisms are traditional types that have various members function implementation. The rigid-body mechanism has wearing, backlash, huge weight and high assembly cost and time as disadvantages. The use of rigid-body mechanism has also faces the need for regular maintenance because there is a need for performance with good stability of mechanism. In the recently several technology has been developed that reduces the effect of disadvantages of wearing, backlash, huge weight and high assembly cost and time and one of them is compliant mechanism technology. The technology has been applied in robotics, biomedical, machine tools, transportations-components and adaptive structures. But there is difficulty in designing tools using compliant technology mechanism. Two (2) methods is known for analysing and designing compliant mechanism and they include:

i. kinematics analysis
ii. structural optimisation analysis

According to Sevak and McLarnen (1974), compliant mechanisms are flexible link mechanisms, which gain some or all of their motion through the deflection of flexible members. These mechanisms can be fully compliant or partially compliant. A fully compliant mechanism is one that has no rigid body joints. A partially compliant mechanism is one that has some compliant members and some non-compliant joints (Wittwer, 2001). According to Ugwuoke (2008), developing of compliant mechanism (CM) design technology is recognised as a need. Constant force compression spring (CFCS) is an application of CM that produces a same force based on wide range of displacement as input (Ugwuoke, 2008).

The compliant mechanisms are applicable in different engineering function but it is based on constant output force with wide range of displacement as an input. The compliant mechanism could be based on slider as displacement component with constant resultant force as output. It is not like linear spring in which applied force increases as displacement increases. However, the applied force of compliant mechanism remains same as displacementsincreases (Ugwuoke, 2008). Methods such as Finite Analysis, chain algorithm analysis and elliptic integrals method and chain algorithm method face recent competitionof using compliant mechanism as a computational analysis. The computational analysis of compliant mechanisms (CM) design and simulation is based on principle of pseudo-rigid-body (PRB) modelling technique.The pseudo-rigid-body model (PRBM) has been developed for its analysis (Ugwuoke, 2008).

This method gives support to rigid-body analysis for helping to analyse compliant mechanism (Salamon, 1989). Complex and other nonlinear deflection such as beam deflection is well analysed using PRBM (Howell, 2001). PRBM has also help to analyse motion of energy storage components with better output (Ugwuoke, 2008; Opdahl, Jensen, and Howell, 1998).

2.3 Advantages of Compliant Constant Force Mechanisms (CCFM)

According to Frecker, Kota and Kikuchi (1999), a compliant mechanism can be defined as single-pieceflexible structure, which uses elastic deformationto achieve force and motion transmission. Howell (2001) also states that CCFM generates its motion from the relativeflexibility ofits members rather than from rigid body joints alone. This mechanism has built-in flexible segments which aresimpleto replaceits multiple rigid parts, pin joints andadd-on springs(Shuib, Ridzwan and Kadarman, 2007). Therefore tends to save product space andreduce costs of parts, materials and assembly labour.The advantages of compliant mechanisms include:

i. cost reduction because of part-count reduction, reduced assembly time, and simplified manufacturing processes
ii. increased performance due to increased precision, increased reliability, reduced friction and wear, reduced weight, and reduced maintenance
iii. require no assembly
iv. require less space and are less complex
v. have less need for lubrication
vi. integrate energy storage elements (springs) with the other components

CCFM are designed as in single-piece that could replace rigid-link mechanisms. Manufacturing of product with CCFM is possible through the following processes (Howell 2001):

i. injection molding,
ii. extrusionand rapid prototyping for medium size devices
iii. silicon surface micromachining
iv. electroplating techniques

CCFM has numerous advantage but difficult to design andanalyse but the analysis can be done using Finite Element Method (FEM) for performance (Frecker, 1997).

2.4 Leverage Mechanism and the Governing Laws

A mechanism is defined as "a device for the coupling and transforming of energies" (Hall, 1953). When a lever is used to bring about inputting force to a favourable output force, it is called a leverage mechanism. The law that control a leverage mechanism are both law of energy conservation, force and moment balance equation. In an ideal situation (a rigid lever arm without bending and a perfect pivot with free rotation or rigid support), the moment with respect to the pivot point should be balanced, $F_{in}L_{in} = F_{out}L_{out}$, while the lever is statically balanced. The mechanical work done by the input force should equal to that done by the output force,$F_{in}\delta_{in} = F_{out}\delta_{out}$, out if no strain energy is consumed at the pivot or by bending of any flexure beam. For a compliant mechanism the input energy should be equal to the output energy plus the elastic bending energies of the flexible components.

Where;

F_{in} = input force

F_{out}= output force

L_{in}, L_{out}= length between the input and output for the i^{th} lever arm

$\delta_{in}, \delta_{out}$= deflection corresponding to length of lever arm

When a lever is used to perform a function, a trade-off is made between the force and displacement. For example, to lift an object to a certain height, a greater force is needed to move a shorter distance while a smaller force is needed to travel a longer distance.

2.4.1 Compliant Leverage Mechanisms

According to Su (2001), similar to its wide range of applications in the macro-world, levers have been widely used in micro-electromechanical systems (MEMS), and are called micro-leverage mechanisms. With current micro-fabrication technology constraints, a micro-leverage mechanism is produced using planar flexures through mechanical transformation of its elastic bending members. This group of micro-leverage mechanisms is also called compliant micro-leverage mechanisms.

Compliant micro-leverage mechanisms can bring about an input such as force to an output force to gain advantages on its mechanism. The mechanism advantage includes mechanical/ geometrical advantage in MEMS, such as changing force directions between pushes and pulls and amplifying force or displacement. For example, in the case of an actuator a leverage mechanism can attenuate the force and the displacement generated by the original actuation mechanism to a desired output. Other applications include magnifying inertial forces in inertial sensors such as micro-accelerometers and gyroscopes to increase sensitivity, amplifying the tensile force in tensile testing equipment, and tuning a micro-resonator.

Similar to the role of the operational amplifier (common-source amplifier and multi-stage amplifier) in microelectronics, micro-leverage mechanisms (single- and multiple-stage) are mechanical amplifiers in MEMS.

2.4.2 Classifications of Compliant Leverage Mechanisms

A compliant leverage mechanism consists of four major parts as follows (Su, 2001).

i. input mechanism
ii. lever arm (rigid part),
iii. pivot,
iv. output mechanism

Positioning of pivot will based on input and the output mechanism type to be used as a lever arm that serves as leverage mechanism. There are three kinds of leverage mechanisms. The first-kind is defined by the pivot lying between the input and the output. When the output lies in the middle of the pivot and the input, it is second type of lever. If there aretwo lever arms of as second lever at any joint such as hinge, it is called a double second typelever. A third-kind lever is defined by the input placed between the pivot and the output. The third-kind lever is used to amplify displacement. A second-kind lever is mainly for force amplification.

A first-kind lever can be used for either force or displacement function which depends distance in between the input and the pivot and the distance between the output and the pivot. If arms of two third-kind levers join together as in the case of a pair of tweezers, the leverage component or mechanism is called a double third type lever. The compliant leverage mechanisms are sub divided into two as follow:

i. S-type: This type has output mechanism and pivot mechanism on same lever arm

ii. D-type: This type has output mechanism and pivot mechanism on different lever arm

A single-stage leverage mechanism is known with code number such as 1, 2 or 3with a given lever type as an identification. The identification letter (S or D) is followed by number 1, 2, and 3 as subtype for instance, 2S, 2D and 3S. A compound leverage mechanism or multiple-stage leverage mechanism is formed by stacking multiple stages of lever together. Different kinds of levers can be stacked together. If individual single-stage levers are properly configured, their amplification factors will be multiplied. In a compound leverage mechanism, each lever stage needs to be identified for reference.

There are major two kinds of classifications:

i. Downstream classification (from output to input) and upstream classification (from input to output).

ii. In the downstream classification, the one connecting to the output system is called the first-stage, then the second-stage, until the input system.

In the upstream classification, the one connected to the input system is called the first-stage, and the one connected to the first-stage is called the second-stage, and so on till the output system. In this thesis, the downstream classification is used for the force amplification leverage mechanism. The upstream classification method is used for the displacement amplification leverage mechanism. A lever is used to trade a force with distance, or vice versa, to make a job function "easier" to do. The L/l value is called the lever ratio where L is the distance between the input and the pivot and l between the output and the pivot (Su, 2001).

2.5 Designs for Manufacturability

According to Salvendy (2001), the primary goal of functional design is to incorporate manufacturability into design in early stage. Design for manufacturability will help to design a product that attract customer within competitive environment. Based on requirement, customer requires a product that has aesthetic design with more reliable, maintainable and fashionable. Quality product is design to have reasonable impact on the customers' needs within a given time.

Some principles are known if equipments products are to be designed for manufacturability and they include (Salvendy 2001;Bralla, 1986 and Stillwell, 1989).

i. Simplifying and improvement for assembling of product
ii. Meeting functional requirement and needs of designed products
iii. The use of group technology for functional design
iv. Material are to be selected based on quality and cost
v. Design for easy and maintainability is necessary to maximise the value added in each setup.

2.6 Equipment Design Using CAD

According to Godfrey (2011) states that performance can be achieved in machine if design is well articulated through application of Computer Aided Design (CAD) as computational modelling before manufacturing. The efficiency of the produced manufactured products is based on better overall tasks. CAD functions are used in design modelling as follows:

i. geometric modelling,
ii. engineering analysis calculations,
iii. automated evaluation

iv. automated drawing

Kutz (2006) gives relationship between design process, a four stages approach and CAD technology and the final four stages of the design process (Kutz, 2006).

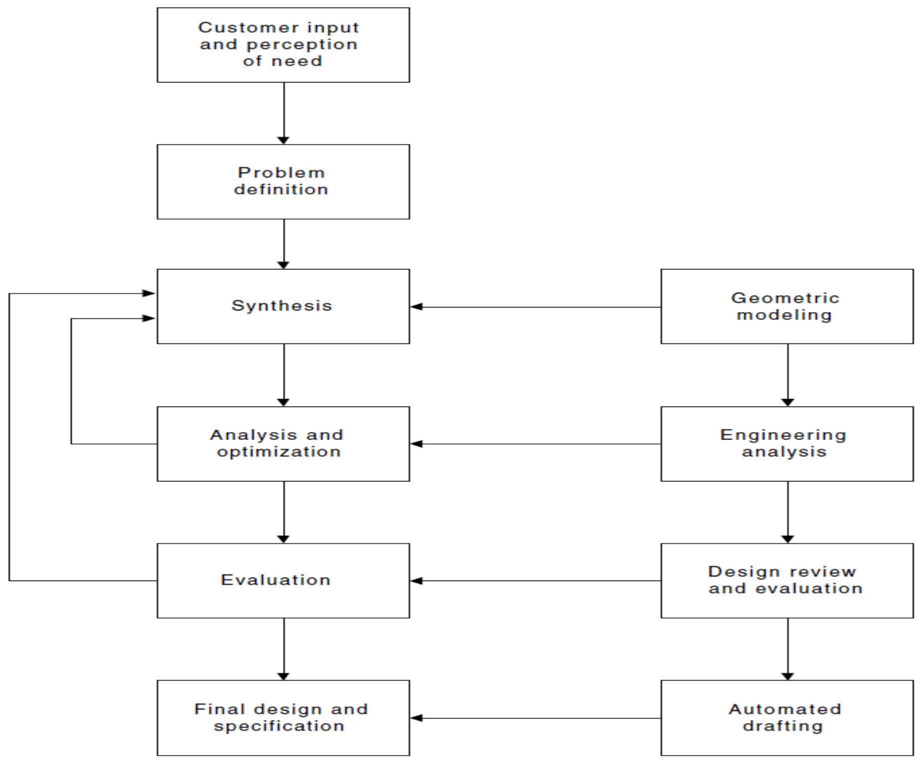

Figure 2.1: Design Process Review (Kutz, 2006)

2.7 Optimum Design Analysis

Engineering design is an iterative process, aiming at the best possible result. If the first design is not satisfactory further modifications are to be carried out till the best performance is obtained. This is known as the design process optimisation (Vijayaraghavan and Vishnupriyan, 2009).

2.7.1 Optimization Applications

The design is more complex when using unreliable tools. In past decades using of Finite Element Analysis (FEA) becomes necessary tool for identifying and design complex components. The use of CAD is increased with efficiency by providing possible solution to design using FEA to analyse. In the recent design has been rectified using trial by errors. The FEA can be used by engineers to correct such a thing to avoid extra time. Optimisation of design can help to less production time by applying design analysis for modification process (Godfrey, 2011).

2.7.2 Virtual Prototyping

Physical model is evaluated using virtual prototype by employing kinematic and dynamic analyses using computer. The experimental results from physical prototype give physical modelling a way to produce manual documentation. The manual documentation is assembled using applicable instrumentation such as virtual prototyping(Godfrey, 2011).

2.7.3 Rapid Prototyping

The CAD technology of rapid prototyping as physical models is one of the best ways to design engineering product. The use of CAD for rapid prototype helps to reduce time and cost for physical modelling(Kutz, 2006).

2.7.4 Computer-Aided Manufacturing (CAM)

Computer-Aided Design and Manufacturing (CAD/CAM) approaches are used in design to functionalise products based on modelling. However, Computer-Aided Manufacturing technique applied information from Computer-Aided Design technique to functionalise manufacturing process by applying tool such as numerical analysis tools (Kutz, 2006).

2.8 Compliant Mechanisms Design Optimisation

Parkinson, Howell and Cox(1997) states that several optimization-based strategies have been proposed for compliant mechanism design. Optimization-based method could be used for compliant mechanisms that are modelled parametrically within an optimization and a finite element analysis package. Optmization-based strategies for the design of compliant mechanisms can be used to exploit the nonlinear nature of compliant mechanisms. Ananthasuresh introduced two forms of structural optimization for compliant mechanism design that are capable of generating designs from well-defined sets of constraints and boundary conditions. Both utilize the homogenization method, wherein the design begins as a region of material that defines the design space. Boundary and loading conditions are identified and the space is modelled as a grid. Analysis varies the density of the material in each cell of the grid, determining which are necessary. This analysis leaves a rough image of the compliant mechanism that can then be refined to become a final design. The first of Ananthasuresh's methods, the "spring method," includes the workpiece as a spring of known stiffness.

The second, "multi-criteria model," performs structural optimization with strength and output displacement requirements as opposing objectives. Utilizing homogenization and the multi-criteria model in a new way, Frecker and other developed a strategy for optimization-based design. An initial design is provided in the form of a web of truss elements. These interconnected truss elements define the design space. Truss members are removed as analysis determines that they are unnecessary.

At convergence, the few truss elements that remain represent a minimum volume, maximum strength, optimized design. The method presented by Frecker differs from that of Ananthasuresh in many ways. The mechanism design (the design for maximum deflection at a specific point in a specific direction) is achieved by maximizing the mutual energy. The structure design, a maximization of stiffness, requires the minimization of strain energies. The method distinguishes itself further by requiring an initial design, which speeds the gradient-driven optimization. This requirement also enables this method's use in the refining of an existing design. The strategy is hampered by the use of truss elements which are not suitable for analysis of bending or non-axial loads. Each of these methods is capable of creating original designs (Parkinson, Howell and Cox, 1997).

According to Dado (2005), the motion or deflection of flexible members of compliant mechanism is an important advantage because its motion does not control by its kinematics pairs. The kinematic pair always experiences rigid-body motion. The features of compliant mechanisms have priority over conventional mechanisms because it reduces manufacturing and operating costs. The principle of compliant mechanism helps in eliminating noise and wear of regular kinematic pairs (Sevak and McLarnan, 1974). The compliance gives further output variables for improving design of products. There are various researches which are being developed for modelling and synthesis using application of compliant mechanism.

2.9 Controller Design for Exercise Equipment

Itis good to develop Expert-Based Variable Resistance/Assistance (EVRA)equipments by designing and testing a component that can analyse knee joint, and by extension and other the possible limb muscles. The maintenance ofupright posturein designing EVRA equipment must be simple (Motamarri, Barbieri, Malki and Charlson, 2004).The study seeks to design,develop, and test a one degree-of-freedom, expert-based,variable-resistance/assistance (EVRA) exercise prototypeequipment. The equipment shall remove the problems associated with possible constant-resistance force in designing exercise equipments.

A unique feature of the system is capability of analysing kinetic and other neuro-physiological movement using EVRA's feedback technology. The EVRA's feedback technology gives the signal against a pre-information with specified range. This will help to engage or assist in motion of designed components.

The EVRA will help in detecting important factors in kinematic andneuro-physiological movement profiles and also create a database that can provides assistance. The database gives room for updating of data using possible tools as mechanical assistance. This will help to maintain movement in coordinating fashion.

Artificial neural networks (ANNs) were originallydeveloped as tools for the exploration and reproduction ofhuman information processing tasks such as speech,touch, knowledge processing. Today, most research isdirected towards the development of artificial neuralnetworks for applications such as data compression,optimization, pattern matching, system modelling,function approximation, and control. Artificial neural networks give control systems avariety of advanced capabilities. EVRA controlling mechanism develops bases on neural network control system. A successful prototype will pavethe way for more advanced applications, such as Pre/Post-Flight

Neuromuscular Control.Most real world systems exhibit nonlinear behaviourand are often complex to model using existingconventional techniques. Moreover, their properties areoften unknown and time varying. The neural network hasshown to be a promising technique to overcome thisproblem as it is useful for building good models from measured data. Recently, several researchers haveshown the advantages of neuro-controllers with thecapability of nonlinear system identification and control (Kantapanit, Treesatayapun and Wiriyasuttiwong, 2001).

2.10 Review of Design of Exercise Equipments

According to Coombs (1997), it is necessary to check available product of exercise equipment in local market before design.The review of design will help to save time in the design process in which repetition can be avoided. The review of design will tend to improve on previous design. Universal Gym and Life Fitness Company recently introduce electronic system into design exercise equipment(Coombs, 1997). The primary aim is to give smart design that optimises user time. This could be achieved through appropriate measurement using strength curve(Soper and Randall, 1995; Tidwell and Paul 1996).

2.10.1 Design Require of Wheelchair Exercise Equipment

The following design parameters are required for designing and fabricating wheel chair exercise equipment (Benjamin, 2005):

i. Functional requirement

a. Geometry: The product was intended to be used by everyday consumers therefore final design would be ideally small to fit in for every potential home user's.
b. Material and Cost: Materials require for manufacturing the product affect the overall cost of production.
c. Forces: Analytical calculation of stresses, tensile forces etc required.
d. Ergonomics: the product must be designed for people who have resisted movements.
e. Maintenance and Safety: the product should be designed for maintainability and safety

ii. Product Characteristics Design

The designed elements are as follows:

a. Rollers:This is the most critical module of the product, as this is the main "technology" of the product. If the rollers are not functional or problems with the rollers cannot be resolved, the product is essentially useless.
b. Frame: The frame has to be designed to accommodate the motion of the rollers, so integration between the two parts is crucial. Secondly, the frame needs to be able to bear the load that is applied on it by the wheelchair user and wheelchair, as well as fit various wheelchair sizes within it. Three, the frame defines the aesthetic appeal of the product, and is a direct result of the functional requirements of Geometry, Material, Cost, Forces, and Safety.
c. Ramp:The ramp, though seemingly a small part of the entire design, is importantbecause it caters to the overall comfort level of the user.

CHAPTER THREE

3.0 MATERIALS AND METHODS

There are a number of considerations necessary for successful design of the exercise equipment. However, the design and fabrication of the equipment will require material selection and compliant mechanism as its design principle.

3.1 Materials

The materials involved in constructing the exercise equipment are grouped base on design function:

i. Equipmentframe

ii. Input unit

iii. Pivot unit

iv. Output unit

3.1.1 Equipment frame

It was rigid set which forms body of the equipment with v-shape. This serves as a base of support for stability and constructed using steel material.

3.1.2 Input unit

The section involves a steel rod as handle and rope. The input unit of the equipment is a steel rod that helps to insert an effort through two lines of rope. The transmission of force on the rope was between handle and CCFM unit through pulley as a pivot unit. The rope were used to transmit the applied effort during exercise from one pulley to other pulley and hence into CCFM.

3.1.3 Pivot unit

The pivot unit of the equipment is a pulley with rigid arm. The input force or pulling force through handle of equipment was achieved by redirecting its effort through a rope to form output force in the CCFM. The pivot unit was located between the points of input and output force.Four pulleys were used for transmitting the motion of applied effort during exercise. Thereforethere were two pulleys for each of the arm of the equipment.

3.1.4 Output unit

The output was the CCFMconsist of long flexible segment, pin joint and long flexible segment (LPL):

i. Long flexible segment: Spring steel was used to provide energy absorption and strength. This will form six bar link mechanism with pin joint. Each arm of the equipment has six bar link mechanisms.
ii. Joint design it is a pin joint
iii. Compliant mechanism unit is a rigid part that houses the long flexible segment.

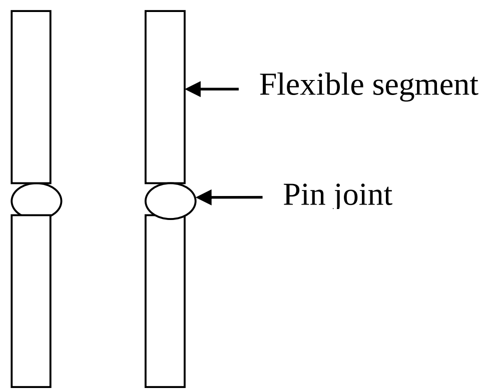

Figure 3.1: Compliant Mechanism Element

3.2 Design Analysis

The design assumptions for fabricating exercising equipmentwere as follow:

i. The equipment is designed to have weight of the arm's elbow as source of resistance force
ii. The resistance force is varying towards strengths of different people
iii. The exercising equipment is designed for muscle group called lateral pull down
iv. The design process requires compliant force mechanism approach to reduce assembly time
v. The rope can withstand shocking load
vi. the weight of wire rope is lighter comparing to the resistant force by arm's elbow

vii. the weight of pulley block is small as compared to the weight of the lifted and thus may be neglected in calculation

viii. The friction between the pulley surface and the rope is negligible, and thus the two tensions of the wire ropes passing round the pulley are equal in magnitude.

The design analyses used in the study were:

i. Muscle force analysis

ii. Kinematic analysis

iii. Lagrangian equation analysis

iv. Strain energy equationanalysis

The exercise equipment design framework is illustrated in Figure 3.2.

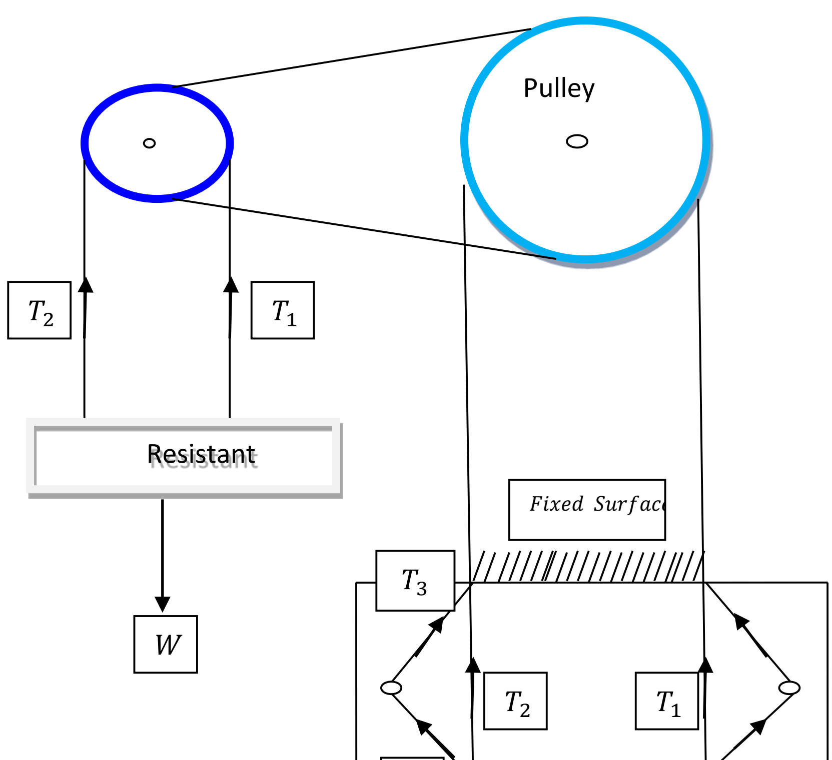

Figure 3.2: Exercise Equipment Design Framework

Where:

W= Resistant force is the exercise pulling-effort by elbow's arm

T_1 = the resultant force of CCFM in the first arm

T_2 = the resultant force of CCFM in the second arm

T_3 = the tension in first group of spring steel in the first arm

T_4 = the tension in second group of spring steel in the first arm

3.3 Muscle Force Analysis

The maximum force a muscle can generate depends on its physiological cross sectional area (PCA) of the muscle. If the line of action of muscle does not match the line of action of fibres then the muscle is known pennate. The muscle force equation was given as (McGinnis, 1999).

$$PCA_p = \frac{m cos\theta}{\rho L_m} \quad (3.1)$$

$PCA_{np} = \frac{m}{\rho L_m}$(3.2)

$$C = 20\ to\ 100\ Ncm^{-2}$$

$$\rho = 1.056gcm^{-2}$$

$F_m = PCA * C$(3.3)

Where:

PCA_p= pennate PCA;

PCA_{np}= non-pennate PCA

m= mass of the muscle;

θ = Angle of pennate;

L_m = Length of muscle

ρ = Muscle density;

C= PCA constant

F_m = Maximum force a muscle can generate

3.4 Kinematic Analysis

The analysis involves relative motion between the various parts of the equipment (Khurmi and Gupta, 2003). By considering a section of compliant mechanism in Figure 3.2, therefore the skeletal drawing of compliant mechanism was shown in Figure 3.3:

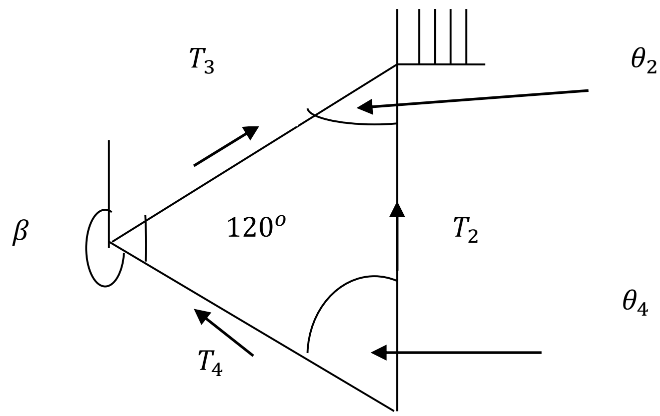

Figure 3.3: Vector loop model

In Figure 3.3, $\theta_3 = (120 + \beta)^0$

3.4.1 Relative Position Analysis

The application of complex number to the tension vector loop gives (Ugwuoke, Abolarin and Ogwuagwu, 2009; Ugwuoke, 2008; Kreyszig, 2006):

$T_3 + T_4 - T_2 = 0$(3.4)

Equation (3.4) can be expressed in terms of polar coordinate (r, θ) with following position vectors:

$r_3 e^{i\theta_3} + r_4 e^{i\theta_4} - r_2 e^{i\theta_2} = 0$(3.5)

The Euler equivalent is (Kreyszig, 2006):

$e^{i\theta} = cos\theta + isin\theta$(3.6)

Substituting Equation (3.6) into Equation (3.5) gives:

$r_3(cos\theta_3 + isin\theta_3) + r_4(cos\theta_4 + isin\theta_4) - r_2(cos\theta_2 + isin\theta_2) = 0$(3.7)

The real part of Equation (3.7) gives:

$$r_2(cos\theta_2) = r_3(cos\theta_3) + r_4(cos\theta_4)$$

$r_2 = \frac{r_3(cos\theta_3)+r_4(cos\theta_4)}{(cos\theta_2)}$ (3.8)

Deformation (θ_2) in the rope is neglected, therefore Equation (3.8) becomes:

$$r_2 = \frac{r_3(cos\theta_3) + r_4(cos\theta_4)}{(cos0)}$$

$r_2 = r_3(cos\theta_3) + r_4(cos\theta_4)$(3.9)

The imaginary part of Equation (3.7) gives:

$$r_3(isin\theta_3) + r_4(isin\theta_4) = r_2(isin\theta_2)$$

$$r_3(sin\theta_3) + r_4(sin\theta_4) = r_2(sin0) = 0$$

$sin\theta_3 = -\frac{r_4(sin\theta_4)}{r_3}$(3.10)

Where:

r_2= length of rope

r_3 = Length of link 3

r_4 = Length of link 4

θ_3 = Angular displacement of link 3

θ_4 =Angular displacement of link 4

3.4.2 Relative Velocity Analysis

Section 3.4.1 gives position modelling of the CCFM system. Since velocity is rate of change of displacement with time, therefore Equation (3.5) can be partially differentiated by taking $r_3, r_4, and\ \theta_2$as constant while r_2 varies with time (Ugwuoke, Abolarin and Ogwuagwu, 2009):

If; $\frac{d(e^{i\theta_t})}{dt} = ie^{i\theta_t}$

$r_3 e^{i\theta_3} + r_4 e^{i\theta_4} - r_2 e^{i\theta_2} = 0$(3.5)

$\frac{d(uv)}{dt} = u\frac{dv}{dt} + v\frac{du}{dt}$gives:

$ir_3 e^{i\theta_3} + ir_4 e^{i\theta_4} - \dot{r}_2(e^{i\theta_2}) = 0$(3.11)

Substituting Equation (3.6) into Equation (3.11) to have:

$$ir_3(cos\theta_3 + isin\theta_3) + ir_4(cos\theta_4 + isin\theta_4) - \dot{r}_2(cos\theta_2 + isin\theta_2) = 0$$

$ir_3 cos\theta_3 - r_3 sin\theta_3 + ir_4 cos\theta_4 - r_4 sin\theta_4 - \dot{r}_2 cos\theta_2 - i\dot{r}_2 sin\theta_2 = 0$(3.12)

The real part gives:

$\dot{r}_2 cos\theta_2 = r_3 sin\theta_3 + r_4 sin\theta_4$(3.13)

$\dot{r}_2 = \frac{r_3 sin\theta_3 + r_4 sin\theta_4}{cos\theta_2}$(3.14)

The imaginary part gives:

$$ir_3 cos\theta_3 + ir_4 cos\theta_4 - i\dot{r}_2 sin\theta_2 = 0$$

$$r_3 cos\theta_3 + r_4 cos\theta_4 - \dot{r}_2 sin\theta_2 = 0$$

$\dot{r}_2 = \frac{(r_3 cos\theta_3 + r_4 cos\theta_4)}{sin\theta_2}$(3.15)

Equation (3.15) is the linear velocity of the slider (rope) and equation (3.16) is the general linear velocity equation:

$\dot{r} = r\dot{\theta}$(3.16)

The relative velocity (V_r)of the slider (rope) is given as:

$V_r = V_3 + V_4$(3.17)

Let, $V_3 = r_3\dot{\theta}_3$

$$V_4 = r_4\dot{\theta}_4$$

Therefore, equation (3.17) becomes:

$V_r = r_3\dot{\theta}_3 + r_4\dot{\theta}_4$(3.18)

Where:

V_r= relative velocity of slider

$\dot{\theta}_3$ =Angular velocity of link 3

$\dot{\theta}_4$ = Angular velocity of link 4

V_3 = Linear velocity of link 3

V_4 = Linear velocity of link 4

3.5 LagrangianEquation Model

Lagrangian mechanism applies to systems that may conserve energy or momentum. It provides conditions under which energy or momentum is conserved. By choosing a generalised coordinate as $(\theta_4)$from Figure 3.3 which helps to determine kinetic and potential energy of the system and Lagrangian equationas follow:

$\mathcal{L} = T - V$(3.19)

Where:

$\mathcal{L}$ = Lagrangian symbol

T = Total kinetic energy

V = Total potential energy

The compact form Lagrangian equation is given by (Ugwuoke, Abolarin and Ogwuagwu, 2009; Sandor and Erdman, 1988):

$\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial Q_r}\right) - \left(\frac{\partial \mathcal{L}}{\partial Q_r}\right) + \left(\frac{\partial K}{\partial Q_r}\right) = F_{Q_r}$(3.20)

Where:

F_{Q_r} = Constant of Lagrangian equation of first kind

Q_r =Generalisedposition coordinate

If $\frac{d}{dt}\left(\frac{\partial \mathcal{L}}{\partial Q_r}\right) = \frac{\partial \mathcal{L}}{\partial \dot{Q}_r}$(3.21)

And $\left(\frac{\partial K}{\partial Q_r}\right) = 0$

Therefore, equation (3.21) becomes

$\frac{\partial \mathcal{L}}{\partial \dot{Q}_r} - \left(\frac{\partial \mathcal{L}}{\partial Q_r}\right) = F_{Q_r}$(3.22)

Where: $\dot{Q}_r$ =generalised velocity

In relating equation (3.22) to generalised coordinate $(\theta_4)$of Figure 3.3 gives:

$\frac{\partial \mathcal{L}}{\partial \dot{\theta}_4} - \left(\frac{\partial \mathcal{L}}{\partial \theta_4}\right) = M_{\theta_4}$(3.23)

Where:

M_{θ_4}= momentum of the system

$\dot{\theta}_4$= angular velocity of the system

The center of mass of each link is moving with linear velocity and each link is also rotating about the center of mass with angular velocity, therefore the study considers the following stated parameter:

Flexible segment length= L

Maximum deflection, $\theta_{max} = 0.6 * L$

Translation due to kinetic energy, $T_t = \frac{1}{2} m v^2$

Rotation due kinetic energy, $T_r = I\dot{\theta}^2$

$$T = \frac{\partial \mathcal{L}}{\partial \dot{\theta}_2} = T_r + T_t$$

$T = \frac{1}{2}mv^2 + I\dot{\theta}^2$(3.24)

$T = \frac{1}{2}\sum_{i=1}^{n} mv^2 + I\dot{\theta}^2$(3.25)

$I = \frac{kL}{E}$(3.26)

Where;

I = Moment of inertia of link member

L =Length of link member

E =Modulus of elasticity

k =Torsional constant

n = Number of element

The link member behaves like torsional spring, k, as in Figure in 3.4:

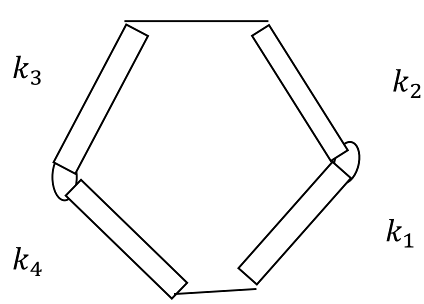

Figure 3.4: Formation of link member

$$k_{s1} = \frac{1}{k_1} + \frac{1}{k_2}$$

$$k_{s2} = \frac{1}{k_3} + \frac{1}{k_4}$$

$k = k_{parallel} = \frac{1}{k_{s1}} + \frac{1}{k_{s2}}$(3.27)

Considering the potential energy, V of the system

$$V = \frac{1}{2}k\theta^2$$

$V = \frac{1}{2}\sum_{i=1}^{4}\frac{1}{2}k\theta^2$(3.28)

Considering equation (3.19)

$\mathcal{L} = T - V$(3.19)

$\mathcal{L} = \frac{1}{2}\sum_{i=1}^{4} mv^2 + I\dot{\theta}^2 - \frac{1}{2}\sum_{i=1}^{4}\frac{1}{2}k\theta^2$(3.29)

Equation (3.29) is the lagrangian equation of the system.

The static analysis is analysed by considering each compliant segment separately as in Figure 3.5.

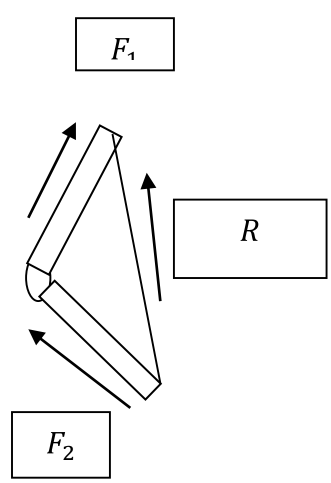

Figure 3.5: Skeletal Drawing of Static Analysis of the System

Resultant force, $R = \sqrt{\sum F_v{}^2 - \sum F_h{}^2}$(3.30)

$F_v = F_1 sin\theta + F_2 sin\theta$(3.31)

$F_h = F_1 cos\theta + F_2 cos\theta$(3.32)

$tan\theta = \frac{F_v}{F_h}$ (3.33)

Where:

F_v =Vertical force

F_h =horizontal force

θ =angle of inclination

3.6 Strain Energy Analysis

In reference to Figure 3.3, the links are joined by flexural member this has capability to store energy so that compliant mechanism could be reliable. Therefore it is necessary to determine failure in flexural member or the links. According to Rajput (2003), failures of a material occur when the total strain energy in the material reaches or beyond elastic limit of the material in simple tension. This theory is called strain energy theorem.

Let,

$U = \frac{1}{2E}\left(\sigma_1{}^2 + \sigma_2{}^2 + \sigma_1{}^2 - 2\upsilon(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)\right)$(3.34)

$U = \frac{{S_y}^2}{2E}$(3.35)

$\frac{{S_y}^2}{2E} = \frac{1}{2E}\left({\sigma_1}^2 + {\sigma_2}^2 + {\sigma_3}^2 - 2\upsilon(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)\right)$(3.36)

${S_y}^2 = \left({\sigma_1}^2 + {\sigma_2}^2 + {\sigma_3}^2 - 2\upsilon(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)\right)$(3.37)

Two dimensional analysis will give, $\sigma_3 = 0$, equation (3.37) becomes:

$$\left({\sigma_1}^2 + {\sigma_2}^2 - 2\upsilon(\sigma_1\sigma_2)\right) = {S_y}^2$$

$\left(\frac{{\sigma_1}^2+{\sigma_2}^2}{2} - \upsilon\sigma_1\sigma_2\right) \leq \frac{1}{2}{S_y}^2$(3.38)

Where;

U = Distortion energy

σ_1 =Maximum working stress during exercise

$\sigma_2 =$ Minimum working stress during exercise

$\upsilon =$ The poison ratio of the links

S_y= Yield strength of the links

3.7 Equipment Efficiency

According to Khurmi and Gupta (2003), mechanical advantage is defined to be ratio of weight lifted to applied force and given by:

$$MA = \frac{weight\ lifted\ (2T_2)}{applied\ effort\ (W)} \quad (3.39)$$

Where:

$MA =$ Mechanical advantage

$T_2 =$ Resultant force in the compliant system

There are two CCFMsystems with parallel forces acting in the system, therefore, total resultant forces is double.

The efficiency (η) of the equipmentis given as:

$$\eta = \frac{Machine\ output\ (2T_2 \times x)}{Machine\ input\ (W \times y)} \quad (3.40)$$

$$VR = \frac{y}{x} \quad (3.41)$$

Therefore, equation (3.3) can be expressed as:

$$\eta = \frac{MA}{VR} \quad (3.42)$$

Where:

$T_2 =$Half of the weight lifted

$x =$ Distance moved by weight lifted

$\eta =$ The efficiency of the mechanism

$y =$ The distance covered by the applied effort

$VR =$Velocity ratio

3.8 Exercise Equipment Design Detail Drawing

Figure I of Appendix I on page 71 was the drawing showing slider, roller supported with bearing, rope of 1600mm unit length and spring steel or link member. There are four group of the link and each member consists of 3-Double spring steel with 300mm of length. It means each link has 6 spring steels. This section forms the output unit of the system.

Figure II of Appendix I on page 72 was the drawing showing the formation of input unit. It involves a steel rod as handle (length of 930 mm) and two ropeseach with length of 1200 mm respectively. The rope was mounted in between handle and CCFM unit through pulley as a pivot unit. The pivot unit of the equipment is a pulley with rigid arm. Four pulleys of each diameter 300mm were used for the purpose.

Figures III and IV of Appendix I on page 73 werethe detail drawing of equipment frame and chair that could be used for sitting during the exercise. The v-shape frame was using steel bar with height of 1460 mm, 930 mm width and 1650mm diagonal length. Two parallel arms were mounted on the frame standing at 1460 mm above the ground; 410 mm apart and also each arm was 560mm length.

The chair in Figure IV of the Appendix has frame of length 700mm by 630mm and each supporting leg was 450mm. The material used was steel for the fabrication and foam was used to cover sitting portion of the chair.

Figure V of Appendix I on page 74 was the assembly drawing of the exercise equipment that makes use of CCFM technology to reduce assembly time. It has v-shape frame while two parallel arms were mounted on the frame. Generally, the material used for the fabrication of the equipment was steel and grouped into equipment frame, input, pivot, output units. The input unit were steel rod as handle and rope of total lengthof 1200 mm. The rope can withstand shocking load. Four pulleys were used as pivot system. The output systems involve 24 unit and 300mm length of spring steel as flexible member.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Results

Table 4.1 gives the parameter used in the design analysis.

Table 4.1: Design Parameters

Parameter	Unit
Length of link member(spring steel)	300mm

Mass of the handle	18 kg
Modulus of elasticity of spring steel	207GPa
Yield strength	500 MPa
Mass of the spring steel	0.11 kg
Number of spring steel	24
Number of Link member per each arm	6
Number of CCFM arm	2
Acceleration due to gravity	9.81 m/s^2

4.1.1 Design Analysis of Muscle Force

The muscle mass of 5, 10, 12 and 15 kg respectively were considered with each four different fibre length. The total mass of muscles consist the mass of biceps, brachialis, and triceps all is located in the arm. The maximumisometric force of muscle is multiplied by PCA constant number (C) which is 22.5 N cm^{-2},(Richard and Samuel, 2011).

Equations (3.1) and (3.2) are applied to obtain PCA in Table4.2respectively and muscle force was also determined.

Table 4.2: PCA for 5kg Muscle Force

Muscle Length (cm)	PCA$_p$ (m^2)	PCA$_{np}$(m^2)	F$_p$ (kN)	F$_{np}$ (kN)
10	0.04	0.05	9.00	11.25
12	0.03	0.04	6.75	9.00

15	0.03	0.03	6.75	6.75
18	0.02	0.03	4.50	6.75

Where:

Angle of pennate$(\theta) = 30^o$

Muscle density $(\rho) = 1.05\ gcm^{-3}$

PCA constant (C)= 22.5 $Ncm^{-2} or\ 225\ kPa$

F_p= Pennate muscle force

F_{np}= Non-pennate muscle force

The result in Table 4.2 shows non-pennate muscle has greater force to exert during exercise. The shorter the muscle length the higher the force for instance, the mass of 5 kg of non-pennate muscle has the force of 11.25 $kN$and 10cm, muscle length while it produces muscle force of 6.75 kN with increased length of 18cm.The muscle loads of 10, 12 and 15 kg respectively were considered in order to obtain maximumisometric muscle force that could be considered during exercise. The Table of 4.3, 4.4 and 4.5 show the respective muscle force.

Table 4.3: PCA for 10kg Muscle Force

Muscle Length (cm)	**PCA_p (m^2)**	**PCA_{np}(m^2)**	**F_p (kN)**	**F_{np} (kN)**
10	0.08	0.10	18.00	22.50
12	0.07	0.08	15.75	18.00

15	0.05	0.06	11.25	13.50
18	0.05	0.05	11.25	11.25

Table 4.3 shows that muscle mass of 10 kg has maximum force of 22.5 kN (non-pennate muscle) and minimum force of 11.25 kN(pennate muscle). It was the required force needed during the exercise by this group of muscle length with 10 kg.

Table 4.4: PCA for 12 kg Muscle Force

Muscle Length (cm)	**PCA_p (m^2)**	**PCA_{np}(m^2)**	**F_p (kN)**	**F_{np} (kN)**
10	0.10	0.11	22.50	24.75
12	0.08	0.10	18.00	22.50
15	0.07	0.08	15.75	18.00
18	0.05	0.06	11.25	13.50

Table 4.4 shows that muscle mass of 12 kg has maximum force of 24.75 kN (non-pennate muscle) and minimum force of 11.25 kN (pennate muscle). It was the required force needed during the exercise by this group of muscle length with 12 kg.

Table 4.5: PCA for 15 kg Muscle Force

Muscle Length (cm)	**PCA_p (m^2)**	**PCA_{np}(m^2)**	**F_p (kN)**	**F_{np} (kN)**

10	0.12	0.14	27.00	31.50
12	0.10	0.12	22.50	27.00
15	0.08	0.10	18.00	22.50
18	0.07	0.08	15.75	18.00

Table 4.5 shows that muscle mass of 15 kg has maximum force of 31.5kN (non-pennate muscle) and minimum force of 15.75 kN (pennate muscle). It was the required force needed during the exercise by this group of muscle length with 15 kg.

4.1.2 Result of Kinematic Design Analysis

This section involves position analysis and relative velocity analysis of the design element (links or spring steel) used for the equipment. By considering skeletal drawing in Figure 4.1, equations 3.9-3.18 in chapter three were determined.

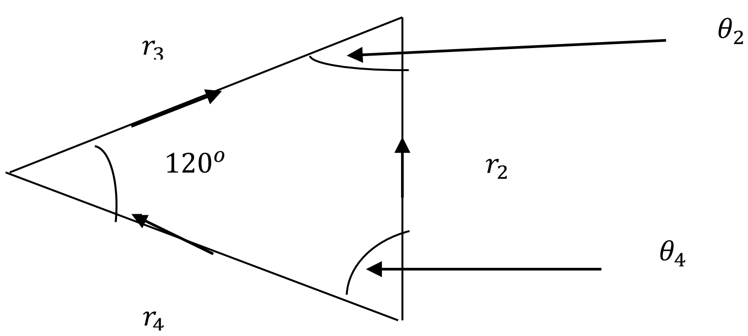

Figure 4.1: Skeletal Design of the Link

4.1.2.1 Result of Position Analysis

Let:

r_2= length of rope

$$r_3 = 300 \text{ mm}$$

$$r_4 = 300 \text{ mm}$$

$\theta_3 = (120 + \beta)^0$in Figure 3.3 of chapter 3

Applying of cosine rule with the respect to length of links in Figure 4.1 gives:

$$r_2{}^2 = r_3{}^2 + r_4{}^2 - 2r_3r_4 \cos 120$$

$$r_2{}^2 = 0.3^2 + 0.3^2 - 2(0.3)(0.3) \cos 120$$

$$r_2{}^2 = 0.18 + 2(0.3)(0.3)0.5 = 0.27$$

$$r_2{}^2 = \sqrt{0.27} = 0.5196\, m \cong 520mm$$

Applying of sine rule with the respect to length of links in Figure 4.1 gives:

$$\frac{\sin 120}{r_2} = \frac{\sin \theta_4}{r_3}$$

$$\sin \theta_4 = \ \ r_3 \frac{\sin 120}{r_2} = \frac{0.3\ (0.866)}{0.52} = 0.4996$$

$$\therefore \theta_4 = \ sin^{-1}(0.4996) = 29.97 \cong 30^o$$

The sum of the angle in a triangle is 180^o:

$$\therefore \theta_2 = \ 180 - (120 + 30) = 30^o$$

The sum of the angle at a point is 360^o:

$$\theta_3 + 30^o = 360^0$$

$$\theta_3 = 360^0 - 30^o = 330^o$$

$$\theta_3 = (120 + \beta)^0$$

$$\beta = 330^o - 120^o = 210^0$$

Therefore, the rope length across the CCFM using relative position analysis was determined as follow:

$$r_2 = r_3(cos\theta_3) + r_4(cos\theta_4)$$

$$r_2 = 0.3(\cos 330^o) + 0.3(\cos 30^o) = 0.2598 + 0.2598 = 0.5196$$

$$r_2 = 0.5196\ m \cong 520mm$$

$$sin\theta_3 = -\frac{r_4(sin\theta_4)}{r_3} = -\frac{0.3\ (sin30^o)}{0.3} = -0.5$$

$$\therefore \theta_3 = \ sin^{-1}(-0.5) = -30^o = 330^o$$

4.1.2.2 Result of Velocity Analysis

The relative velocity component of the slider (rope) and links member was determined as follows:

The real part of slider velocity is:

$$\dot{r}_2 = \frac{r_3 sin\theta_3 + r_4 sin\theta_4}{cos\theta_2} = \frac{0.3\ (-0.5)\ + 0.3\ (0.5)}{\cos 30} = \frac{0.3\ (-0.5)\ + 0.3\ (0.5)}{\cos 30} = 0\ m/s$$

The imaginary part gives:

$$\dot{r}_2 = \frac{(r_3 cos\theta_3 + r_4 cos\theta_4)}{sin\theta_2} = \frac{0.3\ (0.866)\ + 0.3\ (0.866)}{0.5} = 1.04\ m/s$$

Therefore the initial slider linear velocity,$\dot{r}_{2i} = i1.04ms$

$$\dot{r}_2 = r_2\dot{\theta}_2 = 0.3\dot{\theta}_2$$

$\dot{\theta}_2 = 3.47i$ Deg/s

The analysis of total resultant force on CCFM was determined as follow:

Mass of link (m) = 0.11 kg

Weight of each compliant(w) = 1.1 N

The each link member $(F) = 2.2\ N$

The potential angle(θ) between the link = 120^0

Vertical force $(F_v) = F_1 sin\theta + F_2 sin\theta = 2.2 \sin 0 +\ 2.2\ sin120 = 1.91\ N$

Horizontal force $(F_h) = F_1 cos\theta + F_2 cos\theta = 2.2 \cos 0 +\ 2.2 \cos 120 = 2.2 - 1.1 = 1.1\ N$

Resultant force of link, $R = \sqrt{\sum {F_v}^2 + \sum {F_h}^2} = \sqrt{1.91^2 + 1.1^2} = 2.21\ N$

Angle of inclination $(\theta) = \tan\left(\frac{F_v}{F_h}\right)^{-1} = \tan\left(\frac{1.91}{1.1}\right)^{-1} = 60^0$

Let consider the resultant force on the two arms of the CCFM, three link resultant acted on the hinge or pivot point at each arm in the same horizontal level as in Figure 4.2.

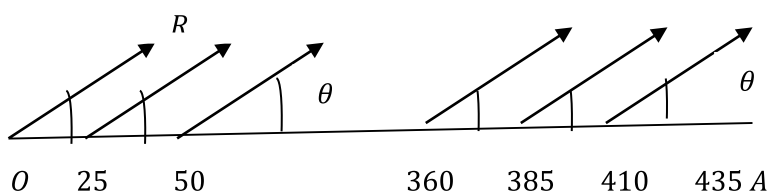

Figure 4.2: Link Design on CCFMSystem

Where:

Link Force, $R = 2.21\ N$

Angle of inclination $(\theta) = 60^0$

The distance between each link member was 25mm on hinge while each arm was separated at distance of 310mm apart.

Vertical force $(F_v) = 6(2.21\ sin60) = 6(1.91) = 11.48\ N$

Horizontal force $(F_h) = 6(2.21 \cos 60) = 6(1.1) = 6.6\ N$

Resultant force of link, $R_t = \sqrt{11.48^2 + 6.6^2} = 13.24\ N$

Resultant force of 13.24N is theforce of CCFM.

Angle of inclination $(\theta) = \tan\left(\frac{F_v}{F_h}\right)^{-1} = \tan\left(\frac{11.48}{6.6}\right)^{-1} = 60^0 = 1.047\ rad$

Taking moment of the vertical components of the forces and the resultant force about O in Figure 4.2 and equating the sum to have position of total resultant of the links gives:

$$11.48x = 1.91(0) + 1.91(0.025) + 1.91(0.05) + 1.91(0.36) + 1.91(0.385) + 1.91(0.41)$$

$$11.48x = 0.0478 + 0.0955 + 0.6876 + 0.7354 + 0.7831 = 2.3494$$

$$x = \frac{2.3494}{11.48} = 0.205\ m \cong 205\ mm$$

This was the distance for point of action of resultant force.

Torque or moment of the compliant $(M) = \ 2.35\ Nm$

4.1.3 Result of Lagrangian Analysis

Design based on Lagrangian mechanism will help to conserve energy in the system mechanism.

Total kinetic energy, $T = 0\ J$

Initial angular displacement of the system, (θ_4) = $1.047\ rad$

Total kinetic energy, $T = 0\ J$, this was because initial angular velocity was zero.

Let stiffness, $k = \frac{T}{\theta} = \frac{2.35}{1.047} = 2.24\ Nm/rad$

Moment of inertia of resultant link member, $I = \frac{kL}{E} = \frac{2.24 \times 0.3}{207 \times 10^9} = 3.24 \times 10^{-12} m^4$

The potential energy, V of the system

$$V = \frac{1}{2} k\theta^2 = 2.24 \times 1.047^2 = 2.46\, J$$

Lagrangian model, $\mathcal{L} = T - V = 0 - 2.46J = 2.46\, J$

$$V = 2.46 = R_t \times \text{Flexible segment length } (L)$$

$$\text{Flexible segment length}(L) = \frac{2.46}{13.24} = 0.186m = 186mm$$

The flexible segment length (L) was the linear displacement expected in the compliant after applying force on it.

The compliant has actual length $(L_r) = 300$ mm

Strain in compliant length, $\varepsilon = \frac{186}{300} = 0.62$

Maximum displacement expected in the compliant length, $L_{max} = L + L_r = 486\, mm$

$$L_{max} = 0.486\, m$$

4.1.4 Result of Strain Analysis

The strain energy analysis was determined as follow:

Let, $\sigma_{min} = E\varepsilon = 207 \times 0.62 = 128.3\, GPa$

Poisson ratio of the links$(\upsilon) = 0.3$

Let, $\sigma_2 = 0$

$$U = \frac{{S_y}^2}{2E} = \frac{(500 \times 10^6)^2}{2 \times 207 \times 10^9} = \frac{2.5 \times 10^{17}}{2 \times 207 \times 10^9} = 6.03 \ \times 10^{-3+17-9} = 6.03 \ \times 10^5$$

Distortion energy, $U = 0.603\ MPa$

$U(0.603\ MPa) \leq \ S_y(500\ MPa)$.

Therefore, yield will not occur since distortion energy of the CCFM is less than yield strength.

Let, resultant force of the links, $R_t = U \times A(area)$

$$R_t = 6.03 \ \times 10^5 \times (0.3 \times 0.05) = 9.045\ kN$$

This the maximum force required for the loading the system and therefore CCFM forces were:

$$R_{t(\min)} = 9.045\ kN$$

$$R_{t(\max)} = 13.24\ N$$

4.2 Testing

Testing of the equipment through the use of mechanical advantage and it was determined as stated in Table 4.6. Muscle force in section 4.1 was tested using the equipment.

Let:

$$x = r_2 = 0.52m$$

$$y = rope\ total\ length - 0.52m = 1.2 - 0.52 = 0.68m$$

$$VR = \frac{y}{x} = \frac{0.68}{0.52} = 1.31$$

$$MA = \frac{R_{t(\max)}}{Muscle\ force}$$

$$\eta = \frac{MA}{VR}$$

Table 4.6: Result for Efficiency by Minimum Force

Muscle's Mass (kg)	Minimum Force (kN)	MA	Efficiency
5	4.5	2.01	1.53
10	11.25	0.804	0.61
12	11.25	0.804	0.61
15	15.75	0.574	0.44

Table 4.6 shows that muscle mass of 5 kg has maximum efficiency of 0.61using the equipment.

Table 4.7: Result for Efficiency by Maximum Force

Muscle's Mass (kg)	Maximum force (kN)	MA	Efficiency
5	11.25	0.804	0.61
10	22.50	0.402	0.31
12	24.75	0.365	0.28

15	31.50	0.287	0.22

Table 4.7 shows that muscle mass of 5 kg has maximum efficiency of 0.61using the equipment.

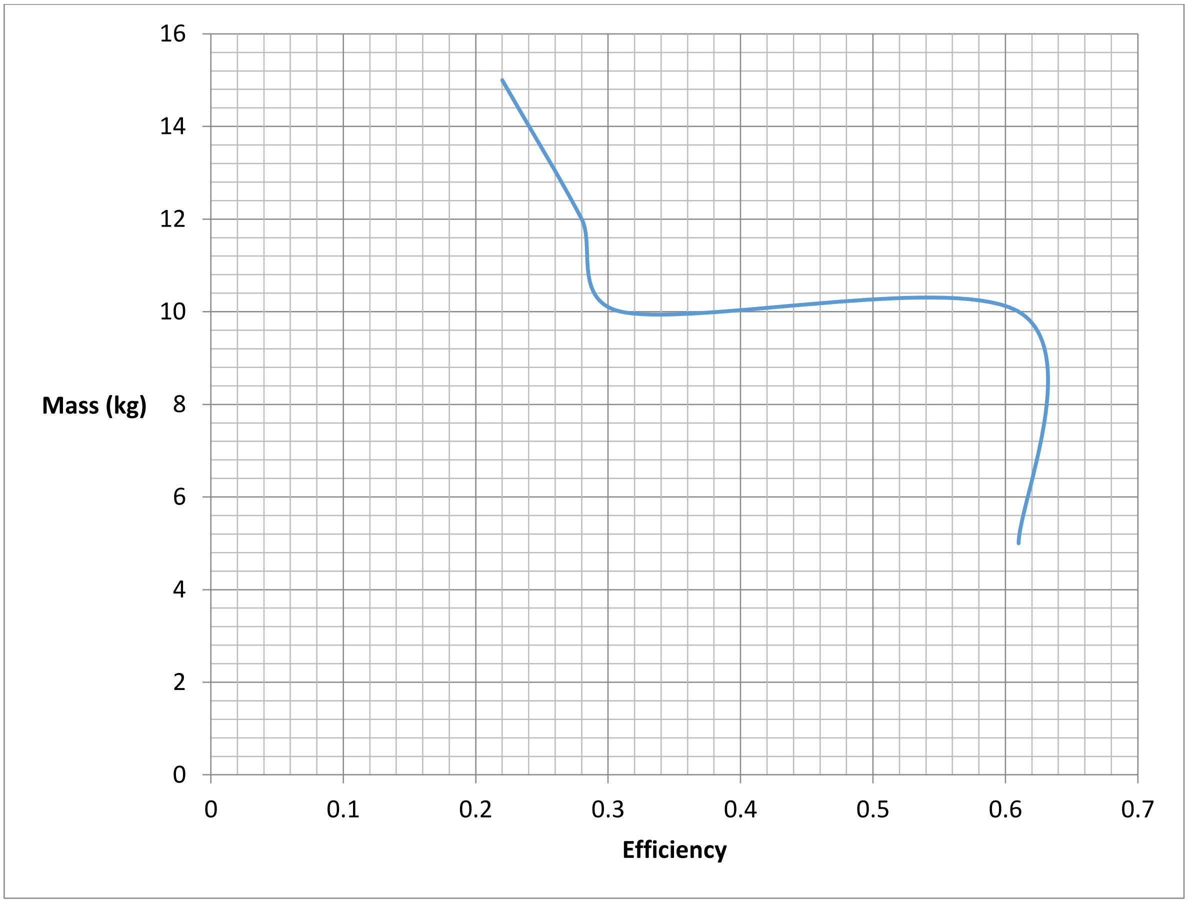

Figure 4.3: Equipment Efficiency

Figure 4.3 indicates the equipmentusefulness for exercise if the muscle load is within the range of 1 to 10kg of mass. The efficiency is better when use the equipment with muscle load of 1 to 5kg. The Figure 4.3 shows that the average efficiencyof the equipment was 0.61. However, the relationship between muscle force (pulling force/ applied effort) and weight of the mechanism $R_{t(\max)}$was obtained as follow:

$$\eta = \frac{MA}{VR} = 0.61 = MA/1.31$$

$$MA = \frac{R_{t(\max)}}{Muscle\ force} = 0.7991$$

$$R_{t(\max)} = 0.7991 \times Muscle\ force$$

4.3 The Exercise Equipment

The following pictures arethe plates of exercise equipmentthat was fabricated. The Plate I is a chair that could be used for sitting purpose during the exercise. The chair was fabricated based on the stated design principle in chapter three. Plate II was the CCFM system that was design to operate under maximum load of $9.045\ kN$ and minimum load of$13.24\ N$. The CCFM was designed moved at maximum distance (distance across the rope) of 520 mm. The Plate II will help to exert muscle force during the exercise. The Plate III was V-design shape and side view of the equipment. Plate IV was the CCFM system assembled in order to have complete equipment and designed based on CCFM principle.

Plate I: The chair

Plate II: CCFM system

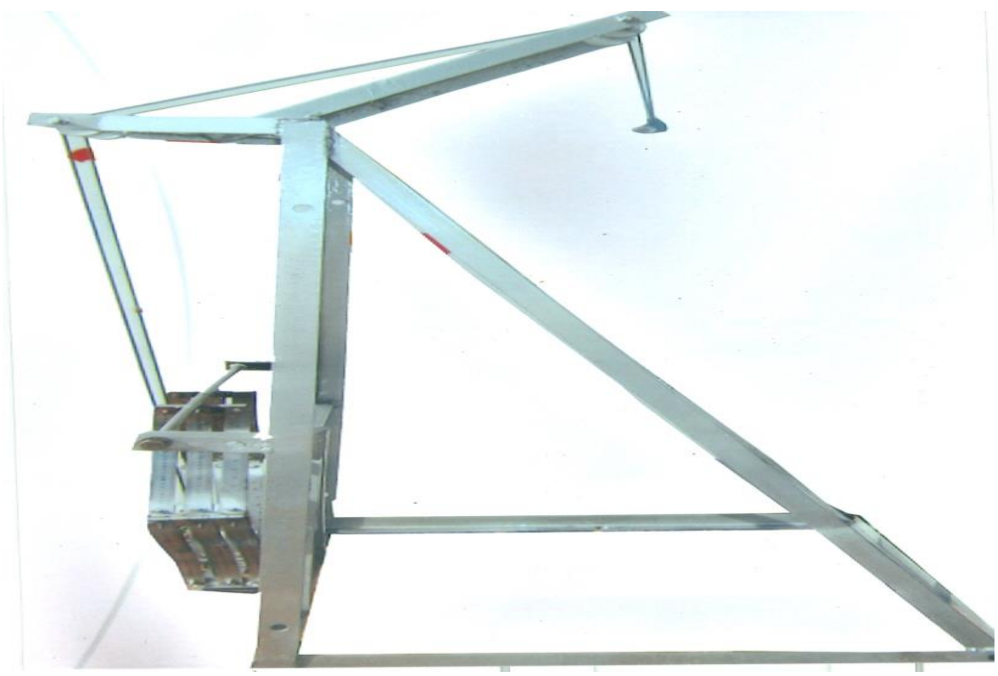

Plate III: The V-Design Shape/Frame of the Equipment

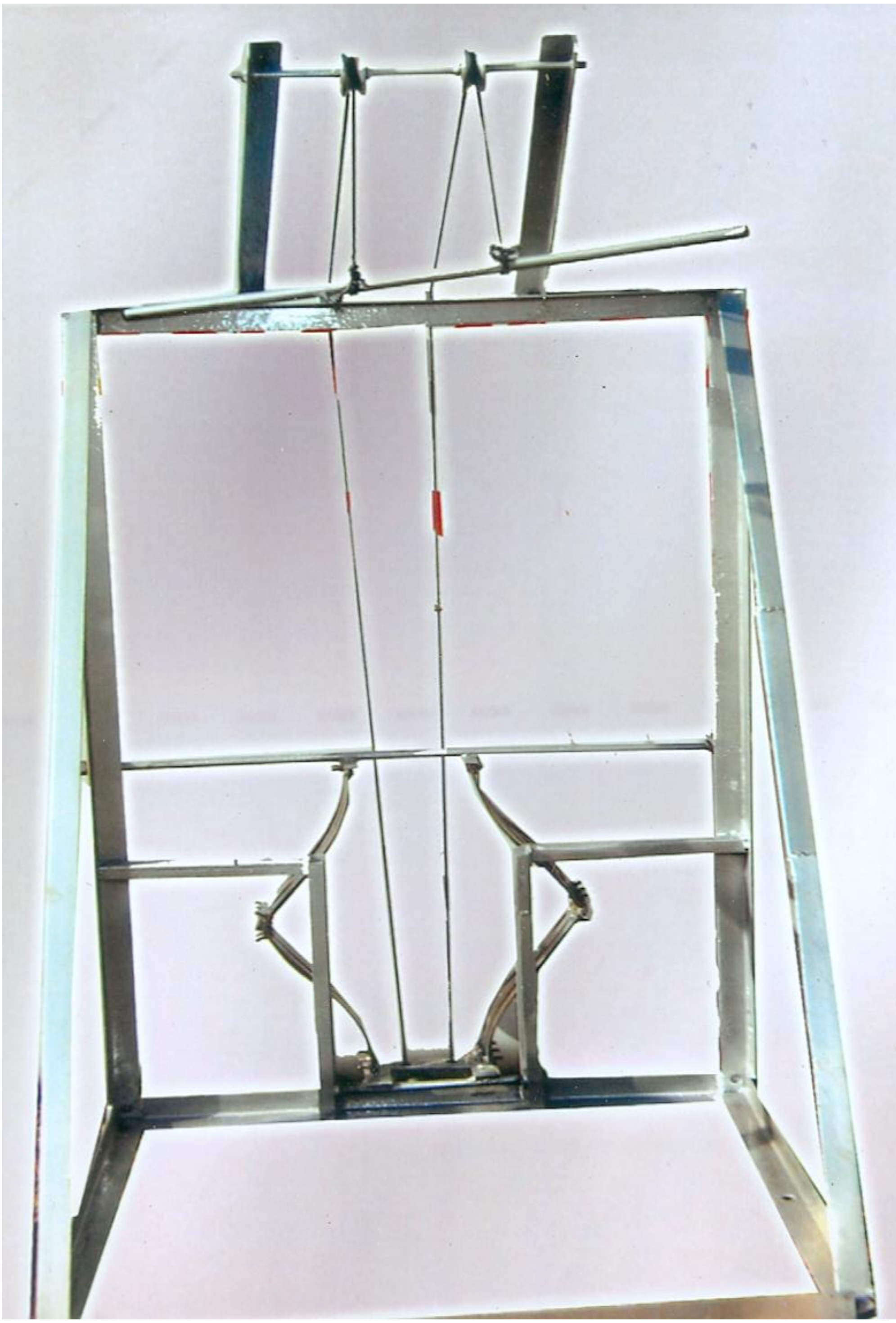

Plate IV: The Exercise Equipment

4.4 Production Cost of the Equipment

The cost of fabrication used for producing the equipmentwas listed in Table 4.8.

Table 4.8: Fabrication Costof Equipment

Materials	Quantity	Cost (Naira)
Spring steel	24	13,200.00
Angle bars (3 inches)	4	2400.00
Angle bar (1 inch)	1	300.00
Pipe (2 inches)	1	1200.00
Steel rod	1	800.00
Pulley	4	4800.00
Electrode	2	1200.00
Bolt and nut (10mm)	24	480.00
Hinges	2	800.00
Foam	1	500
Labour cost and overhead	1	15,000.00
Total		40, 680.00

The cost of fabrication of the equipment was 40,680.00 naira as at March, 2012 in Nigeria.

4.5Discussions

The design parameters required for the study are stated in Table 4.1. The design muscle load ranges between 5 to 15kg. The load within 1-10 kg gives a better efficiency of 61%. The muscle load was pennate muscle and also called a penniform muscle. This is a muscle in a slanting position to its tendon and in the present 30^{o} degree was used as pennation angle.

These types of muscles generally allow higher force production but smaller range of motion. When a muscle contracts and shortens, the pennation angle increases. Other type of muscle considered in the study was non-pennate muscle in which line of fibre are arranged without slanting, the pennation angle was zero. This type of muscle has higher forces on production than pennate muscle of the same fibre length.

To determine maximumisometric force by a muscle, PCA was multiplied by the constant number (C) which was 22.5 N cm^{-2}and it was experimental figure for mammalian and given by Richard and Samuel (2011), and muscle force was observed to be higher in non-pennate muscle. For instance, in Table 4.3 the muscle load of 10 kg has maximum force of 22.5 $kN$by a non-pennate muscle and minimum force of 11.25 $kN$with a pennate muscle. Using this exercise equipment the muscle of non-pennate within 6-12 kg will be required to use the equipment because the efficiency of using it was 61% as in Table 4.6.

However, the muscle group for both pennate and non-pennate within the range of 1-5kg are appropriate load for the equipment because the efficiency of 61% was achieved in using it.The maximum distance moved by the effort applied or the muscle was 680 mm with velocity ratio of 1.3:1. To determine the mechanical advantage of the equipmentthe muscle force were required. However, lifting the maximum load produced by the equipment which was 9.045 kN a constant compliant force requires appropriate of muscle load of 1-5 kg. In the design friction force between the pulley and slider or rope was neglected and the stiffness that was experienced by the compliant was 2.46 Nm/rad. The stored potential energy in the compliant was 2.46 J. The equipment's average efficiency was determined to be 61%. Therefore the use of CCFM reduces cost of materials and assembly time due to simplifiedmanufacturing processes, less maintenance, less lubrication in comparison to rigid-link mechanisms (Shuib, Ridzwan and Kadarman, 2007).

However most design principle of exercise machine have made use of rigid-link mechanism or long flexible segment, pin joint, pin joint (LPP) principle (Ugwuoke, Abolarin, and Ogwuagwu, 2009). In the present study, long flexible segment, pin joint and long flexible (LPL) was used and it include steel rod and hinges at a joint point as in Figure I of Appendix I on page 63.

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study has produced cost-effective and environmentally friendly exercise equipment that based upon CCFM technology. The use of CCFM will not allow much time for assembling. The slider or other equipment component can be within seconds and using the equipment will constitute no harm because it helps to reduce fatigue in the body. Therefore, for its design analysisCCFM were used to provide the output force required for reducing fatigue during the exercise. Rope was used as drive mechanism to transmit velocity ratio of 1.3:1 in system. According to Ugwuoke (2008), developing of compliant mechanism (CM) based on computational analysis can be used to produce constant force as output which depends on wide range displacement as an input. In conclusion the study achieved the following:

i. The required pennate and non-pennate muscle load was in the range of 1 to 10kg
ii. The machine was designed for pennate muscle load in the range of 1-5kg
iii. The constant compliant force designed was 9.045 kN

iv. Weight of the slider mechanism is equal to 0.7791 multiplied by muscle force

v. The designed efficiency of the equipment was 61%.

5.2 Recommendations

The use of CCFM will not allow much time for assembling. The slider or other equipment component can be within seconds and using the equipment will constitute no harm because it helps to reduce fatique in the body. Developing of systematic formulation for the design and analysis of compliant mechanism (CM) is recognised as a need to produce a constant output force for a large range of input displacements.

The study has identify the following recommendations;

i. The equipment should be redesigned for obese who has muscle load above 5kg.

ii. Exercise equipment can be redesigned using other method such as pseudo-rigid mechanism design

iii. The design of exercise equipment with power system using electromechanical elements

iv. Analysis of skeletal muscle design for achieving better compliant constant force

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APPENDIX I

EXERCISE EQUIPMENT DRAWING

The following drawings were detail and assembly drawing used for the designing and fabrication of the exercise equipment.

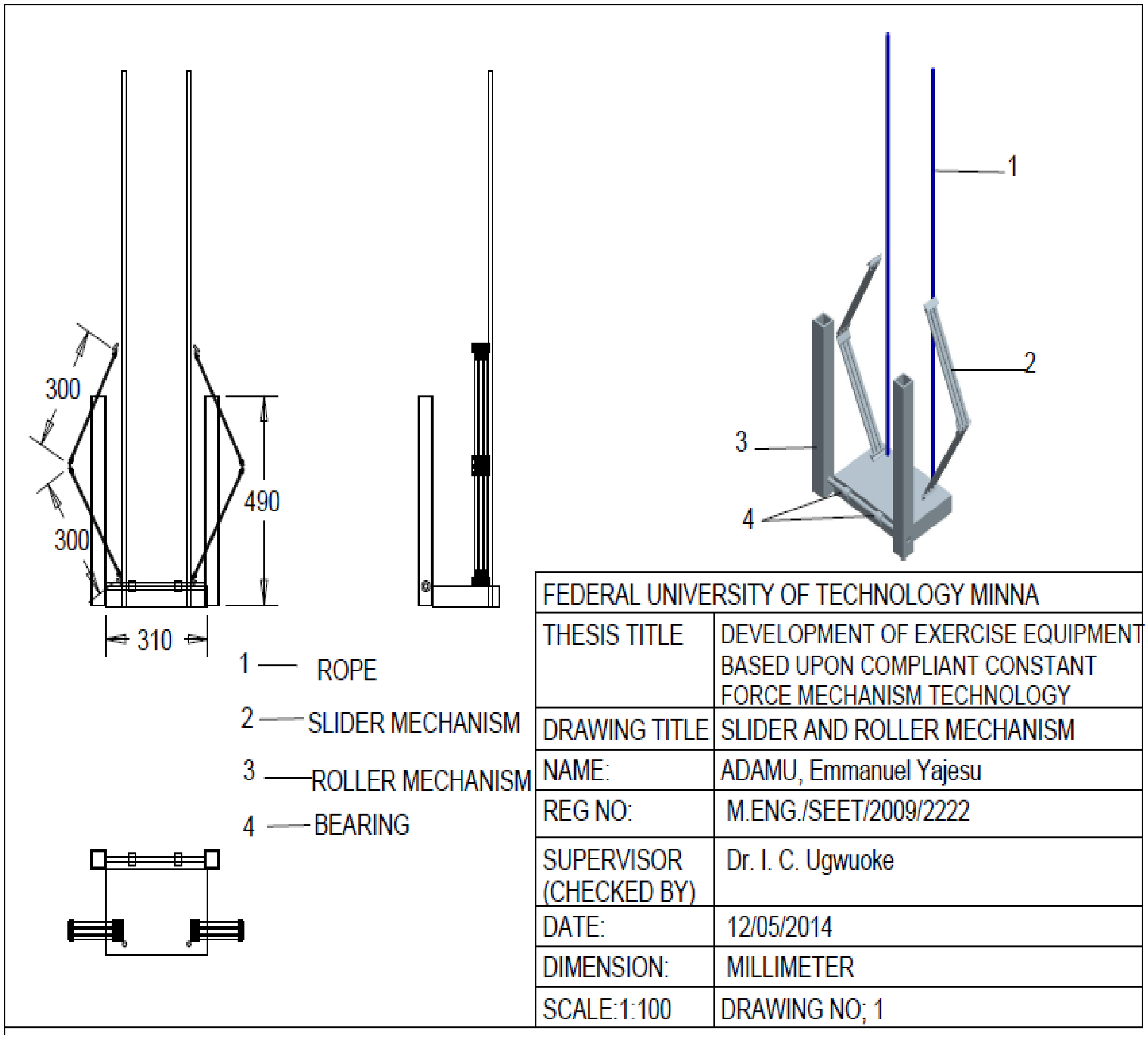


Figure I: CCFM Detail Drawing

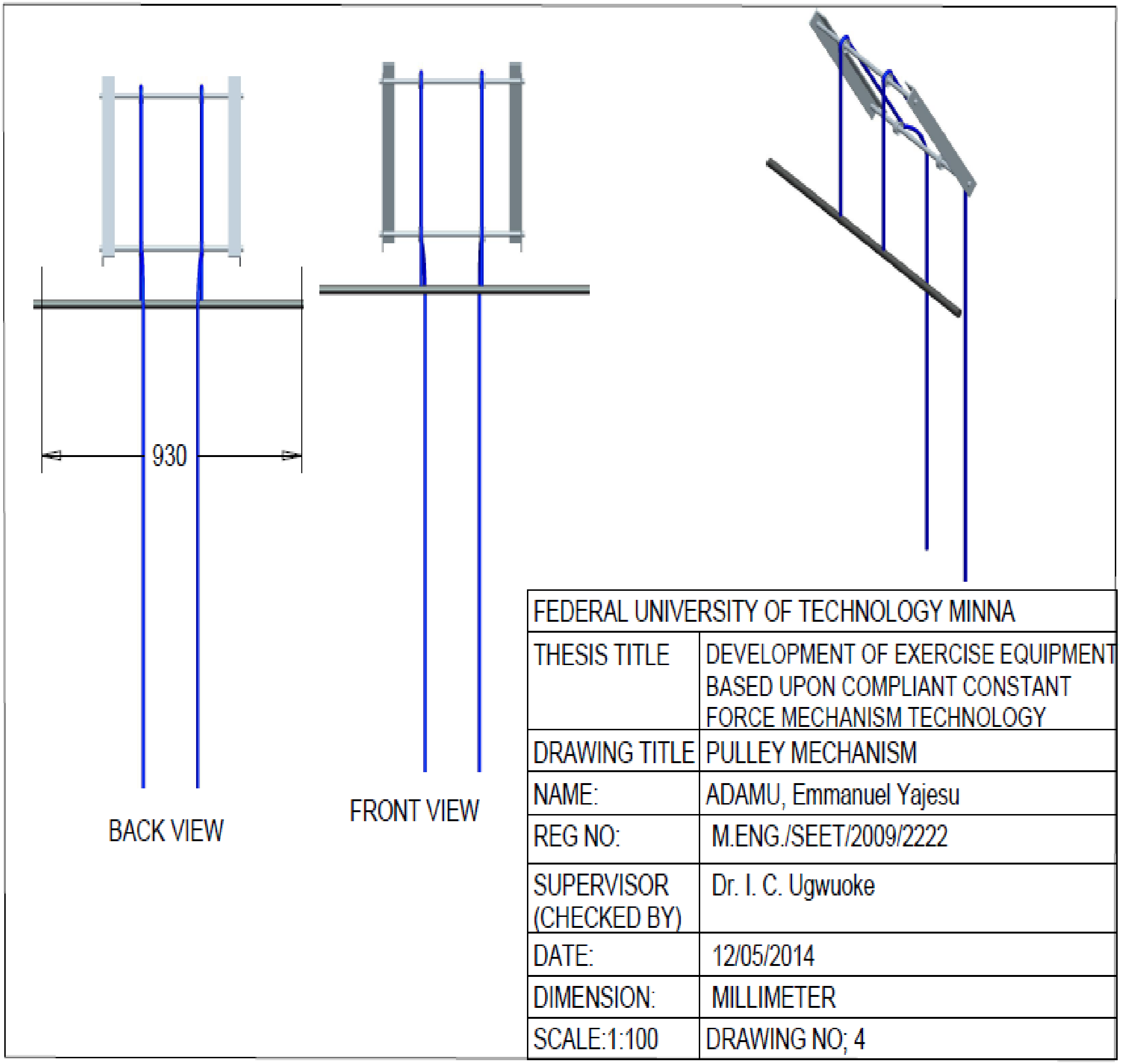


Figure II: CCFM Detail Drawing

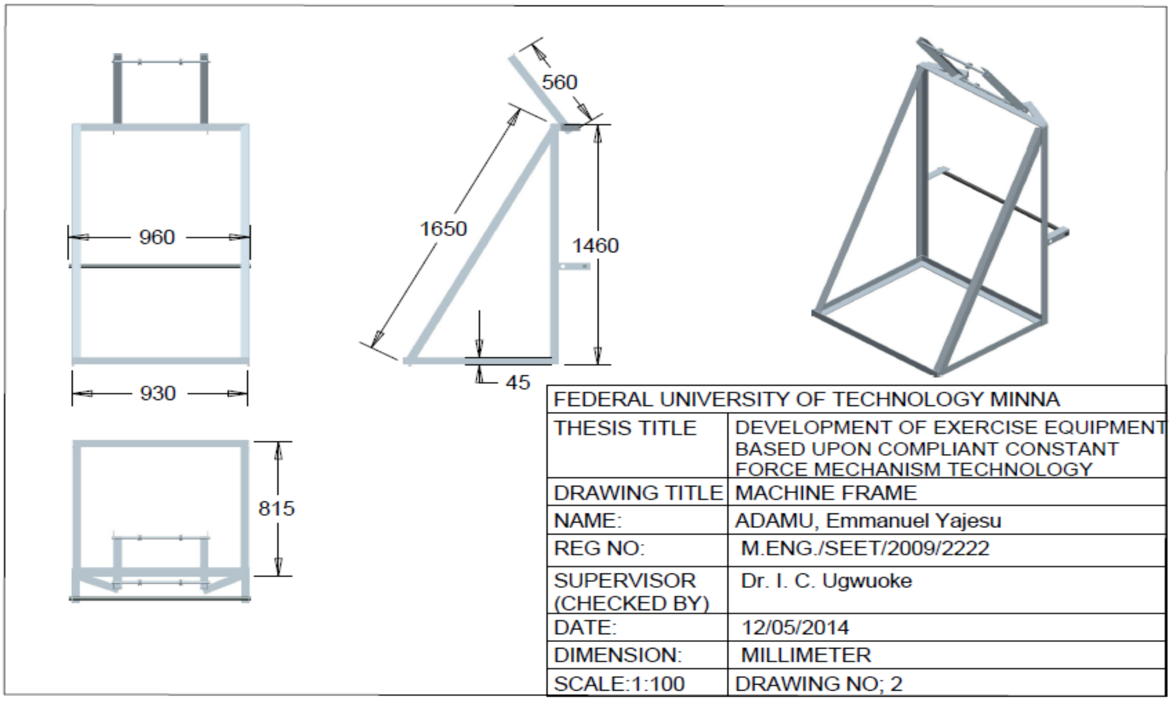


Figure III: Equipment Frame

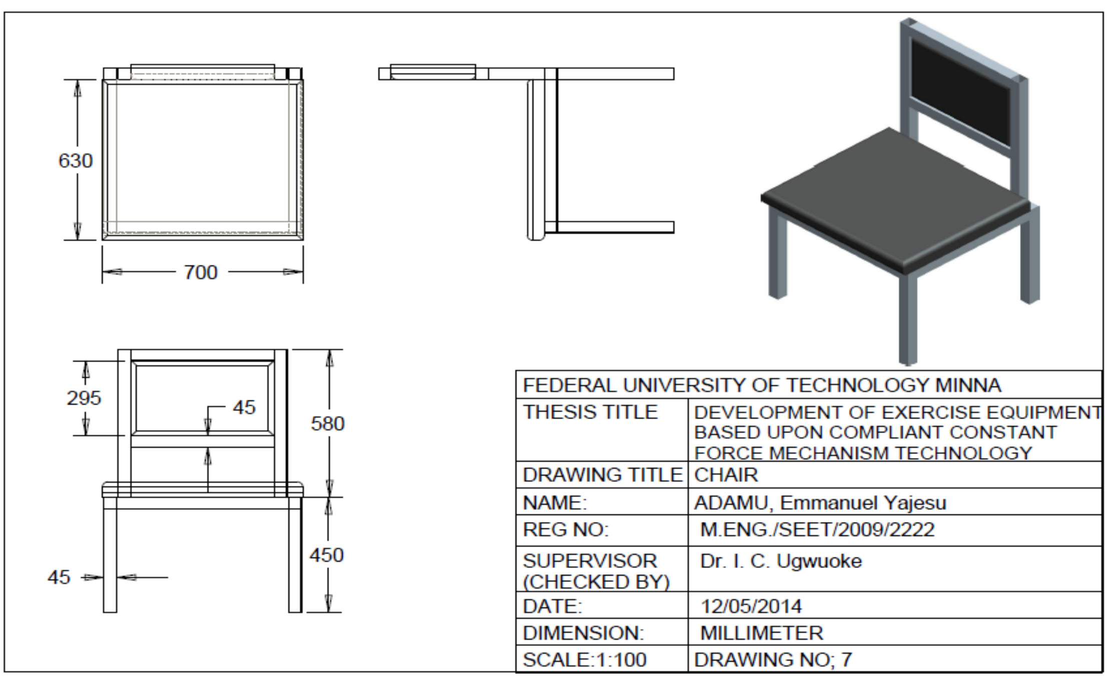
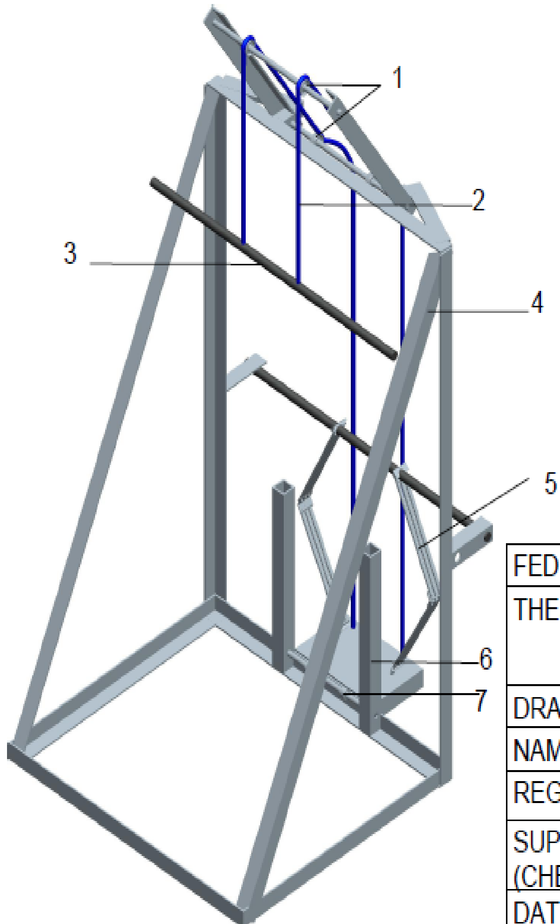


Figure IV: Chair



1 —— PULLEY
2 —— ROPE
3 —— HANDLE
4 —— MACHINE FRAME
5 —— SLIDER MECHANISM
6 —— ROLLER MECHANISM
7 —— BEARING

FEDERAL UNIVERSITY OF TECHNOLOGY MINNA	
THESIS TITLE	DEVELOPMENT OF EXERCISE EQUIPMENT BASED UPON COMPLIANT CONSTANT FORCE MECHANISM TECHNOLOGY
DRAWING TITLE	ASSEMBLY EXERCISE EQUIPMENT
NAME:	ADAMU, Emmanuel Yajesu
REG NO:	M.ENG./SEET/2009/2222
SUPERVISOR (CHECKED BY)	Dr. I. C. Ugwuoke
DATE:	12/05/2014
DIMENSION:	MILLIMETER
SCALE:1:100	DRAWING NO; 5

Figure V: Assembly Drawing of the Exercise Equipment