SEMI-AUTOMATED HUMANOID ROBOTIC LIMBS
&
DESIGN OF LOWER LIMB EXOSKELETON

A PROJECT REPORT

Submitted by

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CERTIFICATE

This is to certify that the dissertation entitled “Semi-Automated Humanoid Robotic Limbs &Design of Lower Limb Exoskeleton” has been carried out by HARSH SUTHAR, SAUMYA MACWAN and RISHI KHAJURIWALA under my guidance in fulfillment of the degree of Bachelor of Engineering in MECHATRONICS (7th Semester) of Gujarat Technological University, Ahmedabad during the academic year 2015-16.

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- Saumya Macwan
- Rishi Khajuriwala
- Harsh Suthar

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CHAPTER 1

INTRODUCTION

1. INTRODUCTION

Many studies on biped walking robots have been performed since 1970. During that period, **biped walking** robots have transformed into biped **humanoid robots** through the technological development. Furthermore, the biped humanoid robot has become a one of representative research topics in the intelligent robot research society. Many researchers anticipate that the humanoid robot industry will be the industry leader of the 21st century and we eventually enter an era of one robot in every home. The strong focus on biped humanoid robots stems from a long-standing desire for human-like robots. Furthermore, a human-like appearance is desirable for coexistence in a human-robot society. However, while it is not hard to develop a human-like biped robot platform, the realization of stable biped robot walking poses a considerable challenge. This is because of a lack of understanding on how humans walk stably. Furthermore, biped walking is an unstable successive motion of a single support phase.

Earlier the biped robots were developed with very low and unstable walking speed. The step time was over 10 secs per step and balance was performed using Centre of Gravity (COG). During the static walking, the robot can stop the walking motion any time without falling down. The disadvantage of **static walking** is that the motion is too slow and wide for shifting the COG.

Researchers thus have started focusing on **dynamic walking** of biped robots with fast and agile locomotive speed of 1 second per step. If the dynamic balance can be maintained, dynamic walking is smoother and more active even when using small body motions. However the inertial forces play an important role here as acceleration of the robot body if not suitably controlled, a biped robot may fall down easily. In addition, during dynamic walking, a biped robot may fall from disturbances and cannot stop the walking motion suddenly. Hence the notion **ZMP (Zero Moment Point)** was introduced in order to control the inertial forces. In the stable single support phase, the ZMP is equal to the COP (Centre of Pressure) on the sole. The advantage of the ZMP is that it is a point where the center of gravity is projected onto the ground in the static state and a point where the total inertial force composed of the gravitational force and inertial force of mass goes through the ground in the dynamic state. Here if the ZMP lie within the supporting polygon made by the feet, the robot never falls down. Mostly the ZMP is used as a walking stability criterion of dynamic biped walking.

The Walking control strategies with use of ZMP can be divided into two approaches:

- The robot can be modelled by considering many point masses and their locations and moment of inertia of the linkage. The walking pattern is then calculated by solving ZMP dynamics derived from the robot model with the desired ZMP trajectory.
- The robot is modelled by a simple mathematical model such as an inverse pendulum system, and then the walking pattern is designed. During the **gait cycle** many controllers are activated to compensate the motion through the use of various sensory feedback including ZMP.

At present various research groups have developed well stable dynamic biped for example ASIMO by HONDA, WABIAN-2 of Waseda University and HRP-3 of AIST are well known bipeds.

FIGURE 1HONDA ASIMO BIPEDAL ROBOT

The project is based on this concept of dynamic walking of the biped robot with semi-automated control algorithms with some advanced actuating systems.

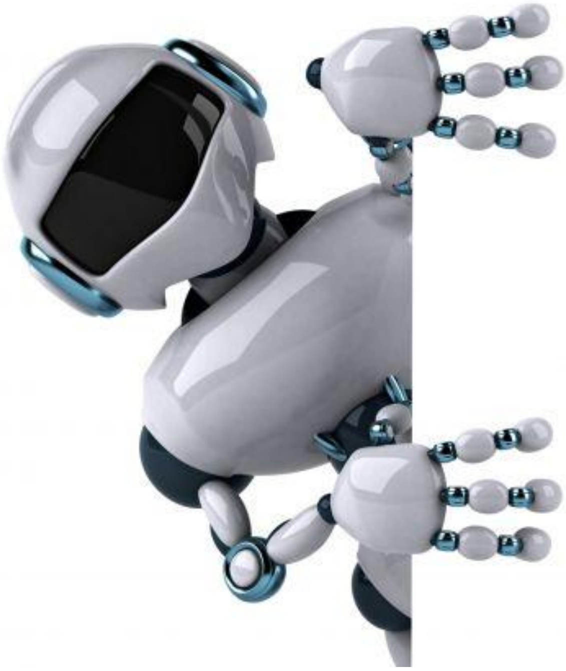
CHAPTER 2

HUMANOID CONCEPT

2.1 INTRODUCTION

There are many types of robots; they are used in many different environment and for many different uses. Various types and categories of robots are developed till the date. Robots vary in type such as type of locomotion, type of purpose etc.

Humanoid robotics is an emerging and challenging research field, which has received significant attention during the past years and will continue to play a central role in robotics research and in many applications of the 21st century. Regardless of the application area, one of the common problems tackled in humanoid robotics is the understanding of human-like information processing and the underlying mechanisms of the human brain in dealing with the real world.



Ambitious goals have been set for future humanoid robotics. They are expected to serve as companions and assistants for humans in daily life and as ultimate helpers in man-made and natural disasters. Considerable progress has been made in humanoid research resulting in a number of humanoid robots able to move and perform well-designed tasks. Over the past decade in humanoid research, an encouraging spectrum of science and technology has emerged that leads to the development of highly advanced humanoid mechatronic systems endowed with rich and complex sensorimotor capabilities. Of major importance for advances of the field is without doubt the availability of reproducible humanoid robots systems, which have been used in the last years as common hardware and software platforms to support humanoids research. Many technical innovations and remarkable results by universities, research institutions and companies are visible.

Basically a humanoid robot is a robot with its body shaped as a human body. This kind of robots are generally also referred to as a bipedal robots.

2.2 PURPOSE

Humanoid robots are used as a research tool in several scientific areas. In depth knowledge of biomechanics is required to build and study humanoid robots. On the other side, the attempt to simulation of the human body leads to a better understanding of it.

Human cognition is a field of study which is focused on how humans learn from sensory information in order to acquire perceptual and motor skills. This knowledge is used to develop computational models of human behavior and it has been improving over time.

Although the initial aim of humanoid research was to build better **orthosis** and **prosthesis** for human beings, knowledge has been transferred between both disciplines. A few examples are: powered leg prosthesis for **neuromuscular** impaired, ankle-foot orthosis, biological realistic leg prosthesis and forearm prosthesis.

Besides the research, humanoid robots are being developed to perform human tasks like personal assistance, where they should be able to assist the sick and elderly, and dirty or dangerous jobs. Regular jobs like being a receptionist or a worker of an automotive manufacturing line are also suitable for humanoids. In essence, since they can use tools and operate equipment and vehicles designed for the human form, humanoids could theoretically perform any task a human being can, so long as they have the proper software. However, the complexity of doing so is deceptively great.

Humanoid robots, especially with artificial intelligence algorithms, could be useful for future dangerous and/or distant space exploration missions, without having the need to turn back around again and return to Earth once the mission is completed.

2.3 ROBOTIC ASPECTS

There are many types of robots and depending on the type of the robot different aspects are considered.

Also there are various groups in which the study of the robot is categorized

2.3.1 MECHANICAL SIDE

- Design
- Analysis
- Study of kinematics
- Type of actuation
- Mechanical construction
- Selection of resources
- Parts manufacturing and Assembly

The mechanical aspect is mostly the creator's solution to completing the assigned task and dealing with the physics of the environment around it.

2.3.2 ELECTRICAL SIDE

- Electrical power source selection and management
- Circuit analysis
- Electronics
- Control of electric drives
- Electronic sensors interfacing

Robots have electrical components which power and control the machinery.Even gas powered machines that get their power mainly from gas still require an electric current to start the gas using process which is why most gas powered machines like cars, have batteries.

The electrical aspect of robots is used for movement (through motors), sensing (where electrical signals are used to measure things like heat, sound, position, and energy status) and operation (robots need some level of electrical energy supplied to their motors and sensors in order to activate and perform basic operations)

2.3.3 SOFTWARE AND PROGRAMMING

- Flowchart and algorithm development
- Coding and debugging
- Software GUI development
- Sensor data acquisition
- Data representation

All robots contain some level of computer programming code. A program is how a robot decides when or how to do something. Programs are the core essence of a robot, it could have excellent mechanical and electrical construction, but if its program is poorly constructed its performance will be very poor or it may not perform at all.

2.3.4 CONTROL

- Mathematical modelling
- Sensor data control
- Feedback control
- Design of controller and compensators

A robot with remote control programing has a pre-existing set of commands that it will only perform if and when it receives a signal from a control source, typically a human being with a remote control. It is perhaps more appropriate to view devices controlled primarily by human commands as falling in the discipline of automation rather than robotics. Robots that use artificial intelligence interact with their environment on their own without a control source, and can determine reactions to objects and problems they encounter using their pre-existing programming. Hybrid is a form of programming that incorporates both AI and RC functions.

The control of a robot involves three distinct phases – perception, processing, and action (robotic paradigms).Sensors give information about the environment or the robot itself (e.g. the position of its joints or its end effector). This information is then processed to be stored or transmitted, and to calculate the appropriate signals to the actuators (motors) which move the mechanical.

The processing phase can range in complexity. At a reactive level, it may translate raw sensor information directly into actuator commands. Sensor fusion may first be used to estimate parameters of interest (e.g. the position of the robot's gripper) from noisy sensor data. An immediate task (such as moving the gripper in a certain direction) is inferred from these estimates. Techniques from control theory convert the task into commands that drive the actuators.

At longer time scales or with more sophisticated tasks, the robot may need to build and reason with a "cognitive" model. Cognitive models try to represent the robot, the world, and how they interact. Pattern recognition and computer vision can be used to track objects. Mapping techniques can be used to build maps of the world. Finally, motion planning and other artificial intelligence techniques may be used to figure out how to act. For example, a planner may figure out how to achieve a task without hitting obstacles, falling over, etc.

2.4 AUTONOMY LEVELS

Control systems may also have varying levels of autonomy.

1. Direct interaction is used for hapticor tele-operated devices, and the human has nearly complete control over the robot's motion.
2. Operator-assist modes have the operator commanding medium-to-high-level tasks, with the robot automatically figuring out how to achieve them.
3. An autonomous robot may go for extended periods of time without human interaction. Higher levels of autonomy do not necessarily require more complex cognitive

capabilities. For example, robots in assembly plants are completely autonomous, but operate in a fixed pattern.

CHAPTER 3

GAIT ANALYSIS

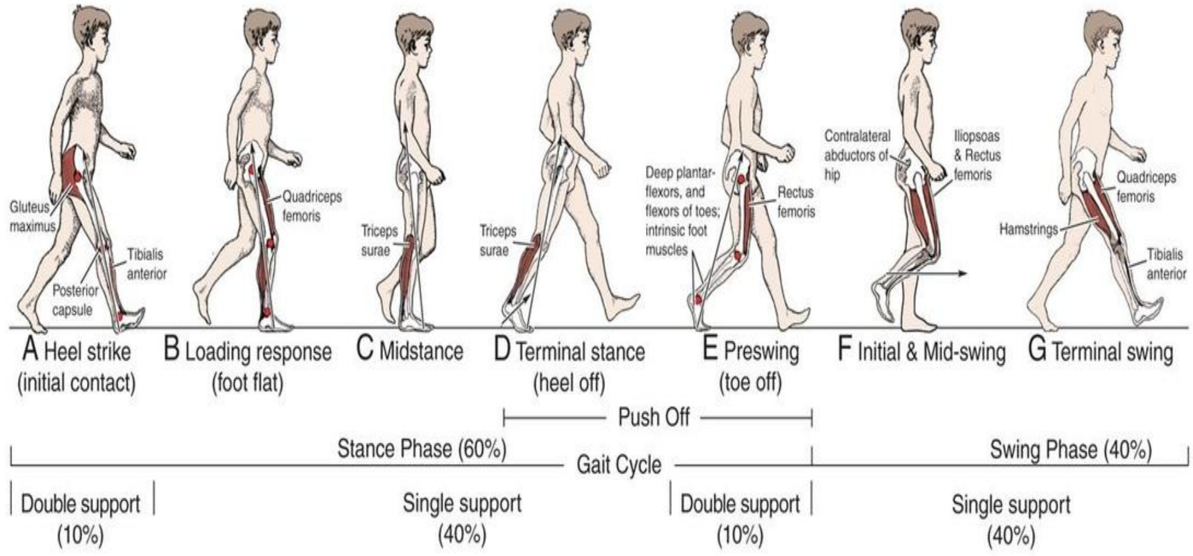


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FIGURE 2GAIT CYCLE

3.1 INTRODUCTION

Gait analysis is the systematic study of animal locomotion, more specifically the study of human motion, using the eye and the brain of observers, augmented by instrumentation for measuring body movements, body mechanics, and the activity of the muscles. Gait analysis is used to assess, plan, and treat individuals with conditions affecting their ability to walk. It is also commonly used in sports biomechanics to help athletes run more efficiently and to identify posture-related or movement-related problems in people with injuries.

3.2 PROCESS AND EQUIPMENT

A typical gait analysis laboratory has several cameras (video and / or infrared) placed around a walkway or a treadmill, which are linked to a computer. The patient has markers located at various points of reference of the body (e.g., iliac spines of the pelvis, ankle malleolus, and the condyles of the knee), or groups of markers applied to half of the body segments. The patient walks down the catwalk or the treadmill and the computer calculates the trajectory of each marker in three dimensions. A model is applied to calculate the movement of the underlying bones. This gives a complete breakdown of the movement of each joint.

To calculate the kinetics of gait patterns, most labs have floor-mounted load transducers, also known as force platforms, which measure the ground reaction forces and moments, including the magnitude, direction and location (called the centre of pressure). The spatial distribution of forces can be measured with pedobarography equipment. Adding this to the known dynamics of each body segment enables the solution of equations based on the Newton–Euler equations of motion permitting computations of the net forces and the net moments of force about each joint at every stage of the gait cycle. The computational method for this is known as inverse dynamics.

This use of kinetics, however, does not result in information for individual muscles but muscle groups, such as the extensor or flexors of the limb. To detect the activity and contribution of individual muscles to movement, it is necessary to investigate the electrical activity of muscles. Many labs also use surface electrodes attached to the skin to detect the electrical activity or electromyogram (EMG) of, for example, a muscles of the leg. In this way it is possible to investigate the activation times of muscles and, to some degree, the magnitude of their activation—thereby assessing their contribution to gait. Deviations from normal kinematic, kinetic, or EMG patterns are used to diagnose specific pathologies, predict the outcome of treatments, or determine the effectiveness of training programs.

3.3 FACTORS AND PARAMETERS

The parameters taken into account for the gait analysis are as follows:

- *Step length*
- *Stride length*
- *Cadence*
- *Speed*
- *Dynamic Base*
- *Progression Line*
- *Foot Angle*
- *Hip Angle*

3.4 TECHNIQUES

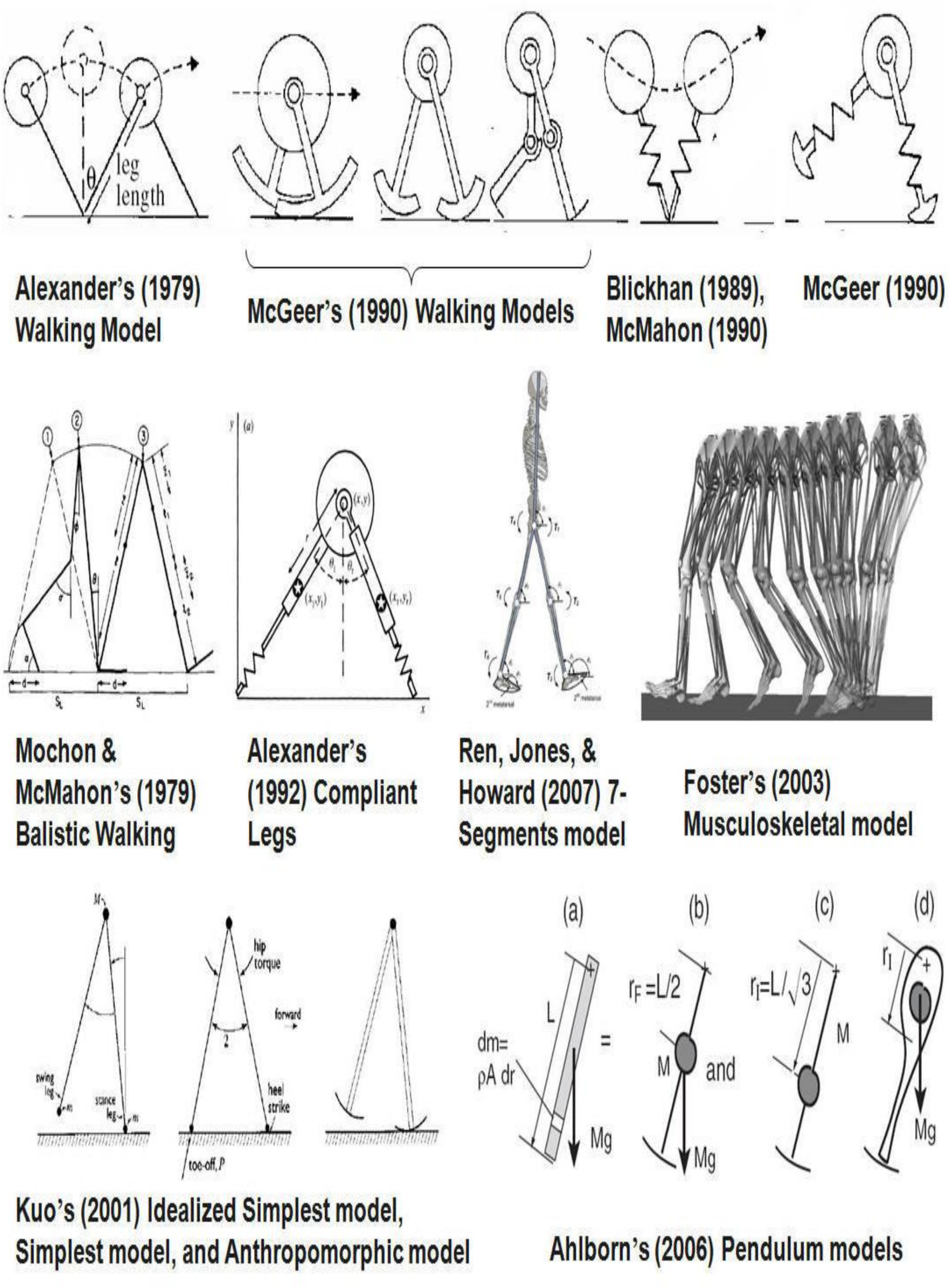
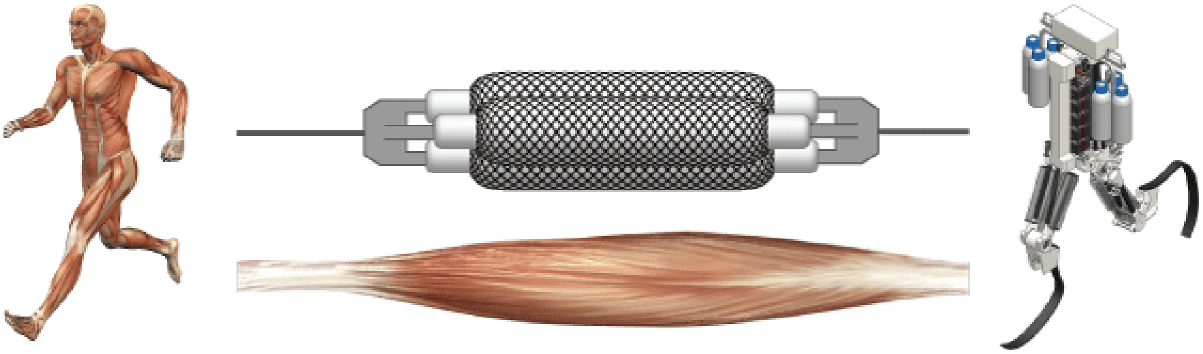


FIGURE 3MODELS OF GAIT ANALYSIS

CHAPTER 4

PNEUMATIC MUSCLE ACTUATORS



4.1 INTRODUCTION

Over the years, researchers have used various typesof actuators on their industrial, robotic and automationapplications. Hydraulic, electric, magnetic andpneumatic actuators are some of the commonly utilizedtypes, with respect to the application's characteristics,function and limitations. During the last decade, therehas been an increase in the use of pneumatic actuatorsin the industrial and medical areas, mainly due to theiradvantages such as low power to weight ratio, highstrength and small weight.

Pneumatic muscle actuator, also known as theMcKibben PAM (pneumatic artificial muscle), fluidic muscle or a biomimetic actuator, wasfirst invented in 1950s by the physician, Joseph L.McKibben and was used as an orthotic appliance for polio patients. PMAs are well suited for theimplementation of positive load feedback, which isknown to be used by animals. They present smooth,accurate and fast response and also produce asignificant force when fully stretched.PMAs are lightweight, which is a particularly useful feature when working with applications that placerestrictions on the weight of the equipment e.g., mobilerobotic applications

4.2 CONCEPT AND OPERATION

PAMs are contractile and linear motion engines operatedby gas pressure. Their core element is a flexiblereinforced closed membrane attached at both ends tofittings along which mechanical power is transferred to aload. As the membrane is inflated or gas is sucked out ofit, it bulges outward or is squeezed, respectively.Together with this radial expansion or contraction, themembrane contracts axially and thereby exerts a pullingforce on its load. The force and motion thus generatedby this type of actuator are linear and unidirectional. Thiscontractile operation distinguishes the PAM frombellows, which extend upon inflation.

A PAM's energy source is gas, usually air, which iseither forced into it or extracted out of it. This way theactuator is powered by the pressure difference of theinside gas with regard to the surroundings. Although it ispossible to design an under pressure operating muscle.

PAMs usually operate at an overpressure:generating and supplying compressed gas is easier toaccomplish and, with ambient pressure mostly at about100 kPa, a lot more energy can be conveyed byoverpressure than by under pressure. Charging anoverpressure PAM with pressurized gas enables it tomove a load, discharging it, conversely, makes it yield toa load.

4.3 PRINCIPLES OF OPERATION

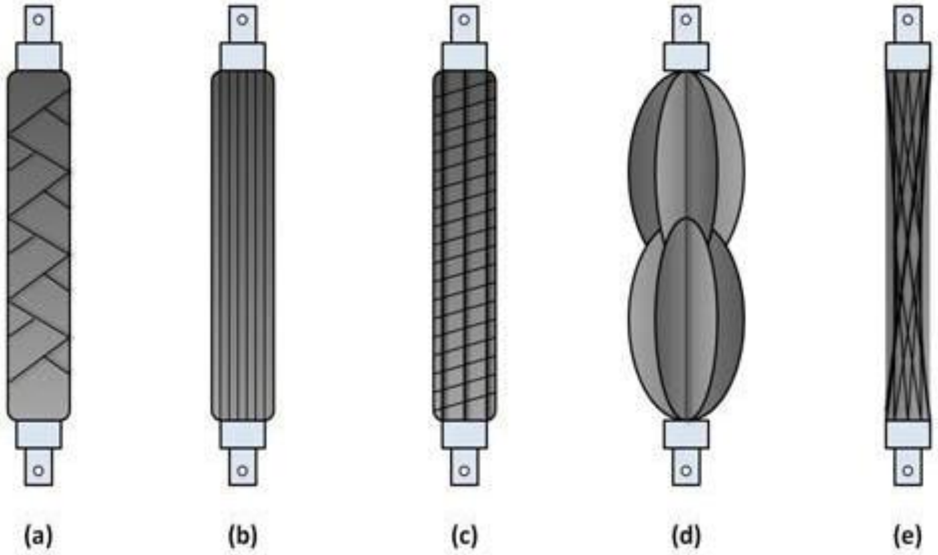


FIGURE 4VARIOUS TYPES OF PMAS:

(a) McKibbenMuscle/braided muscle; (b) pleated muscle; (c) yarlott Netted muscle; (d) ROMAC muscle; and (e) painter Hyperboloid muscle.

The basic principles of the PMA’s operation can becategorized in two cases: (1) under a constant load andwith varying gauge pressure, and (2) with a constantgauge pressure and a varying load. To illustrate thisoperation, a PMA of an arbitrary type is considered. In the first case (Fig. 2), PMA is fixed at one endand has a constant mass load hanging from the otherside. The pressure difference across the membrane, i.e.,its gauge pressure, can be increased from an initialvalue of zero. At zero gauge pressure the volumeenclosed by the membrane is minimal min V and itslength maximal max l . If the actuator is pressurized tosome gauge pressure 1 P , it will start to bulge and at thesame time develop a pulling force that will lift the massuntil the equilibrium point where the generated forcewill equal to the mass weight Mg .

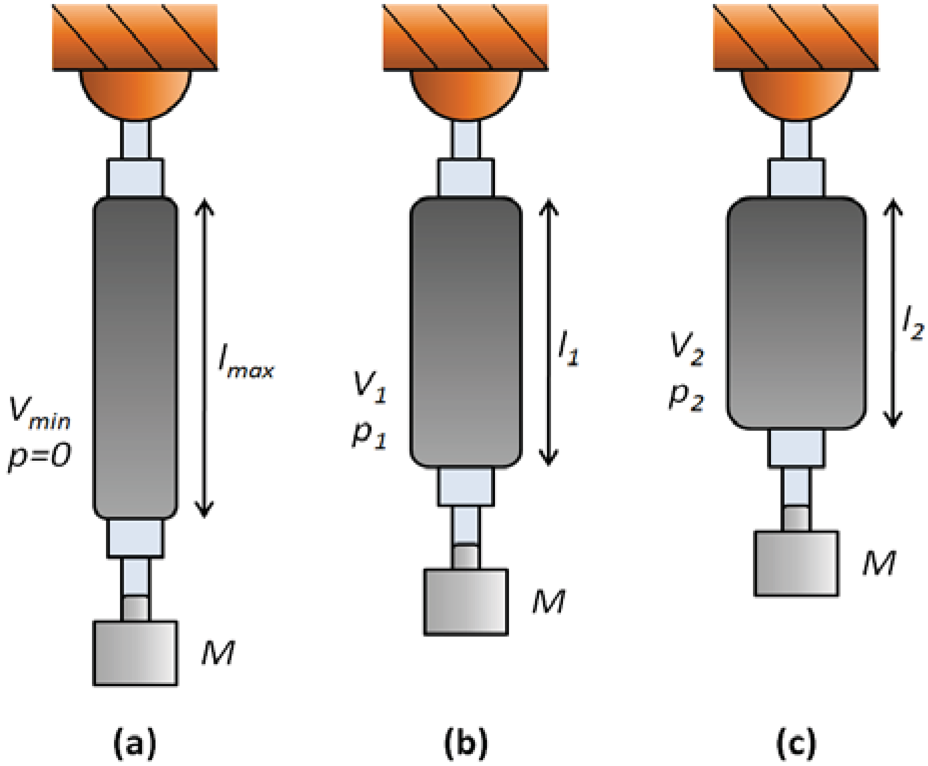


FIGURE 5PMA OPERATION AT CONSTANT LOAD.

At this point the PMA's volume will have beenincreased to 1 *V* and its length contracted to 1 *l* .Increasing the pressure further to 2 *P* will continue this process, until the gauge pressure reaches the maximumallowable value max *P* . During this type of operationPMA: (1) will shorten its length by increasing itsenclosed volume, and (2) will contract against aconstant load if the pneumatic pressure is increased.The second type of PMA's operation, which is thecase of operation under constant gauge pressure, isdepicted in Fig. 3. In this case, the gauge pressure iskept at a constant value *P*, while the load is decreasing,driving the PMA to inflate and decrease its initiallength 3 *l* . If the load is completely removed, theswelling goes to its full extent, at which point thevolume will reach its maximum value max *V* , the lengthof its minimal value min *l* , and the pulling force willdrop to zero. PMA will not be able to contract beyondthis point and it will operate as a bellows at shorter lengths, generating a pushing instead of pulling force.

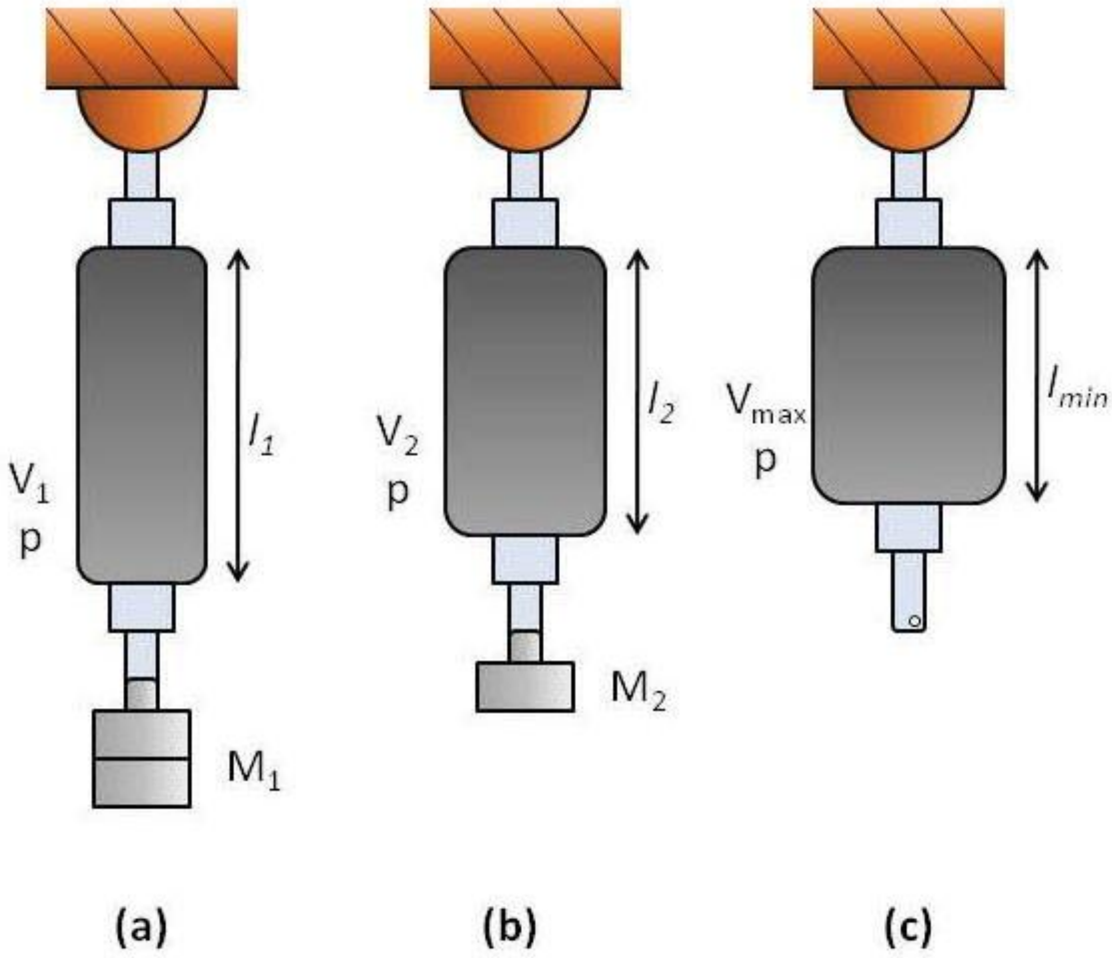


FIGURE 6PMA OPERATION AT CONSTANT PRESSURE.

During this type of operation PMA: (1) will decrease itslength at a constant pressure if its load is decreased, and(2) its contraction has an upper limit at which itdevelops no force and its enclosed volume is maximal.

For these two principal operations, it should behighlighted that for each pair of pressure and load,PMA has an equilibrium length. This characteristic isin a total contrast to the operation of a pneumaticcylinder where the developed actuation force onlydepends on the pressure and the piston surface area sothat at a constant pressure, it will be constant regardlessof the displacement.

4.4MODELLING APPROACHES

In recent years, there has been quite a lot of activityregarding the mathematical modeling of PMAs. Theaim of such a model is to relate the pressure and lengthof the pneumatic actuator to the force it exerts along itsentire axis. In the process of deriving a proper PMAmodel, variables such as pulling force, actuator'slength, air pressure, diameter and material properties,play a major role in the PMA dynamical behavior andthis is why the mathematical models aim to describethe relationships between these factors. Understandingthose relationships is of paramount importance in everyapplication that consists of PMAs and especially if themain goal is to control its overall function (mainly the length of actuation). Unfortunately, PMAs evidencestrong non-linear force-length characteristics that makeit more difficult to control them and obtain thedemanded performance features [33, 44]. In thefollowing subsections an analysis to the most commonand valuable PMA's models will be presented.

GEOMETRICAL MODEL OF PMA

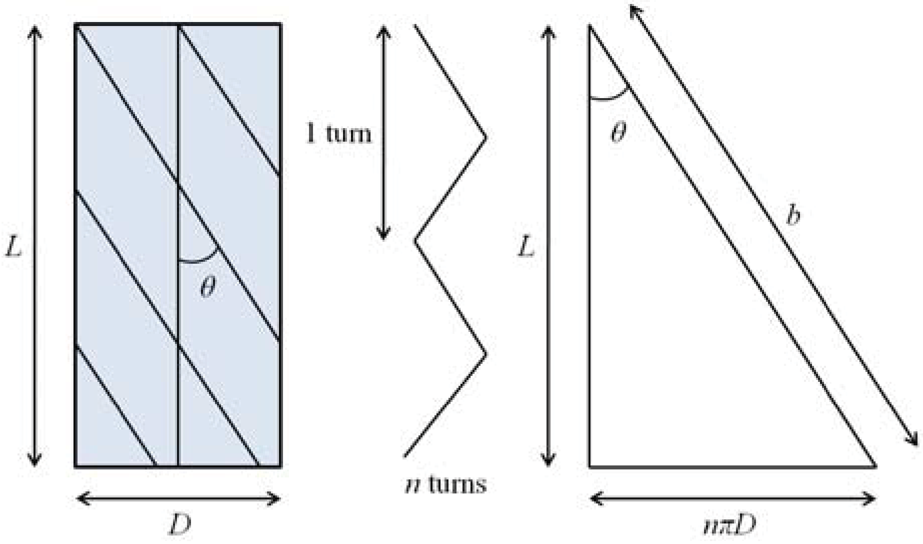


FIGURE 7GEOMETRIC MODEL

The original method of modelling was based on thegeometry of PMA, an approach that has not been veryuseful for predicting the dynamical characteristics ofPMAs because their parameters are not easilymeasured during actuation. Thus, various differentgeometrical models were proposed to describe thebehavior of PMA.

The Chou and Hannaford model is the simplestgeometrical model for a static performance of a PMA.The proposed model is valid under the followingassumptions:

(1) The actuator is cylindrical in shape;

(2)The threads in the sheath are inextensible and always incontact with the outside diameter of the latex bladder;

(3) Frictional forces between the tubing and the sheathand between the fibres of the sheath are negligible; and

(4) Latex tubing forces are negligible.

With this approach the PMA actuator can bemodelled as a cylinder, depicted in Fig. 4, with a length*L*, thread length *b*, diameter *D*, and number of threadturns *n*. The angle is defined as the angle of thethreads with the longitudinal axis.

When the PMA actuator inflates, *D* and *L* change,while *n* and *b* remain constant, while the expressionsfor the PMA's length and diameter can be formulatedas:

$$L = b\cos\theta, D = b\frac{\sin\theta}{n\pi}$$

By combining Eq. (1) the thread length can becalculated as:

$$b = \left(L^2 + D^2 n^2 \pi^2\right)^{1/2}$$

Eq. (2) is referred in the literature as the geometricrelationship for PMA, while its volume is provided by:

$$V = \frac{b^3 \cos\theta \sin^2\theta}{4n^2\pi}$$

Utilizing the energy conservation principle, PMAsimple geometric force *g F* can be calculated as thegauge pressure multiplied by the change in volumewith respect to length (this model can also be found in:

$$F_g = \frac{pb^2\left(3\frac{L^2}{b^2} - 1\right)}{4n^2\pi}$$

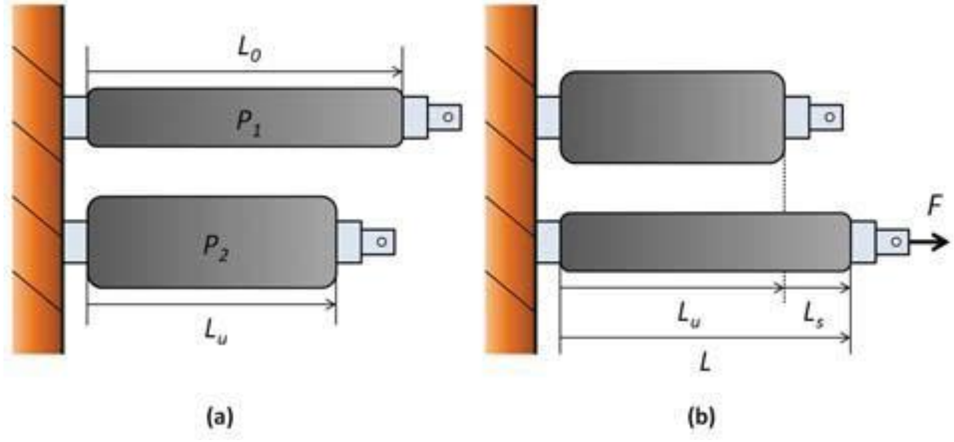


FIGURE 8PARAMETER OF PMA:

(a) initial and final length of the PMA, and (b) length definition when PMA is extended bypulling force.

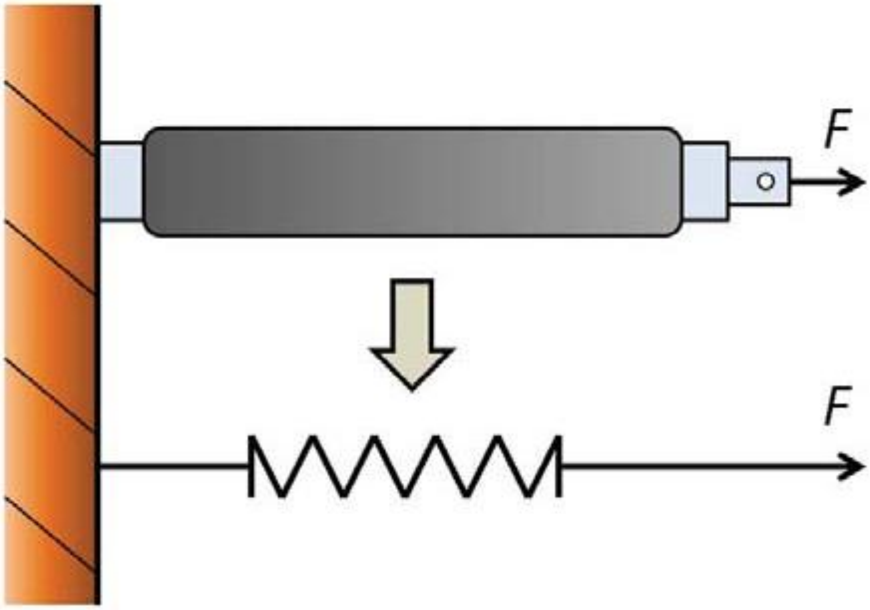


FIGURE 9DIAGRAM OF PMA AND SPRING SYSTEM.

CHAPTER 5

PAM PNEUMATIC CIRCUIT

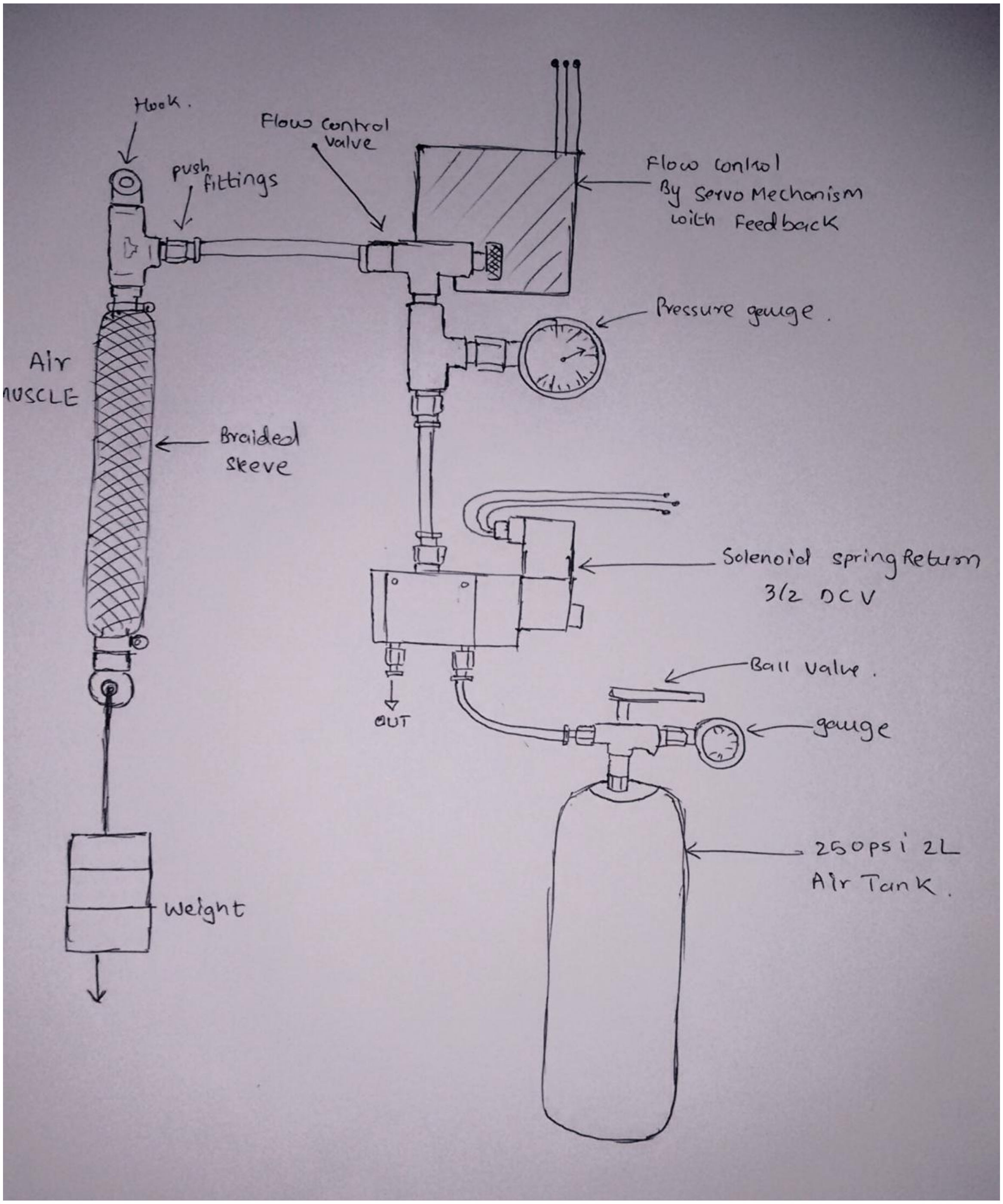


FIGURE 10BASIC PAM PNEUMATIC SYSTEM

This is the basic pneumatic arrangement for the actuation of PAM. The PAM works when connected to load here load is connected to the PAM as shown in the figure. Precision Flow Control Valve is used for control of the air input. This Flow control is made automated by a servo mechanism as shown in the figure. This gives feedback to the microcontroller about the flow rate and hence can be varied dynamically by the microcontroller itself.

Pressure Gauge is connected in series to monitor the pressure of the system at any time while working. A 3/2 solenoid Spring return DCV is used for the direction control. As the muscle works at 8 bar pressure range a 250psi 2L air tank is required.

This completes the whole PAM basic system. The pneumatic circuit is as shown below where PAM is replaced by a single acting spring return pneumatic cylinder.

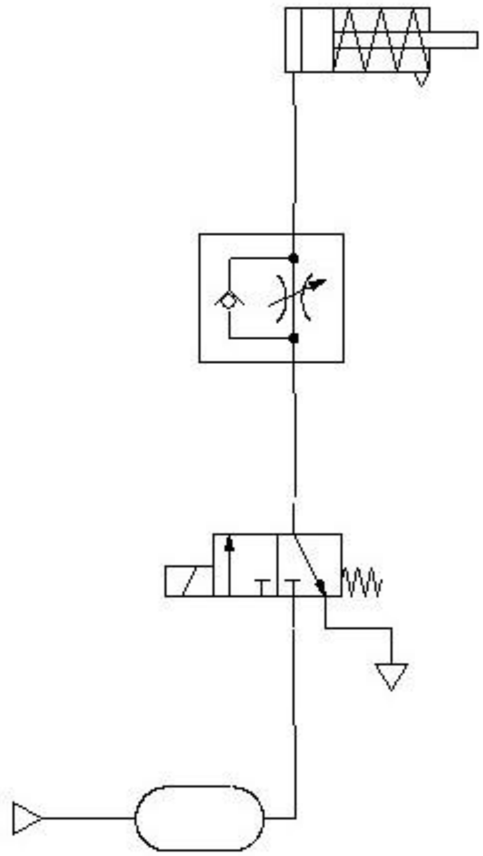


FIGURE 11PNEUMATIC CIRCUIT OF PAM

CHAPTER 6

PAM FEEDBACK CONTROL SYSTEM

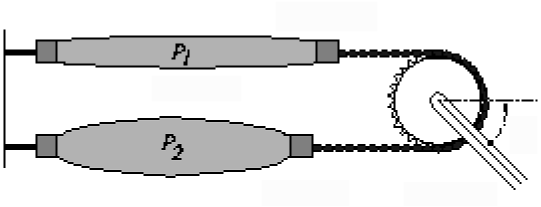


FIGURE 12DUAL AIR MUSCLES CONNECTED TO ROTARY ARM

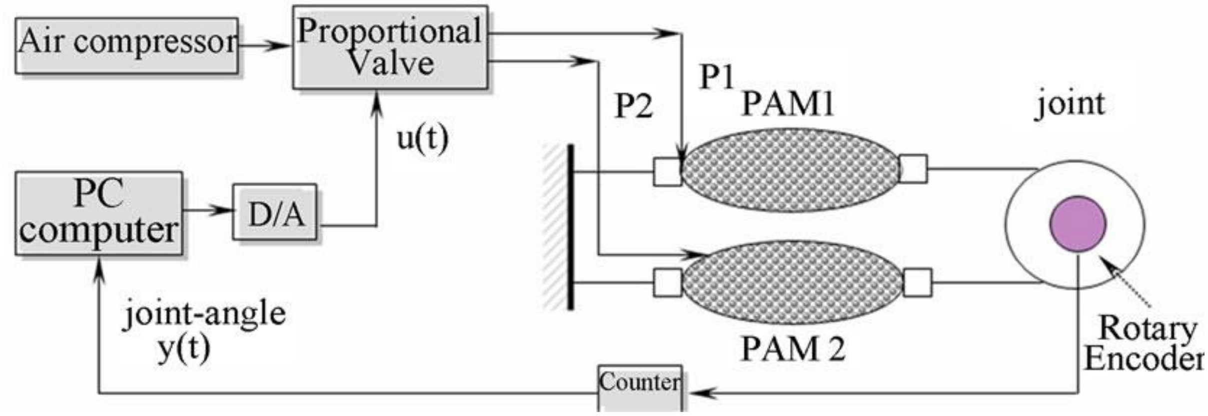


FIGURE 13AIR MUSCLE BASIC CONTROL BLOCK DIAGRAM

6.1 INTRODUCTION

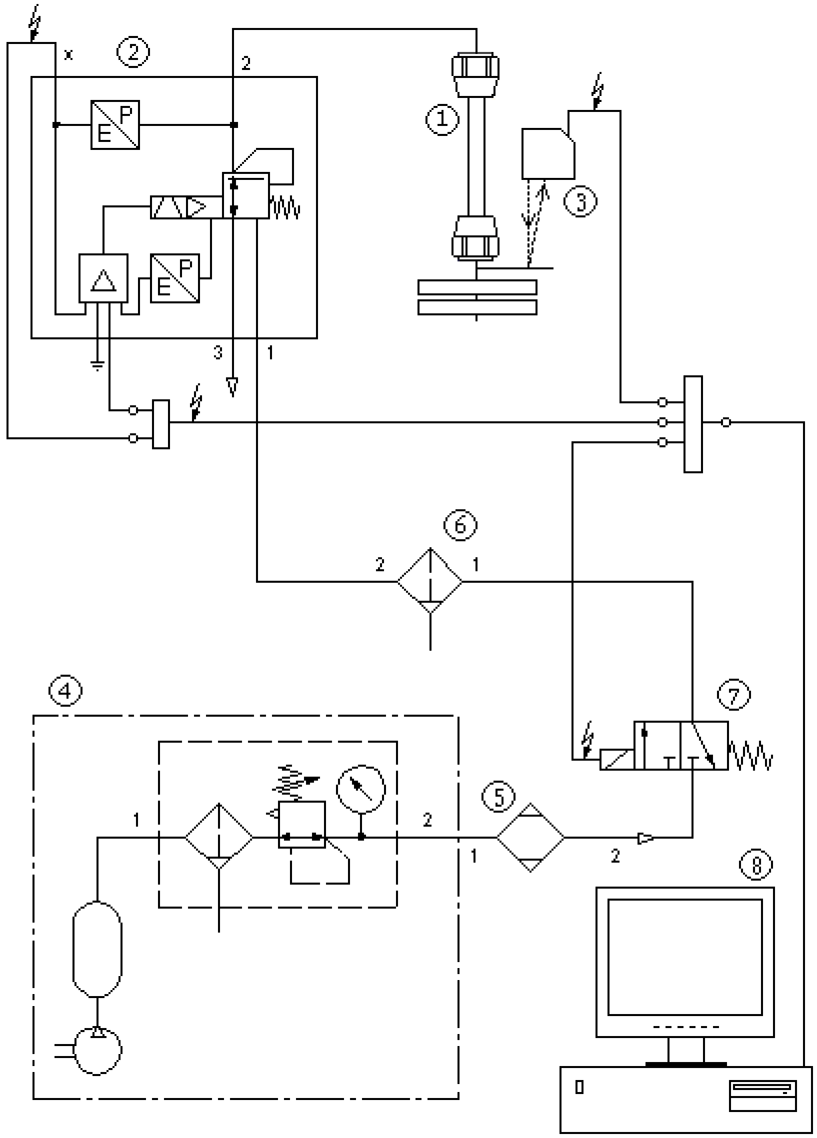


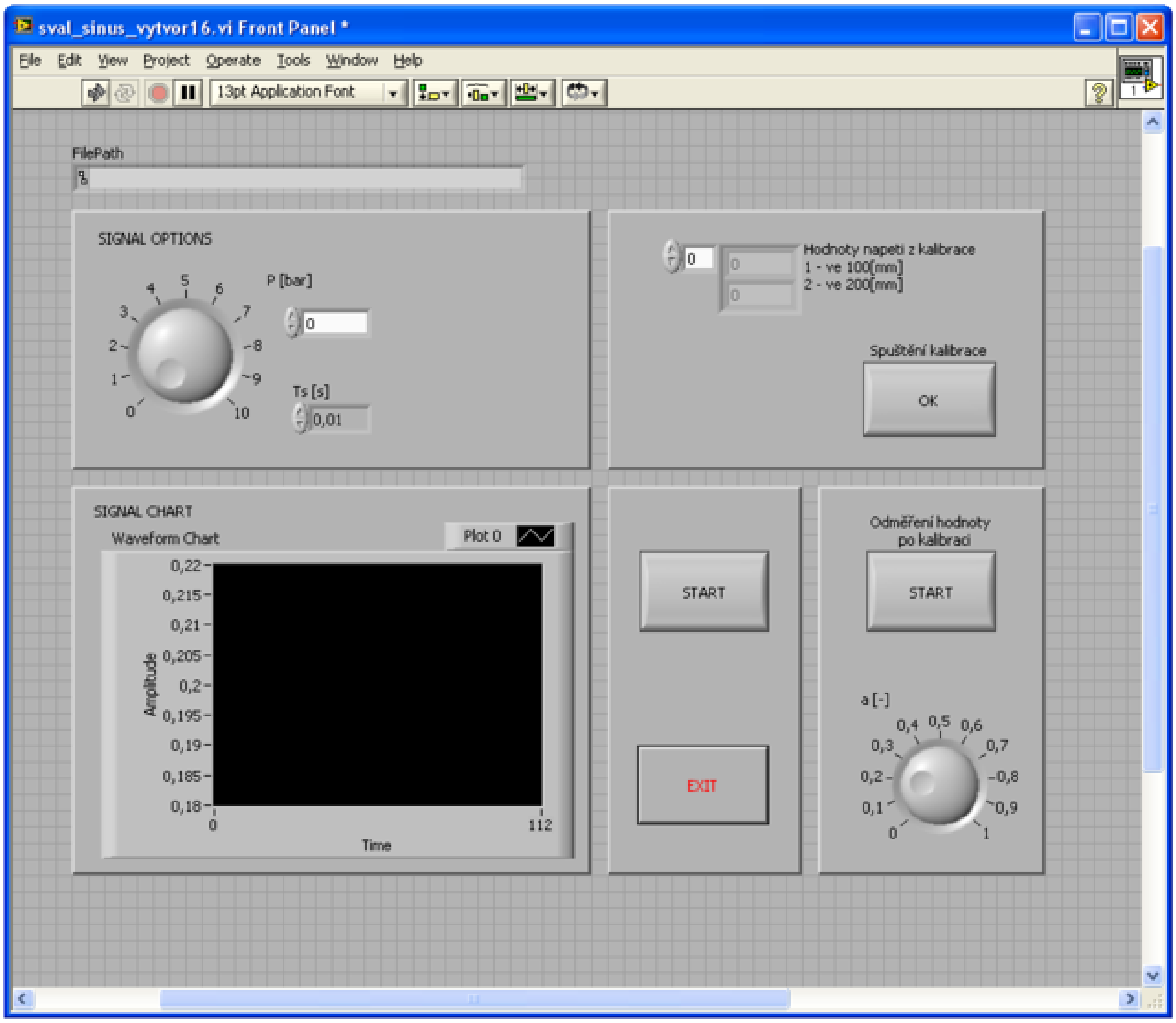
FIGURE 14THE SCHEME OF MEASURING STAND

In the figure 6.3 the scheme of stand is shown.The basic elements of the stand is the pneumatic muscle FESTO MAS-20-605N-AA-MC-O-ER-BG , thepneumatic electro-proportional pressure valve FESTO VPPM-6L-L-1-618-0L10H-A4P-S1C1 and fastprecise distance laser sensor FESTO SOEL-RTD-Q50-PP-S-7L.

The length of the muscle depends onpressure which is in its chamber. The size of the pressure is controlled by means of the proportional valve.The actual length of the muscle is measured by mentioned distance laser sensor.The size of the pressure in chamber of the muscle can be measured by the pressure sensor, which is a part of the proportional valve.

The measuring process was realized by means of an application which was developed in the programming environment LabVIEWof version 8.6.

FIGURE 15THE MEASURING STAND



P [bar]: 0

Ts [s]: 0,01

FIGURE 16THE APPLICATION FOR MEASURING

Hanging of the muscle was purposely chosen as vertical (see figure 3) instead of antagonistic (i.e. twoparallel muscles) because of the elimination the friction. The friction is undesirable. We want to avoid anynon-linearity in the system. Within the experiment, these characteristics: contraction dependence onpressure and loading; hysteresis during loading; measuring of warming up of the muscle during loading weremeasured by the measuring stand. Mechanical properties of the pneumatic muscle have influence on thesecharacteristics. In the next chapter measured characteristics are described.

6.2 EXPERIMENT RESULTS

MEASURING CONTRACTION AND HYSTERESIS OF THE ARTIFICIAL MUSCLE

a) Dependence of muscle contraction on pressure

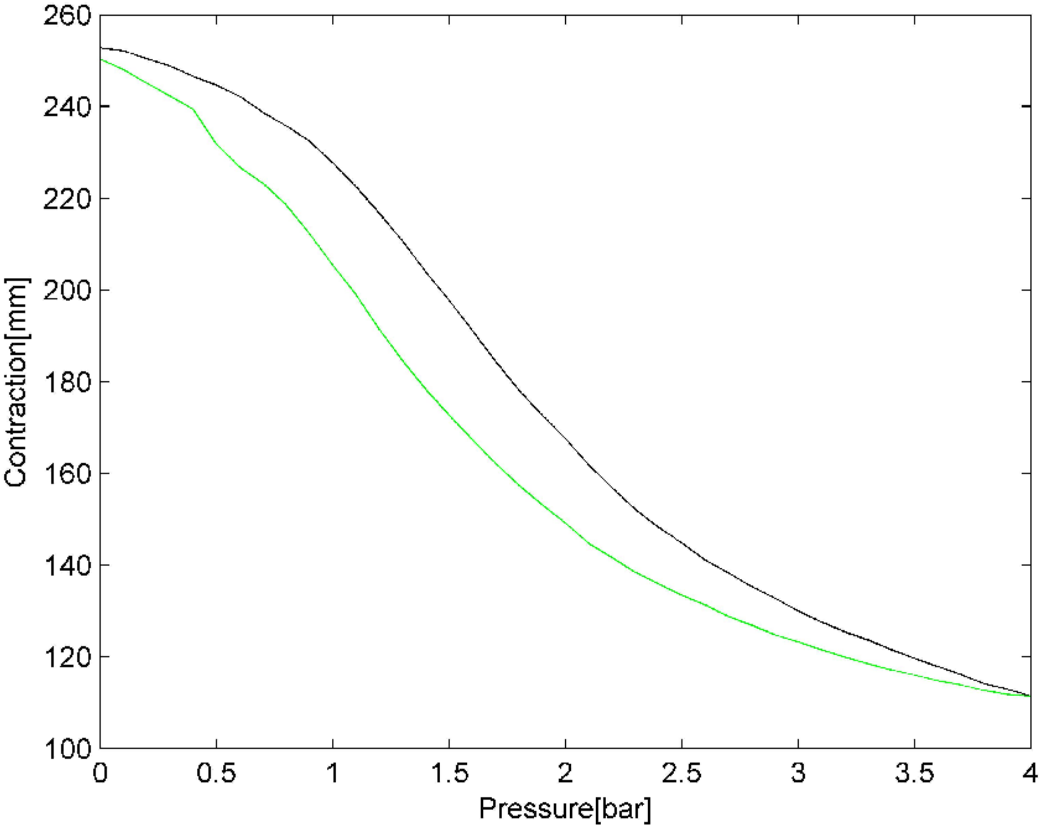
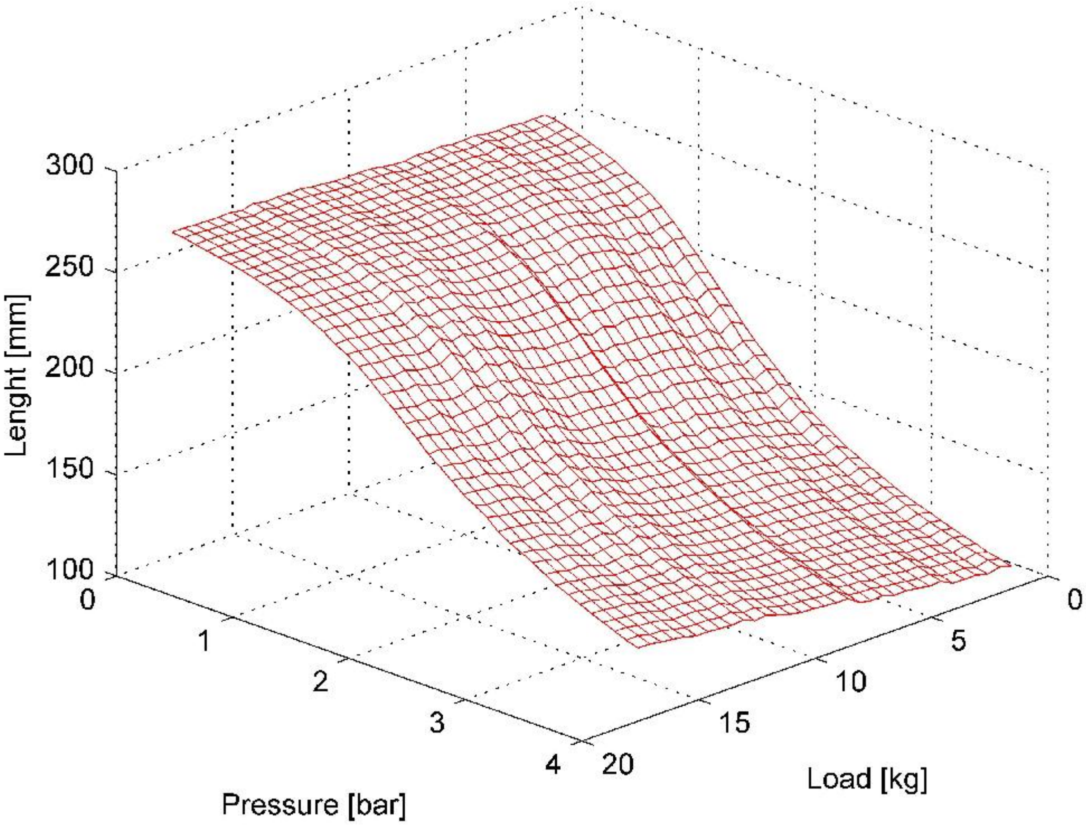


FIGURE 17GRAPH OF HYSTERESIS

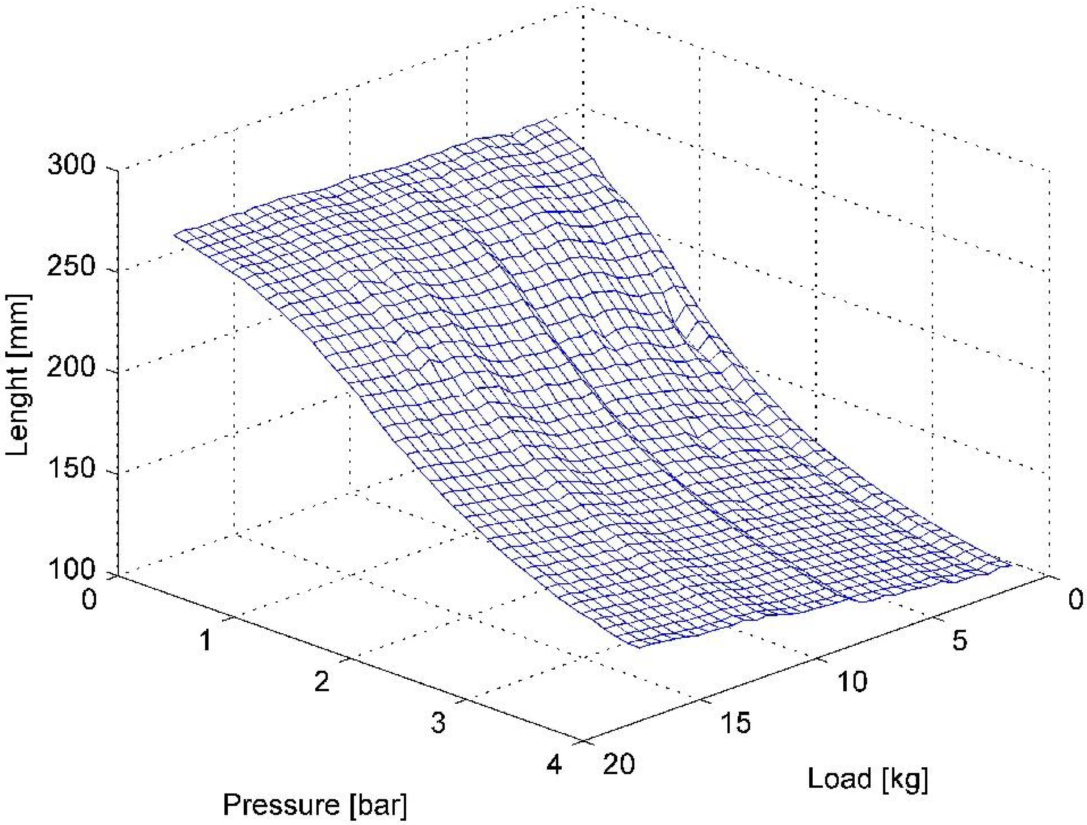
The measurement results show that the artificial muscle has a hysteresis and the loading characteristic(figure 4) is non-linear.

b) Dependence between pressure and contraction with variable loading.

The hysteresis on the muscle was measured in a cycle with variable loading. Figure 5 shows that contraction in dependence on pressure grows with loading. It can be simply said the figure 5 was created from the figure 4 by the addition of the third dimension which is loading.



a) Pressure growing



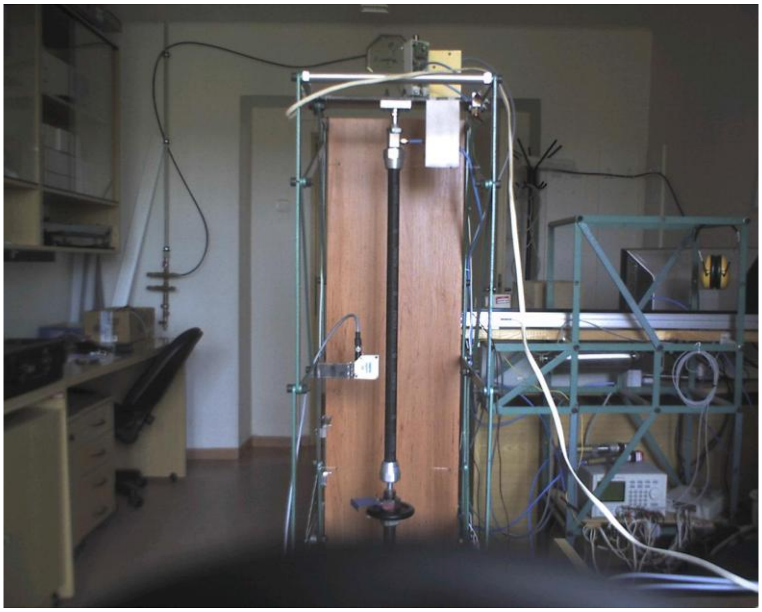
c) Pressure lowering

FIGURE 18CONTRACTION DEPENDENCE ON PRESSURE AND LOADING

The graphs of loading in the figure 5 is split up into two parts due to better visibility. It might be noticed thatthe muscle behavior is non-linear both in pressure growing / lowering and as well in change of the nominalloading. This can be seen in both graphs a), b) – upper limit lines are not parallel with bottom limit lines.

6.3 MEASURING CHANGE OF TEMPERATURE DURING PROGRESS

All known models speak only about “temperature constant model of the artificial muscle” in spite of the fact that the muscle is worming up during progress. However, temperature of the material must not be ignored within the mathematics model development because the temperature of muscle material rises during the loading. The muscle was produced from anisotropic hyper elastic material. This material is distinguished by temperature dependency.



a) Measuring stand for temperature measurement

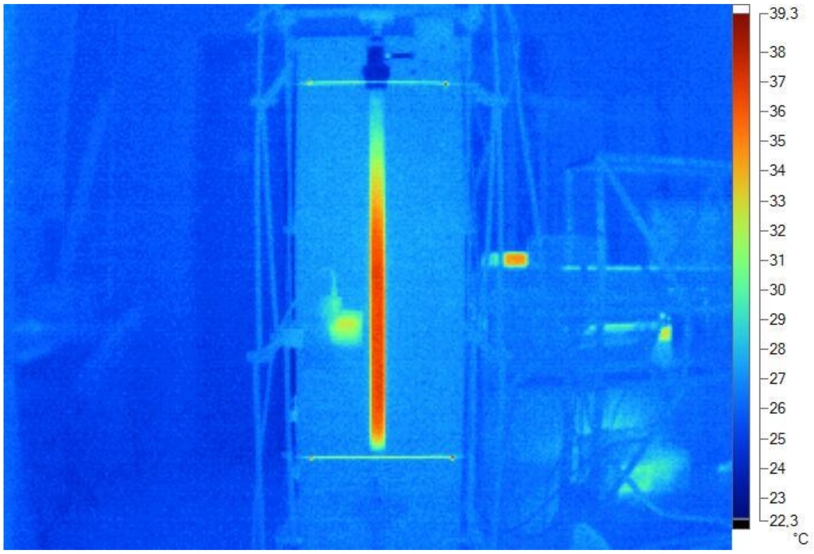
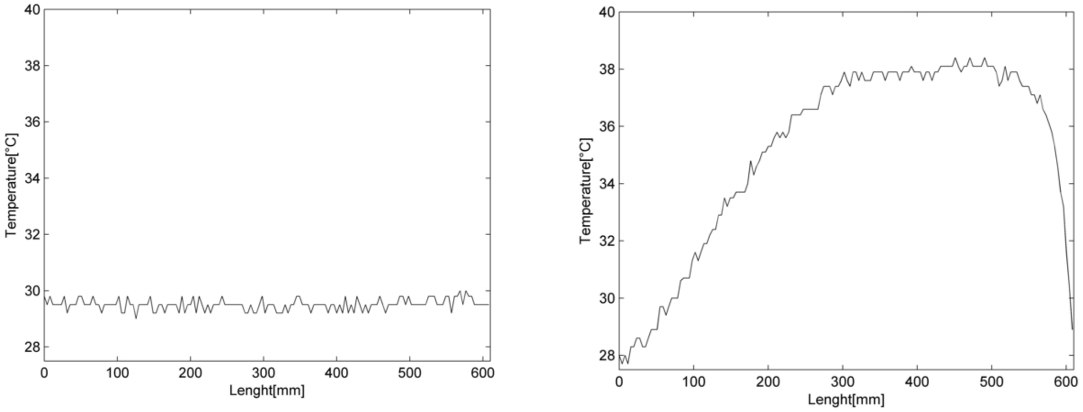


FIGURE 19THE MEASURING STAND WITH THE RESISTANCE WIRES.

b) Variable temperature along muscle's length

The change of the temperature has influence on hysteresis of the load characteristics and mechanicalproperties of the muscle. Thus, to be able to develop mathematical model of the muscle within the nextresearch the temperature of the muscle during progress with defined loading was measured.To do that, the measuring stand had to be modified for temperature measuring of the muscle. Temperaturemeasurement was performed by means of resistance wire. It was placed on top and bottom tail of themuscle. The placement of the wires is visible in the figure 6, which was obtained from thermo-camera.From the thermo-camera pictures there was made a series of graphs of the muscle temperature. One ofthem is shown in the figure 7.



a) Temperature before measuring b) Temperature after 2 minutes of work

FIGURE 20THE TEMPERATURE MEASURING ON THE MUSCLE

The temperature measuring showed that temperature along the muscle is no constant. Temperature at thetop tail of the muscle is lower than at the bottom tail. All graphs were put together into one three dimensionalchart, see figure 8. Obtained knowledge of warming up of the artificial muscle will be used for creating of themathematical model in future.

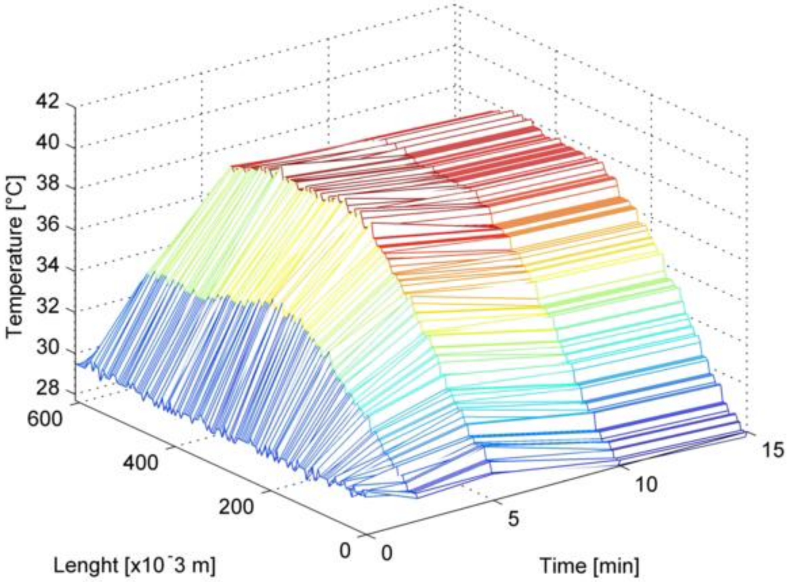


FIGURE 21THREE DIMENSIONAL GRAPH OF TEMPERATURE MEASURING

CHAPTER 7

MECHANICAL DESIGNS

7.1 DESIGN 1

Below are some CAD images of the design 1- Raw Design

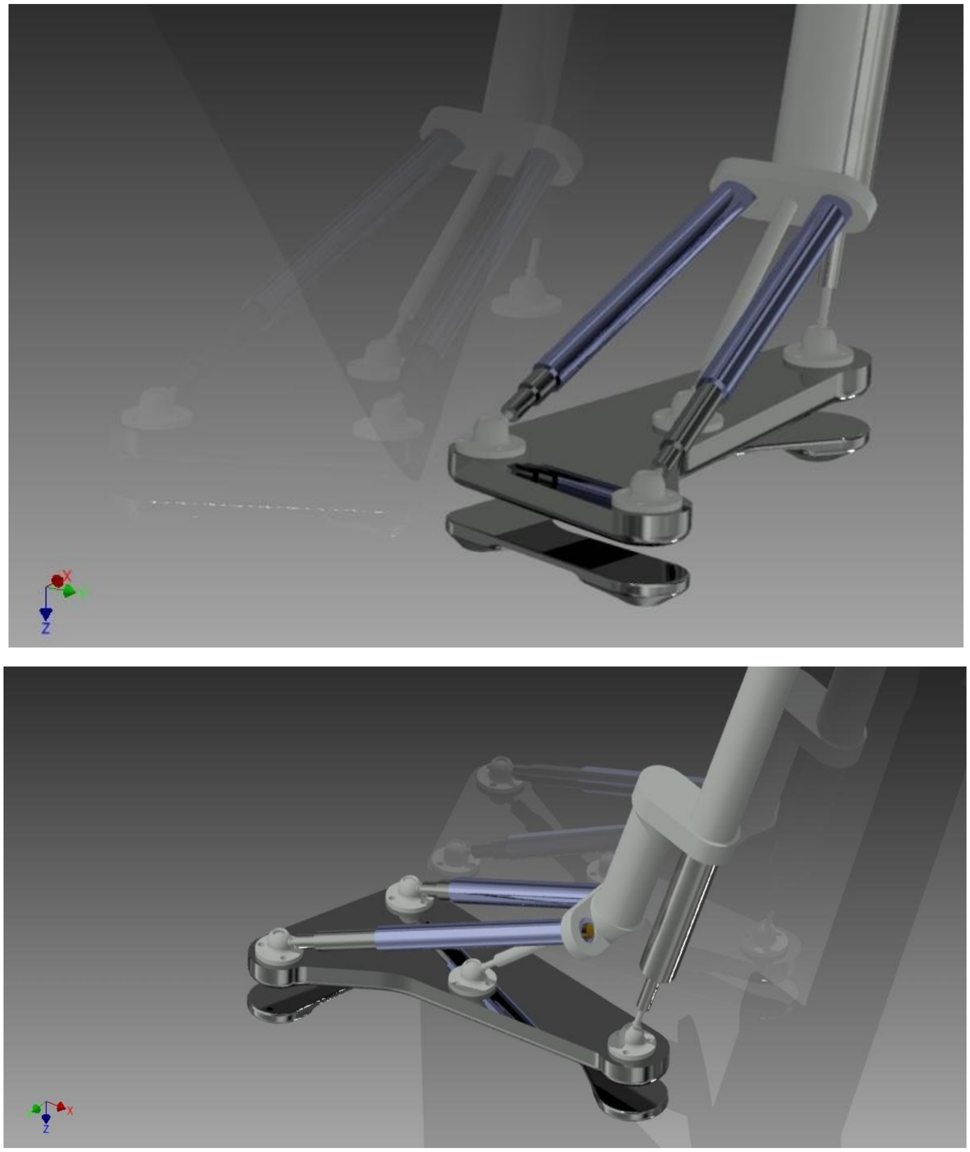
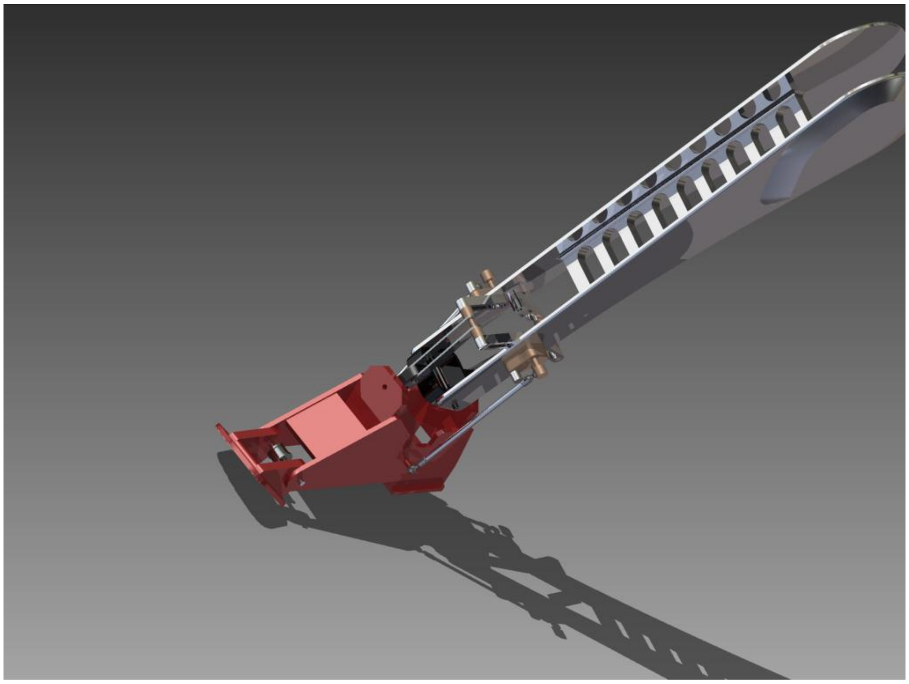


FIGURE 22DESIGN1 FOOT MECHANISM

7.2 DESIGN 2.1

Below are some CAD images of the design 2- Raw Design



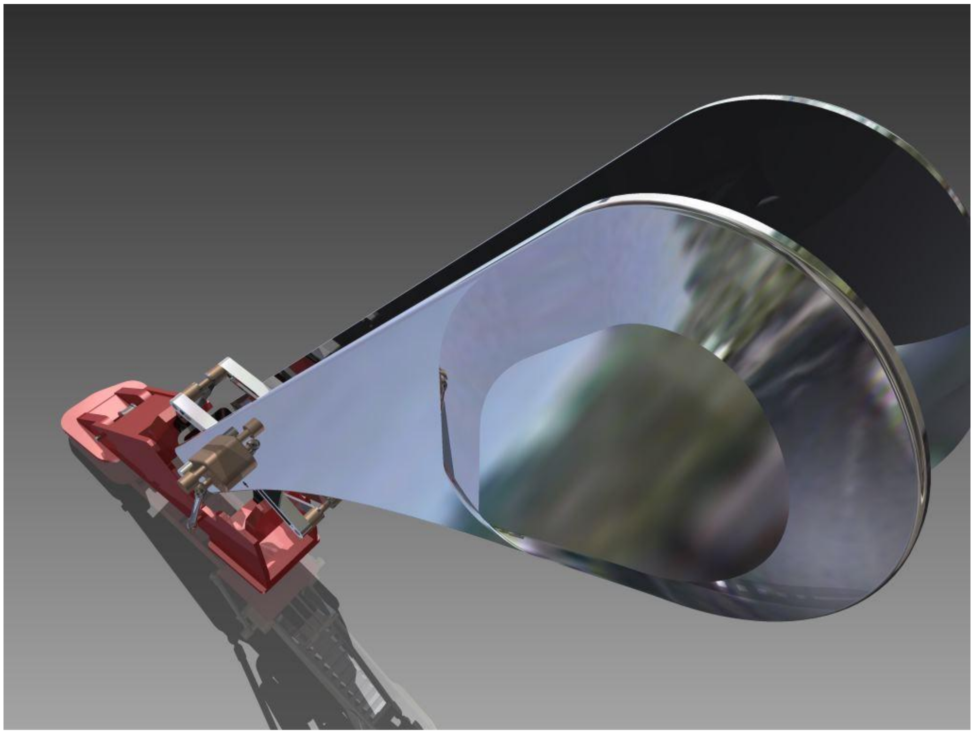
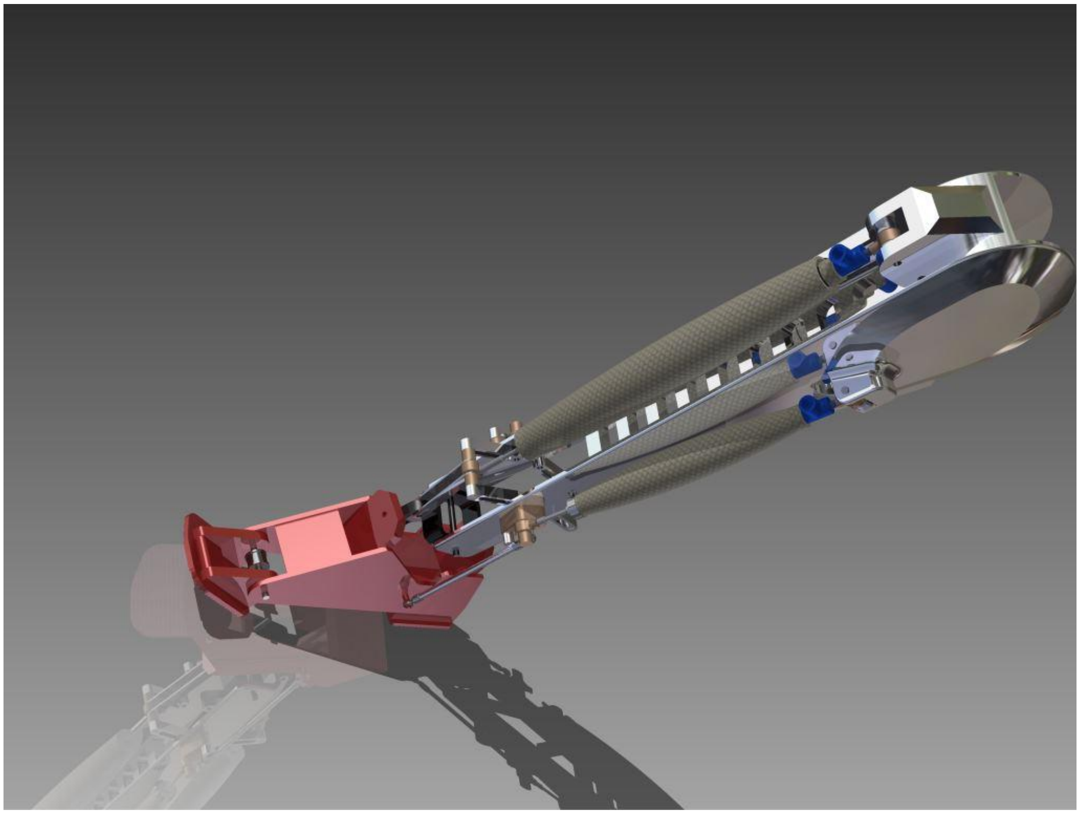
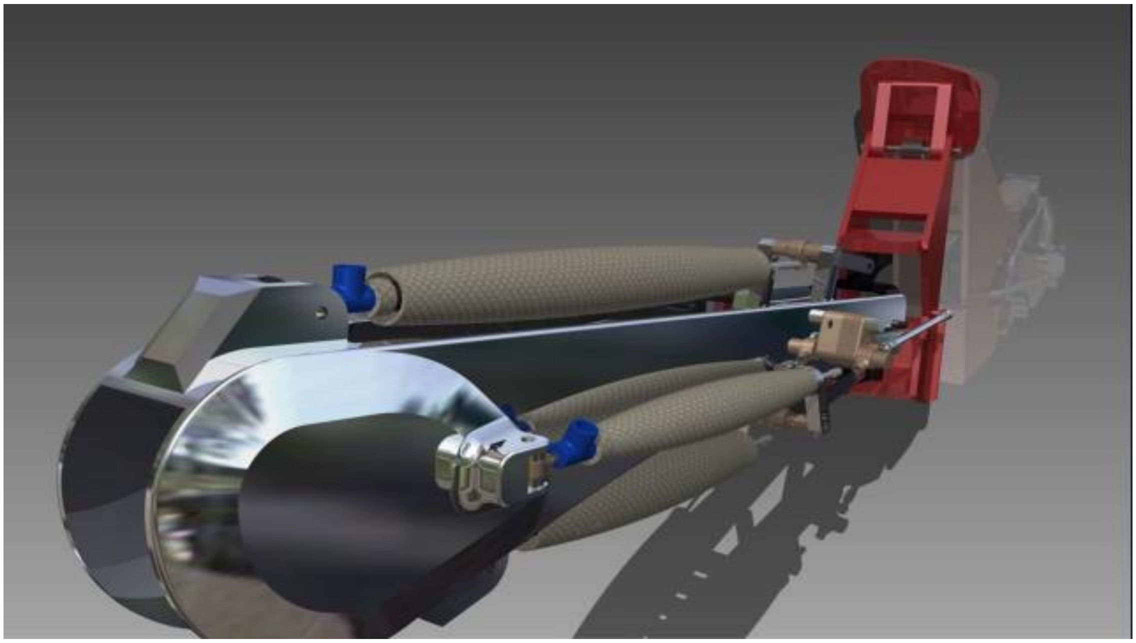


FIGURE 23LEG DESIGN WITHOUT AIR MUSCLES

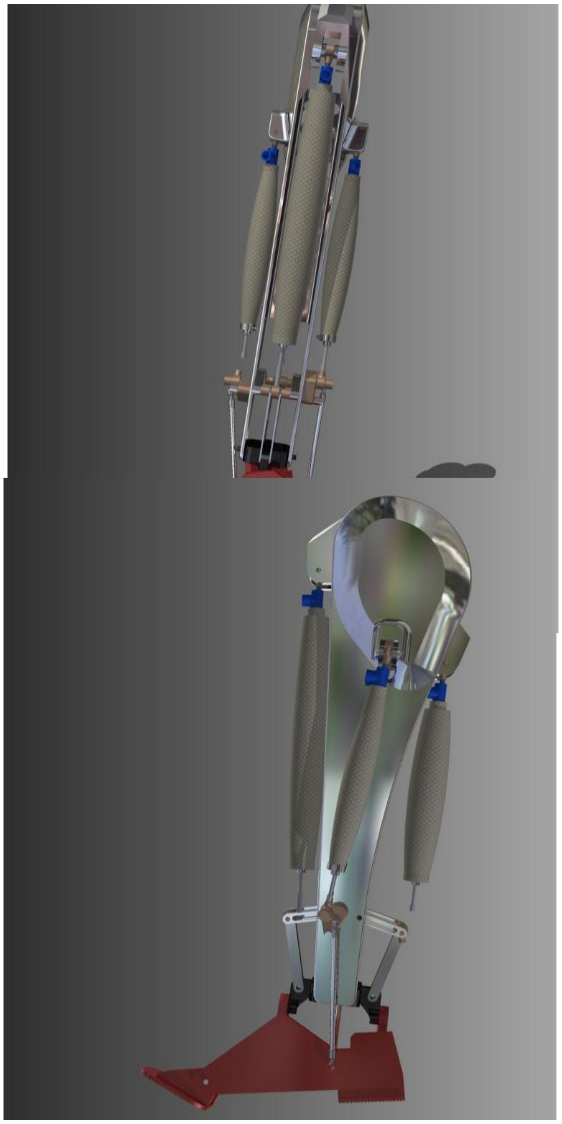
7.3 DESIGN 2.2



(a)



(b)



(c) (d)

Figure 24(a),(b),(c) and (d) leg Design 2.2

7.4 DEGREE OF FREEDOM (ANKLE)

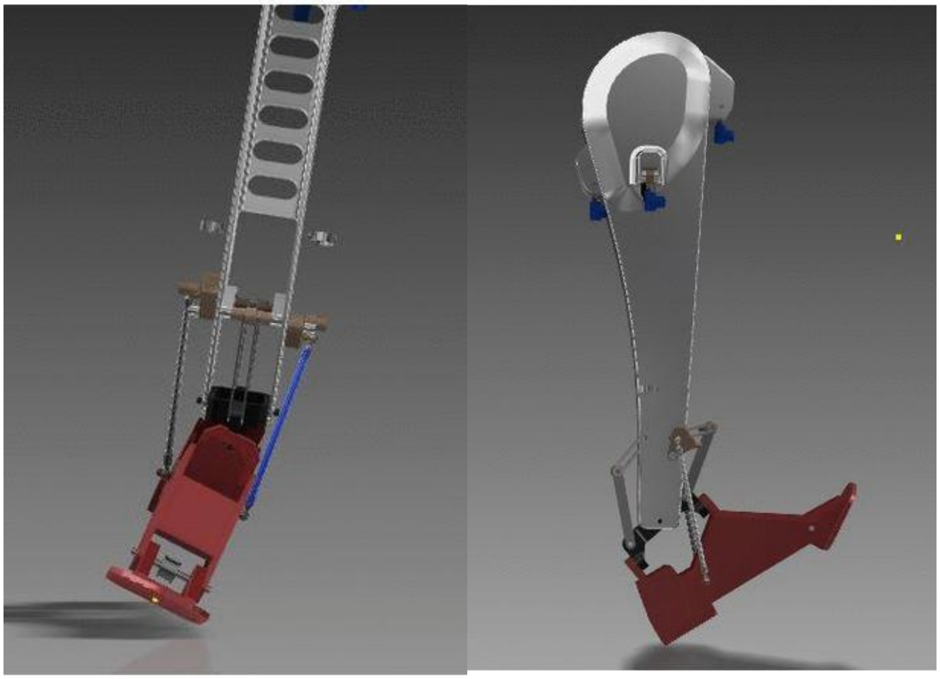


FIGURE 25ANKLE MOVEMENT DOF

7.5 KNEE MECHANISM

Below are some CAD images of Knee Mechanism

FIGURE 26KNEE MECHANISM

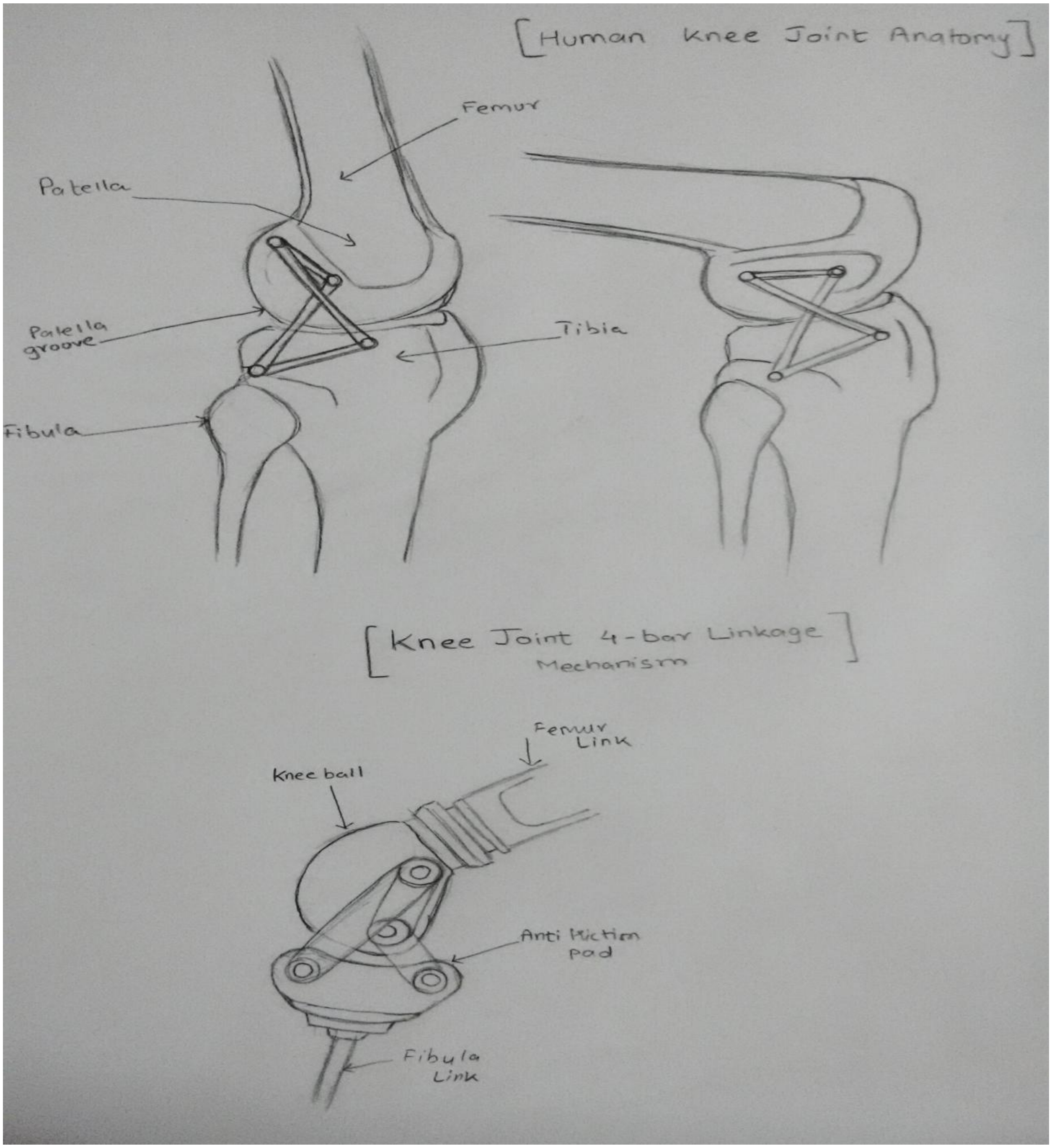

[Human Knee Joint Anatomy]
Femur
Patella
Patella groove
Tibia
Fibula
[Knee Joint 4-bar Linkage Mechanism]
Femur Link
Knee ball
Anti friction pad
Fibula Link

FIGURE 27

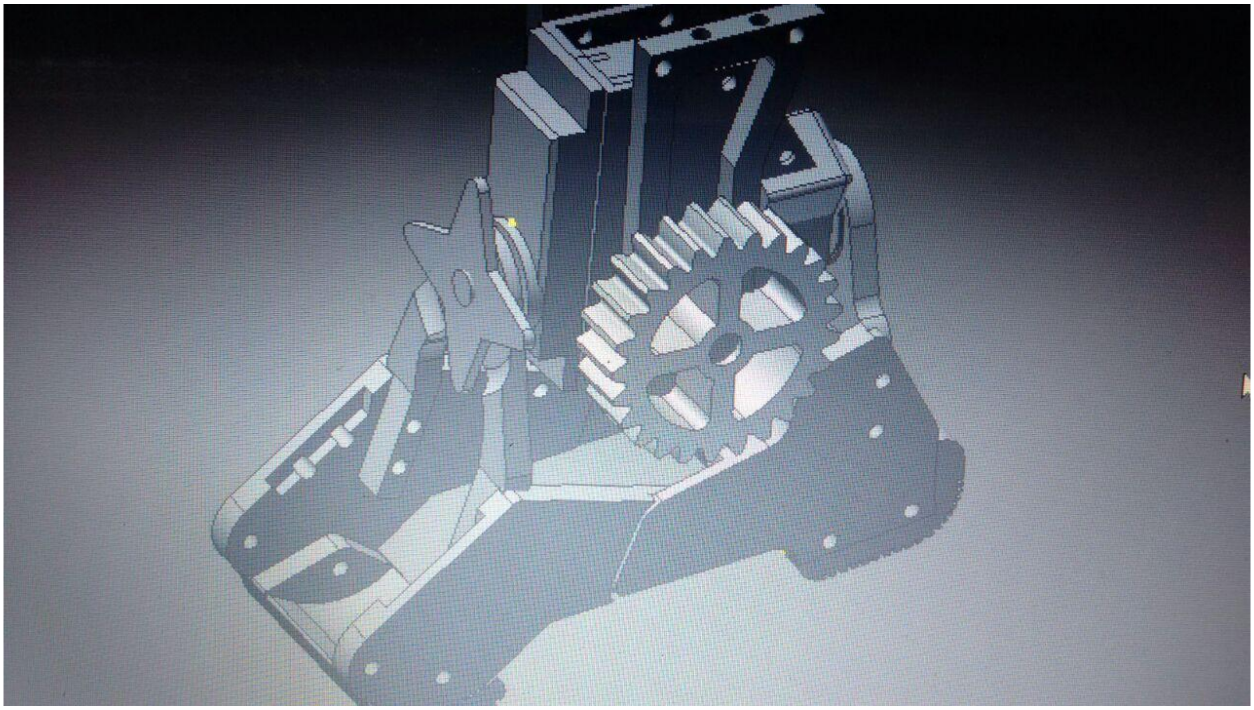


FIGURE 28

.7 3D PRINTED FOOT

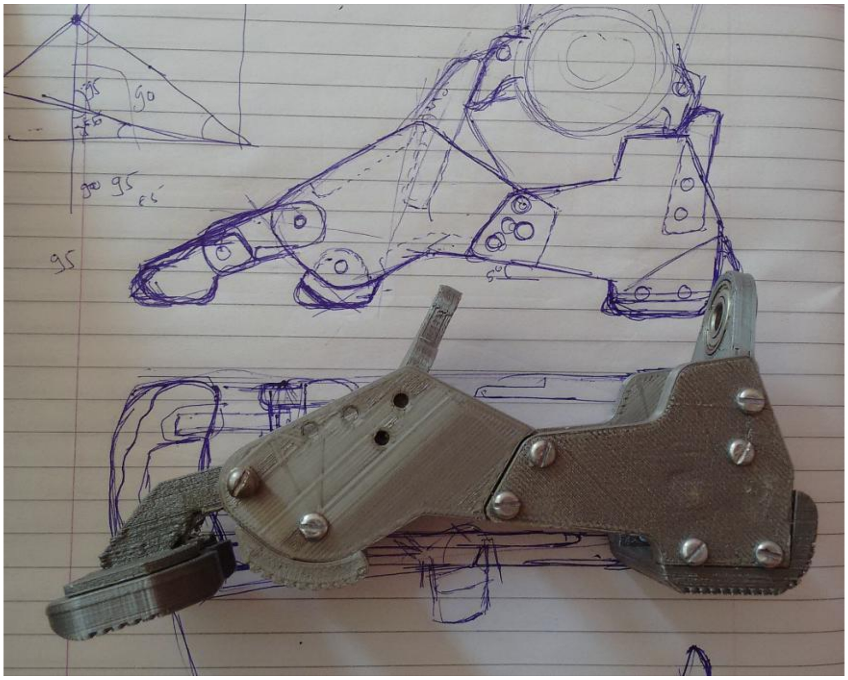
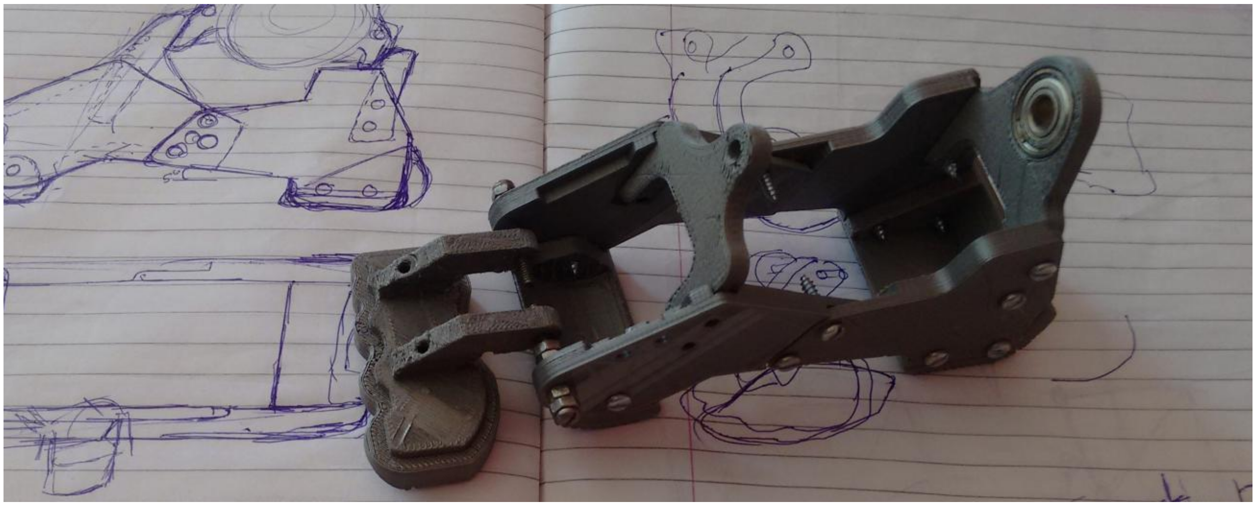


FIGURE 29 3D PRINTED LEG



PNEUMATIC CIRCUIT :

FIGURE

FIGURE 30 AEIOU SUMMARY

FIGURE 27EMPATHY SUMMARY

FIGURE 28IDEATION

FIGURE 29PRODUCT DEVELOPMENT

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   Faculty of Engineering and Information Technology,
   University of Technology, Sydney, Australia
   Ruiyi.tang@student.uts.edu.au, Dikai.liu@uts.edu.au