MAGNETIC ACTUATION OF AN ARTIFICIAL MUSCLE MODEL

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February, 2017

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A thesis submitted in partial fulfillment of the requirement for the degree of
Masters of Science

In
Biomedical Sciences and Engineering

By

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I dedicate this thesis to my parents for their immense support, motivation & love.

ACKNOWLEDGEMENTS

All praise to Allah Almighty for bestowing me with the courage, knowledge and health to carry out this project.

I would like to express my sincere gratitude to my supervisor, Dr. Umar Ansari and Dr. Murtaza Najabat Ali for their guidance; continuous support and providing me with the resources that came in handy throughout my project. I am obliged to Dr. Nabeel Anwar, HoD BMES for his valuable advices and administrative support.

I would like to express my sincerest thanks to Rector NUST and Principal SMME, Dr. Abdul Ghafoor for providing us with an excellent research environment in SMME, NUST.

I am highly gratified to my friends Fatima Darakhshan and Amnah Mahroo for being with me in every thick and thin throughout my Masters and for being a helping hand in every way possible. I would like to say special thanks to my seniors Mariam Mir and Bakhtawar Ghafoor for their assistance, motivation and scientific discussions.

Furthermore I would like to acknowledge lab technician Prosthetics Lab, SMME and MRC personnel for their assistance. I am also thankful to my lab fellows Aisha Tahir, Javairia Yousuf, Amber Zahoor and Hafsa Inam for creating a friendly lab environment.

I owe my gratitude to my friends Sana Javed and Sidrah Naseem for their valuable advices and bearing with me during hard times. Also I would like to say special thanks to Mr Ahmad Raza for providing me with logistics support throughout my project

Finally, an honorable mention goes to my husband Zahid Ali Shah and my entire family for their continuous support and guidance.

Misha Mazhar

ABSTRACT

Human and Animal movement is driven by muscle which is a biological elastic actuator. As muscles can operate in different modes depending on the contraction dynamics and structural implementation, it would be desirable to have an artificial actuator with similar capabilities in order to cater muscular disabilities. A Hill Based muscle model was designed containing a contractile element majorly responsible for active force generation and a nonlinear element responsible for passive force generation. The muscle model was designed on the principle of lead screw mechanism in which a primary magnetic shaft attached to a motor was used to drive the secondary magnetic shaft. The rotatory motion of magnetic shafts was then used to obtain linear motion through a lead screw mechanism giving us a sarcomere like contraction in the secondary shaft. Load vs. RPM testing was performed followed by final parametric testing and Data Analysis.

Keywords*:* *Muscle Models, Magnetic actuation, Design and Fabrication, Force, Velocity*

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LIST OF ACRONYMS

Direct Current	DC
Millimeters	mm
Pneumatic Artificial Muscles	PAMs
Polylactic Acid	PLA
Primary Driving Magnet	PDM
Revolutions per minute	RPM
Robot Muscle ACtuator	ROMAC
Secondary Driving Magnet	SDM

LIST OF FIGURES

CHAPTER 1 INTRODUCTION

Movement is an essential characteristic of all living organisms. Each and every living creature on this planet, move according to its own mechanism and requirement. The human and animal movement is achieved with the help of a muscle which is a biological elastic actuator. If we look at the intricacy and diversity of the movements generated by a muscle, we can see that a muscle is a powerful, versatile and flexible actuator. Since muscles can function in various modes subject to its structural implementation and contraction dynamics, therefore it is able to show such a flexible behavior. Keeping in mind such versatility of a muscle as well as the disabilities related to muscles, it would be desirable to have an artificial actuator which shows similar capabilities.(Haeufle, Günther, Blickhan, & Schmitt, 2011)

Over the course of years, in order to cater muscular disabilities, scientists have tried to make muscle models in order to mimic the action and versatility of an actual biological muscle. Many models have been developed ever since. Some have also been commercialized. But each model has its own pros and cons to be used as an implantable muscle actuator. In this study the basic aim was to develop a muscle model which could be implanted into the human body as a replacement to its disabled counterpart. This actuator should be controlled remotely with the help of magnetic coupling. Thus we have tried to create a mechanical muscle model which shall mimic the action of a physiological muscle when placed inside the human body.

The basic concept behind this project is the use of rotatory motion of magnets which would be translated to a linear motion through a lead screw mechanism. The rotatory motion would be achieved by the insertion of alternating magnetic poles. When the primary shaft rotates the magnetic poles change causing the magnets of secondary shaft to rotate as well.

In order to achieve sarcomere like contraction in the muscle model, it was conceived that if we use opposite threading on both sides of the magnetic assembly, we would be able to achieve the contraction and relaxation of the muscle model upon rotation. So on one side there is right handed threading and on the other it is left handed. Upon rotation of primary shaft, secondary rotates due to the magnetic coupling. Now if the screws on LHS & RHS are kept from rotating, they would move inwards and outwards simultaneously upon rotation of the shaft giving us a linear motion.

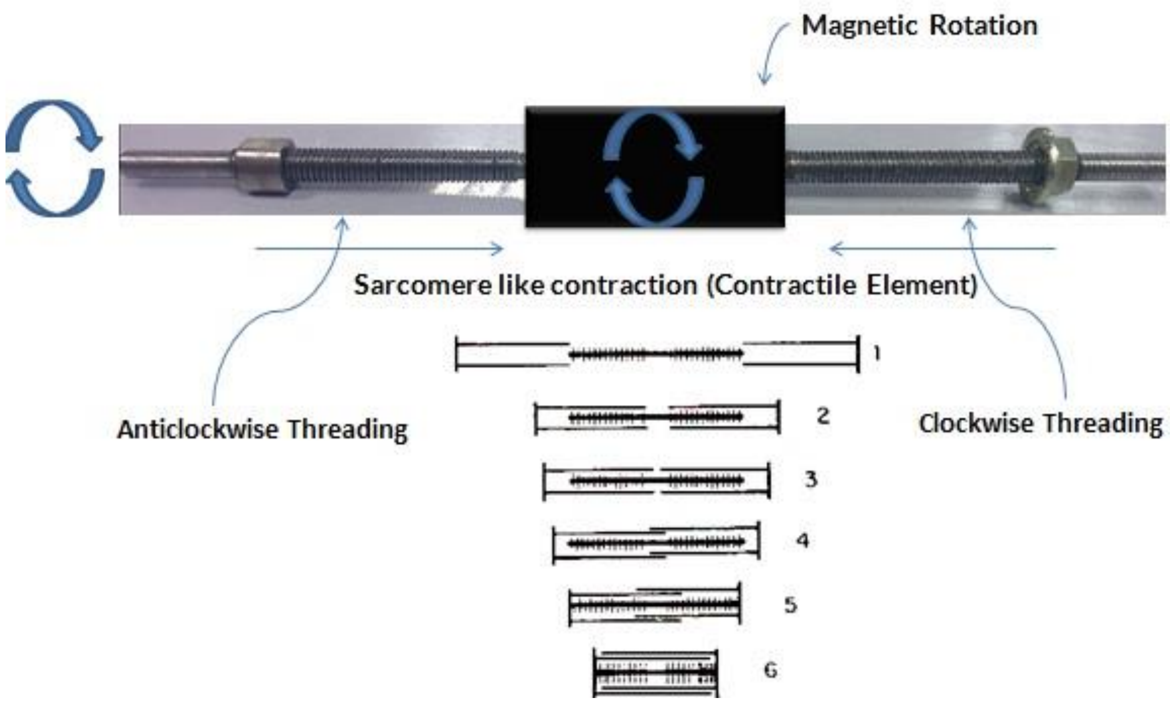

Figure 1.1 *Lead screw mechanism: Concept of designing the artificial muscle model*

As this muscle model would be based on Hill's muscle model. The Elastic Elements must also be incorporated in order to get Muscle behavior closer to a physiological Muscle. Elastic Element would be incorporated by the use of a Polymeric Sheet which would cover the entire muscle model. Also it would give this system a muscle like appearance.

CHAPTER 2 REVIEW OF LITERATURE

Over the course of years, in order to cater muscular disabilities, scientists have tried to make muscle models in order to mimic the action and versatility of an actual biological muscle. Many models have been developed ever since. Some of them would be discussed here in detail

2.1 MUSCLE MODELS

Keeping in view muscle anatomy and biomechanics, many muscle models have been devised with time. These muscle models include Hill's contractile element proposed in 1938 which makes it possible to quantify force-velocity relationships. Huxleys's sliding filament hypothesis proposed in 1957, Bahler's force generator proposed in 1968 analyzes isometric tension development followed by repetitive simulation. Vickers and Sheridan's variable viscosity dashpot proposed in 1968 signifies the dependence of force-velocity relationship parameters on stimulus level. (Apter & Graessley, 1970)

2.1.1 HILL'S MUSCLE MODEL

In 1938 A.V Hill proposed a muscle model based on "systems engineering" perspective. Since then many other models has also been proposed and utilized but has been the choice of scientists for most of the modeling studies of multiple muscle movement systems. (Winters, 1990b) Amongst all the reasons for the use of this system, one major reason is that this muscle model is able to describe most of the prominent features of muscle mechanics in an appropriate way as well as the fact that it is easy to estimate model parameter values. (Winters, 1990b) Therefore most of the muscle models have been based on Hill's muscle model.

It is known that a muscle's total force is composed of 2 components; active and passive force. The active force is provided through the "ratcheting mechanism" of its contractile elements i.e. actin and myosin. Passive force is contributed by its non-contractile elements. The passive force of a muscle has properties which are most correctly designated as elastic. But these elastic properties of passive element can be modeled as a spring. Since the spring like passive element is attached in series to the contractile element, the force produced by the contractile element can be thought of as an active force which is transmitted to the skeleton via a series elastic element. In addition to series elastic element, another elastic element also plays its role in contribution to muscle's passive force known as parallel elastic element.(Shadmehr & Wise, 2005)

In Hill's muscle model such series and parallel elastic elements represent connective tissues.(Winters, 1990b) A V Hill in 1922 along with his colleagues performed various experiments on animal and human movements which were primarily done to observe contractions against inertial loads. These studies and observations lead the scientists to view the muscles as spring like structures that work in a linearly viscous medium. (Winters, 1990b) Hill originally also suggested that the force velocity property was nonlinear rather than linear which was later on confirmed by Fenn and Marsh in 1935.(Winters, 1990b)

Hill noted that when muscles are activated isometrically i.e. at a fixed length, they produce more force than when they shorten. When muscles shorten, it appears that they tend to waste some of their active force in order to overcome the inherent resistance. Since the series elastic element resists lengthening rather than shortening of a muscle, therefore this inherent resistance could not have resulted from SEE. Therefore Hill concluded that this kind of resistance is due to another kind of passive force in the muscle. He found out that less force is generated when a muscle shortens at a faster rate. He concluded that faster shortening lead to a larger resistive force provided the active force is constant. (Shadmehr & Wise, 2005)

Based on Hill's experiments he concluded that less force is produced by a muscle when it shortens. He suggested that this element lies in parallel to the contractile element therefore it can be constituted as a parallel elastic element.(Shadmehr & Wise, 2005)

The Hills muscle model showed that the passive properties of a muscle are constituted by 2 elastic elements and a viscous element. These elastic elements are readily justified by the physical properties of muscle fibers which actually results from the spring like properties of the connective tissues that surround the muscle as well as the connections within a muscle fiber. However the viscous element is not a result of any actual fluid but it is actually due to the actin-myosin contractile mechanism which can be modeled as viscosity in this muscle model.(Shadmehr & Wise, 2005)

Hill's muscle model has been widely used by the researchers in different kinds of artificial actuators in order to characterize muscle performance.(Seow, 2013)

2.2 PNEUMATIC ARTIFICIAL MUSCLES

Pneumatic Artificial Muscles also known as PAMS has been widely used in various applications such as Rehabilitation devices, safe physical human robot interaction and as energy efficient walking robots. These actuators have been in wide use due to their physical flexibility, spring like characteristics, variable stiffness and lightness of weight as compared to others types of actuators.(Villegas, Van Damme, Vanderborght, Beyl, & Lefeber, 2012)

A PAM is a linear and contractile motion engine which is operated by gas pressure. The concept of this system is a very simple one. The core element of the actuator is a flexible closed membrane like a shell or diaphragm. The flexible membrane is attached to end fittings at both ends (clamps/closures). Mechanical power is transferred to a load through these end fittings. The membrane bulges outward when it gets inflated and as the gas is sucked out it gets squeezed. (Daerden, 1999)

As a result of this radial expansion or contraction, the shell of the membrane contracts axially and hence exerts a pulling force on its load. The force generated by this kind of actuator is unidirectional and linear.(Daerden, 1999)

PAMs are light weigh actuators and they operate at an overpressure so that more energy is transferred. Therefore the state of this kind of PAM is then determined by its gauge pressure and length. The compliance of PAMs is not only due to the gas compressibility but also due to the varying force to displacement. And since the compliance can be easily adjusted, they are mostly characterized by their compliance. These actuators are able to produce high output forces at all speeds. Gears are not used in such actuators therefore the introduction of inertia or backlash is minimal. These actuators are easily connected and are mostly hazard free like electric shock, explosion, fire or pollution. (Daerden, 1999)

PAMs are being used in various applications by many research groups. They use them for prosthesis and orthotics and also to power robots of anthropomorphic designs mostly.(Daerden & Lefeber, 2001)

2.2.1 PNEUMATIC SYSTEMS ATTRIBUTES

There are many attributes of pneumatic systems due to which they are being highly used in various applications. Some of the attributes are listed below (Ali, Noor, Bashi, & Marhaban, 2009; Tablin & Gregory, 1963)

- No temperature limitations for gases as compared to hydraulic fluids
- There is no need to collect the actuator's exhausted gases
- There is no long term storage problem since these systems are dry
- No need to use organic materials
- These are light weight actuators but has high power rate than an electromechanical actuator
- They are easy to handle and maintain due to their simple technology
- Low in cost, easy to clean, safe and easy installation

2.2.2 TYPES OF PNEUMATIC ACTUATORS

Scientists have developed different types of pneumatic actuators in an attempt to achieve a muscle model which would closely mimic the action of an actual physiological muscle. The various pneumatic actuators which have been developed can be distinguished on the basis of their design and operation

- Braided Pneumatic Actuators
- Netted Pneumatic Actuators
- Embedded Pneumatic Actuators

Some of these actuators would be discussed and analyzed in detail in this review

2.2.2.1 BRAIDED PNEUMATIC ACTUATORS

Joseph L. Mckibben, an American physician, was the first person to introduce the braided pneumatic actuators to the prosthetics community in late 1950s. The basic concept of these actuators was first described in a U. S. patent issued to Alexander Morin in 1953. (Baldwin, 1969)

Braided muscle actuators consists of a gas filled inflatable inner bladder which is surrounded by a braided mesh. The mesh fibers run helically around the muscle's long axis at an angle which may be referred to as the weave angle, braid angle or pitch angle. (Daerden & Lefeber, 2002) When a gas pressure is applied to the inner bladder, its walls press laterally against the walls of the mesh resulting in a change in weave angle which is then followed by a change in its length, diameter and volume. The lengthwise contraction of the fibers results in a radial expansion unlike bellows which expand on inflation. (Klute, Czerniecki, & Hannaford, 1999) The fibers of the outer mesh provide a tension to the inner bladder due its curvature resulting in balancing of the internal pressure. (Daerden & Lefeber, 2002)

One of the most commonly used and frequently published braided pneumatic actuator till date is the one introduced by Mckibben and is known as *Mckibben Pneumatic Actuator.*

2.2.2.1.1 MCKIBBEN PNEUMATIC ACTUATORS

J. L Mckibben introduced the braided pneumatic actuators as an orthotic appliance for a polio patient who happened to be his daughter. It appeared as an ideal choice to use these actuators for orthotics and prosthetics purposes as these actuators exhibited similarity with skeletal muscles in regards to its length load curves. But due to some practical problems such as the availability or storage of pneumatic power supply and poor quality of valve technology, these actuators lost interest from prosthesis/orthotics community (Daerden & Lefeber, 2002) Few years later the pneumatic actuators re-emerged in 1984 as Bridgestone corporation along with Hitachi introduced their muscle actuators named as "Rubbertuator". The Rubbertuator was designed on the principle of operation of early Mckibben muscle which was able to power a seven degree of freedom Robot and was designed for assembly line work. (Prior, Warner, White, Parsons, & Gill, 1993) Although Bridgestone discontinued their product in 1990s but may other groups continued to work on the actuators which principally followed the actual design put forward by Mckibben.

Mckibben muscles have been used most commonly up to date. This is due to the fact that they have a simple design and are easily assembled. They are composed of an inner rubber tube or a bladder which expands when inflated and is surrounded by a helically braided sleeve. When inflated, the bladder laterally presses against the braided sleeve causing it to expand radially. The working pressure of this kind of muscle typically ranges between 1 – 5 bar and more. As there is a threshold of pressure, these muscles are unable to function properly at pressures lower than the threshold. There also lies a dry friction between the inner bladder and the outer helically braided mesh resulting in deformation of the rubber tube. (Daerden & Lefeber, 2001; Villegas et al., 2012)

2.2.2.1.2 DRAWBACKS OF BRAIDED MUSCLES

Although braided muscles have been used most commonly up till now but there still are various drawbacks of these muscles which makes them unsuitable for certain applications.

- These actuators have substantial Hysteresis due to the dry friction between the tube and the braid (Chou & Hannaford, 1996)
- The force generated by the muscle reduces along with the deformation of rubber tube (Tondu & Lopez, 1997)
- The pressure applied must exceed the threshold in order to start expansion of tube. This value of pressure greatly depends on the toughness of inner tube. (Chou & Hannaford, 1996)
- Rubber fatigue failure has also been described the most common failure mode. (Klute & Hannaford, 1998)

Since there are few drawbacks of these muscles due to which they cannot be used as implantable muscle systems in handicapped and disabled patients. Therefore we have devised a mechanical muscle model which can be implanted and operated remotely with the help of magnetic coupling.

2.2.2.2 NETTED PNEUMATIC ACTUATORS

2.2.2.2.1 ROMAC PNEUMATIC MUSCLES

Another type of pneumatic actuator was developed in late 1980s by MacDonald Detwiller & Associates of Richmond, British Columbia, Canada, termed ROMAC (Robot Muscle ACtuator). ROMAC actuators worked on the same principle as Mckibben muscles. The structure of these muscles consists of a polylobe articulating bladder having a constant surface area. The bladder is surrounded by a flexible but inelastic sheath and a steel wire mesh along with the end fittings. When a pressure is applied, the bladder expands in volume while contracting axially resulting in up to 50% shortening and a lifting of very high loads. (Hoggett, 2012; Prior et al., 1993; Winters, 1990a). ROMAC muscles are known to work at low pressures (60psi) and can generate very high forces (200 pounds) without being perturbed by either friction or material deformation. (Daerden & Lefeber, 2001; Hoggett, 2012). The ROMAC actuators have flexible walls but they are not designed to work as elastomers. However, the specific pyramid geometry of these muscles allows them for a greater contraction.

If the pressure is increased in a pair of pneumatic actuators while the pressure ratio is maintained, the angular position of arm is maintained but with increased stiffness and decreased compliance. (Prior et al., 1993)

Although the ROMAC muscles gave favorable results being able to lift heavy loads still they faced some major drawbacks. The complex shape of these actuators made them difficult to construct. As these are netted muscles i.e. the outer membrane is covered by a wired net, when a pressure is applied it experiences strong stress concentrations in the surrounding wires which leads to early material failure. (Daerden & Lefeber, 2001). Moreover, these actuators are quite expensive and bulky and they use a large amount of gas, thus are not appropriate for application involving artificial limbs or prosthetics. (Winters, 1990a)

2.2.2.3 PLEATED PNEUMATIC MUSCLES

The basic idea for the design of a Pleated Pneumatic Muscle was by the use of a Cylinderical membrane having a high flexibility and a high tensile stiffness. This membrane would then be folded along its central axis same like accordion bellows. Since the membrane needs to expand, it is thus hoarded away inside the folds. Membrane is locked at both ends to fittings containing gas inlet and outlet vessels. When pressure is applied to such an actuator it gets short and bulges outwards.

Due to the high tensile stiffness of the membrane, it expands the most in the middle and steadily goes down towards both ends. No expansion is observed at both the ends. It inflates by unfolding its accordion bellow like folds. As the folds are arranged radially along the membrane, there is no friction involved and hence friction related hysteresis is also not observed. (Daerden & Lefeber, 2001)

CHAPTER 3 MATERIALS AND METHODS

3.1 IN-SILICO DESIGN

In Silico Muscle model was designed using Pro Engineer wildfire 5.0. The Muscle Actuation Device consisted of multiple parts assembled to obtain a final actuation device. Overall Device consisted of

1. Primary Actuation Shaft
2. Primary Driving Magnets
3. Secondary Actuation Shaft
4. Secondary Driving Magnets
5. Lead Screws
6. Weight Lifting Pulley

3.2 FABRICATION OF DEVICE

The material chosen for Primary & Secondary Magnetic Balls was Acrylic which was then changed to PLA (Polylactic Acid) whereas Aluminum Metal was used to fabricate primary and secondary shafts.

Since the magnets play a major role in this muscle model, they were to be selected such that they provide us with maximum load bearing capacity and least amount of slippage between the 2 shafts. For this purpose, Neodymium magnets were selected as they are the strongest magnets commercially available.

The parts were fabricated using Laser cutting equipment Jinan Jinqiang Laser CNC JQ9060, 3D Printing Machine, high speed lathe, milling machine, drill machine, at Manufacturing Resource Centre, NUST (MRC).

The second step in the fabrication process was to arrange these magnets in such a configuration that would give us smooth rotation with maximum strong coupling between the 2 shafts.

3.3 FABRICATION OF PRIMARY & SECONDARY MAGNETIC STRUCTURES

A series of experiments were performed in order to finalize the final configuration in which the magnets were to be attached on primary and secondary shafts. Some of the experiments that lead to the finalization of a Magnetic Configurations have been explained below;

3.3.1 RECTANGULAR MAGNETIC CONFIGURATION

In this Configuration 5 Neodymium Cuboidal Magnets of dimensions 10 mm *10 mm were attached in series on each shaft.

In order to test the feasibility of this type of magnetic configuration, a manually operated rig was designed in which the primary shaft was attached to a pulley on which weights were hanged to drive the System. Secondary shaft also had a pulley which enabled us to calculate the force each system produced. The magnetic coupling was quite strong in this system but it did not prove to be fruitful as it produced jerks during rotation of shafts.

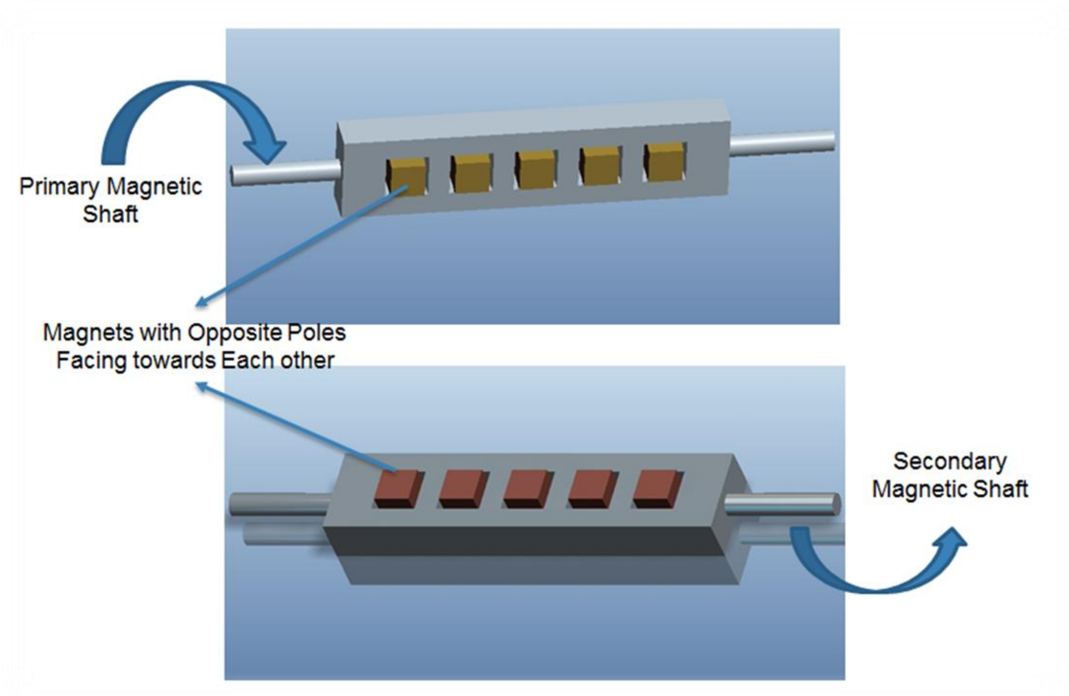

Figure 3.1 *Rectangular magnetic configuration showing primary and secondary magnetic shafts*

3.3.2 CIRCULAR MAGNETIC CONFIGURATION

In this configuration, a total of 18 cuboidal neo magnets of dimensions 10 mm * 10 mm were to be attached on the primary shaft in a circular acrylic structure

And almost 36 small cylindrical magnets of dimensions 5 mm * 6 mm were to be attached on secondary shaft in a circular acrylic structure

This type of configuration was difficult to fabricate through a Laser cutting machine and it was even more difficult to assemble the magnets. So, this configuration was then altered according to available fabrication techniques.

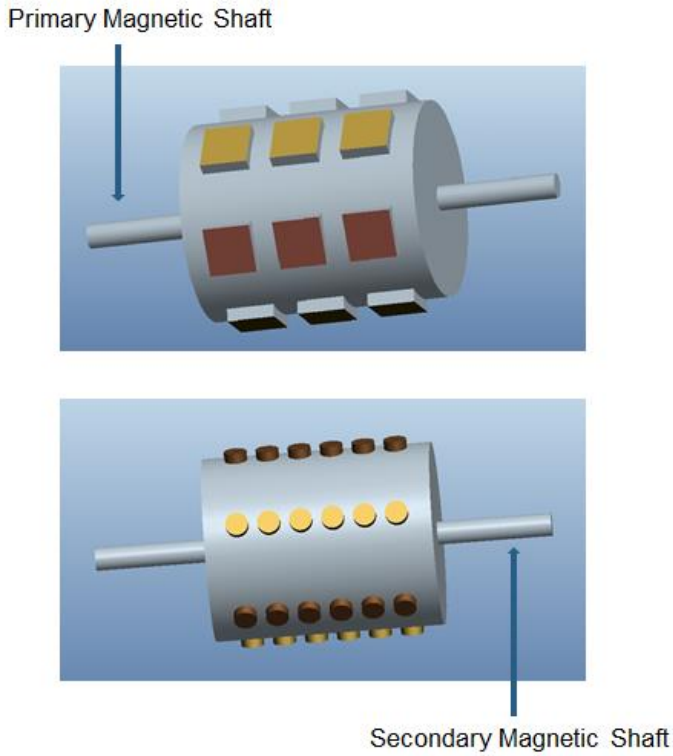

Figure 3.2 *Circular magnetic configuration showing primary and secondary magnetic shafts*

3.3.3 HEXAGONAL CONFIGURATION

In this configuration, 6 cuboidal neo-magnets of dimensions 10 mm * 10 mm were attached in Primary Shaft and 6 cylindrical neo-magnets of dimensions 5 mm * 6 mm were attached in secondary shaft

This type of configuration did not produce favorable results as it showed weak magnetic coupling and slippage between primary and secondary shafts.

The results of this configuration made us to come to a conclusion that the magnets of equal sizes shall be used in both the shafts since small magnets in secondary shaft makes the system weak.

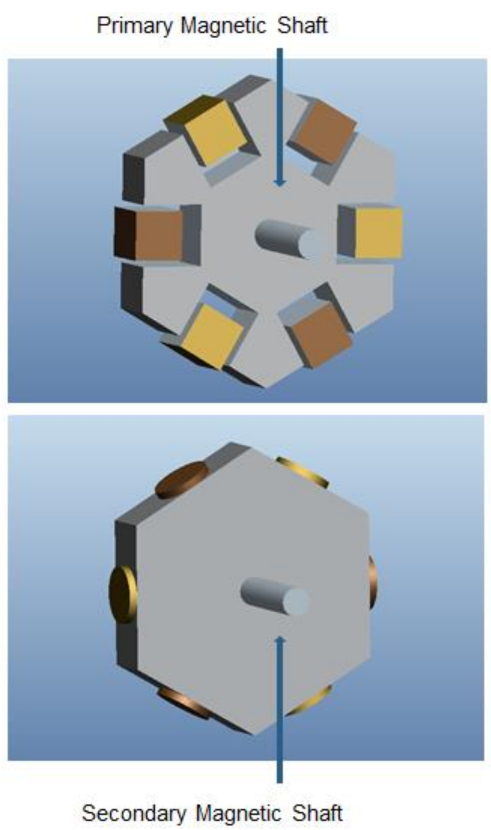

Figure 3.3 *Hexagonal magnetic configuration showing primary and secondary magnetic shafts*

3.3.4 SQUARED CONFIGURATION

In this Configuration, an Octagonal geometry was used with magnets attached on alternate sides forming a squared configuration. Magnets of same size and strength were attached in both the primary and secondary shafts i.e. Cuboidal 10 mm * 10 mm. As a result of this type of configuration, very strong coupling between the two shafts was observed. The rotatory motion was smooth and without jerks. This type of configuration produced desirable results; therefore it was selected for further testing.

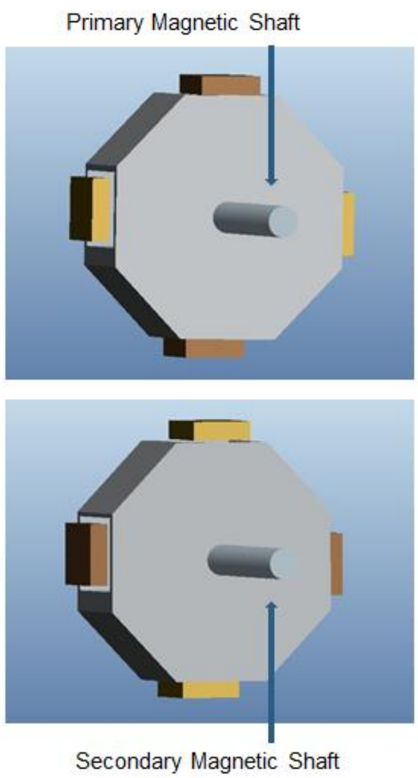

Figure 3.4 *Squared magnetic configuration showing primary and secondary magnetic shafts*

3.4 TESTING RIG ASSEMBLY

A testing rig was assembled using the selected squared configuration of magnetic array. The rig was assembled to identify how much weight this system can lift at an optimum rpm. A motor was attached to the primary shaft to drive the whole system. To the secondary shaft a pulley system was attached for lifting load. The rpm of the system was recorded using a tachometer.

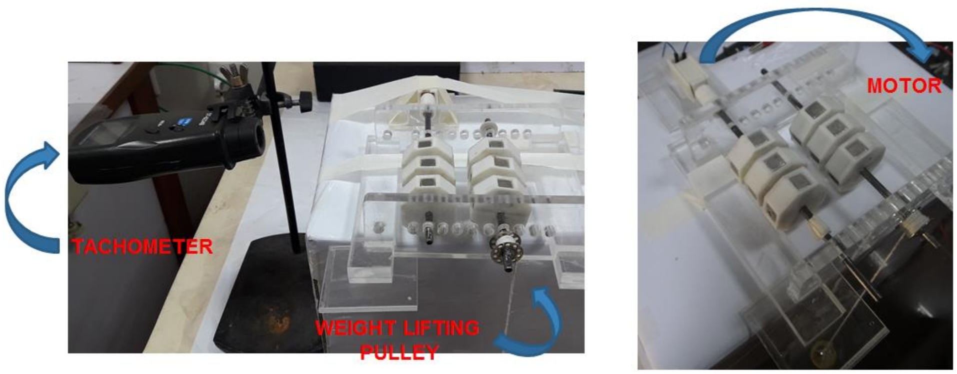

Figure 3.5 *Illustration of assembled Testing Rig with attached motor, weight lifting pulley and Tachometer*

3.5 OPERATION OF DEVICE

The Primary magnetic shaft was rotated using a DC motor. DC motor with following features was used. It operates on 6V-14V DC. This motor is selected because it is a geared motor and gives an rpm ranging from 0 to 300. The motor can rotate both in forward as well as reverse directions by changing the polarity of DC supply.

The rpm of the system varied at varying voltages. At a maximum of 12V the motor was able to give rpm ~ 300. The system was tested at varying rpms to lift weights in order to identify the maximum load bearing capacity at a particular rpm.

3.6 TESTING OF DEVICE

When the final assembling of the device was done, it was tested in both forward and reverse directions at first without load and then with varying loads. At this stage, a pulley system was used in order to test the weight lifting capability of the system. Weights of different sizes were tested on each rpm. Various types of tests were conducted by using this assembly which has been discussed in the next chapter.

After the testing of various magnetic configurations, a final magnetic configuration with best and optimum results was selected and final muscle model was assembled. In this final muscle assembly the primary and secondary magnetic shafts were fixed at a distance of 12 mm. Bearings were used for the final fixation of the shafts in order to obtain smooth rotation. A geared motor of maximum RPM 300 was attached to the primary shaft. Lead screws were introduced at both ends of secondary shaft. Load was attached to one end of lead screw. Final testing was done and Force Velocity and Force Time curves for the system were obtained.

CHAPTER 4 RESULTS & DISCUSSION

4.1 RPM VS. LOAD TESTING

The testing was done using the final squared configuration of magnets. A single magnetic ball containing 4 neo magnets in a circular manner was attached on each shaft. The primary shaft was rotated using a DC motor. Secondary shaft rotated due to the magnetic coupling. Weight was lifted through this secondary shaft.

The **Figure 4.1** illustrates the results of 1 paired magnetic ball of squared configuration. On X axis, Load is shown in grams and on Y axis RPM has been shown. This system can lift loads up to 90 – 100 grams at maximum. These results are quiet opposite of what were expected.

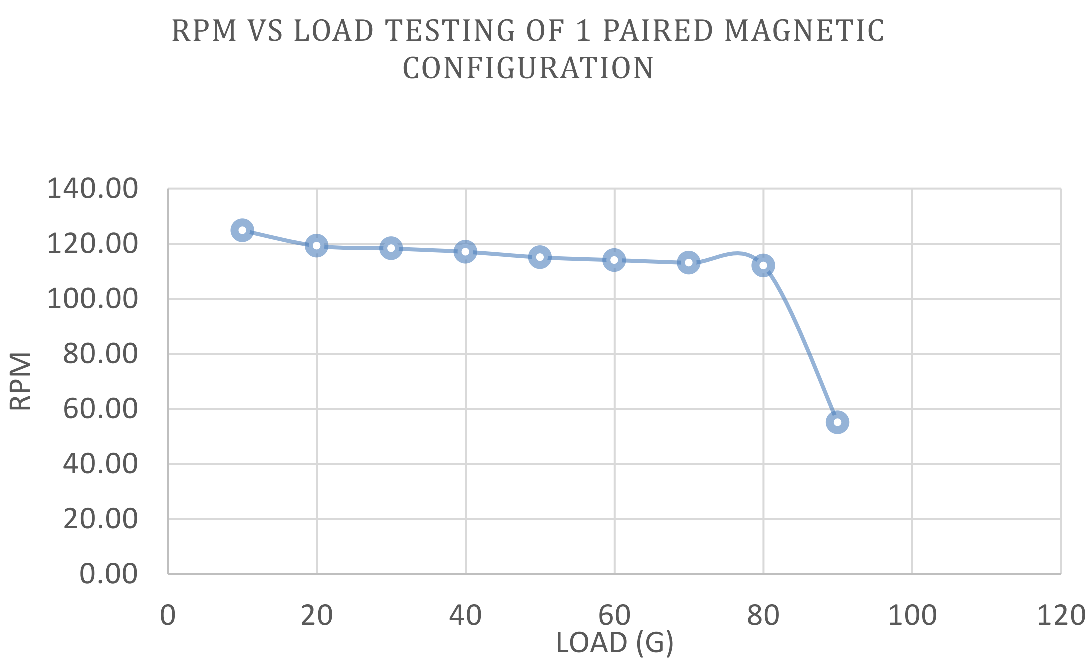

***Figure 4.1** Demonstration of RPM vs Load Testing of 1 paired magnetic ball of squared configuration*

Therefore in order to increase the weight lifting ability of the system, it was conceived that if the number of magnets increase on the horizontal axis of each rotating shaft, the system might be able to lift more weight.

- This could be achieved in two ways; as shown in **Figure 4.2**.

1. Addition of magnetic ball on the horizontal axis in such a way that the two horizontal magnets have opposite poles (a)
2. Addition of Magnetic ball on the horizontal axis in such a way that the two horizontal magnets have same poles (b)

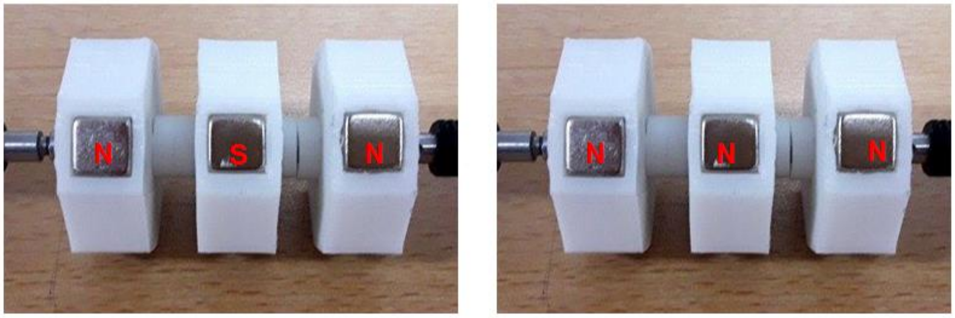

***Figure 4.2** Demonstration of different magnetic configurations on horizontal axis; **Left**: magnets have opposite poles; **Right:** magnets have same poles*

4.1.1 RPM VS. LOAD TESTING OF ALTERNATING MAGNETIC POLES ON HORIZONTAL AXIS

The proposed system was then tested at 2 distances between primary and secondary shaft i.e. 12mm and 24 mm. At D1 the results obtained from testing of alternating magnetic pole configuration showed us that the single pair of magnets show better results than 2 or 3 paired configuration **Figure 4.3**. And at D2 the results were even more undesirable **Figure 4.4**.

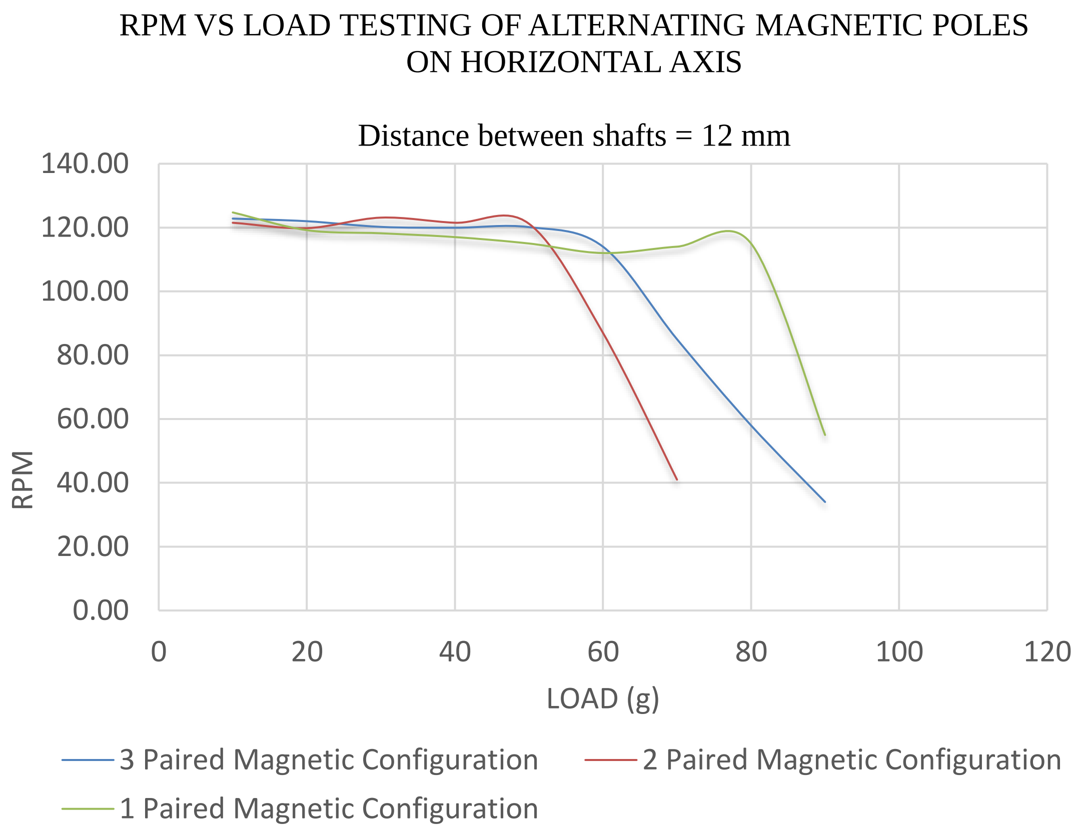

Figure 4.3 *Demonstration of RPM vs load testing of alternating magnetic poles on horizontal axis Distance between shafts = 12 mm*

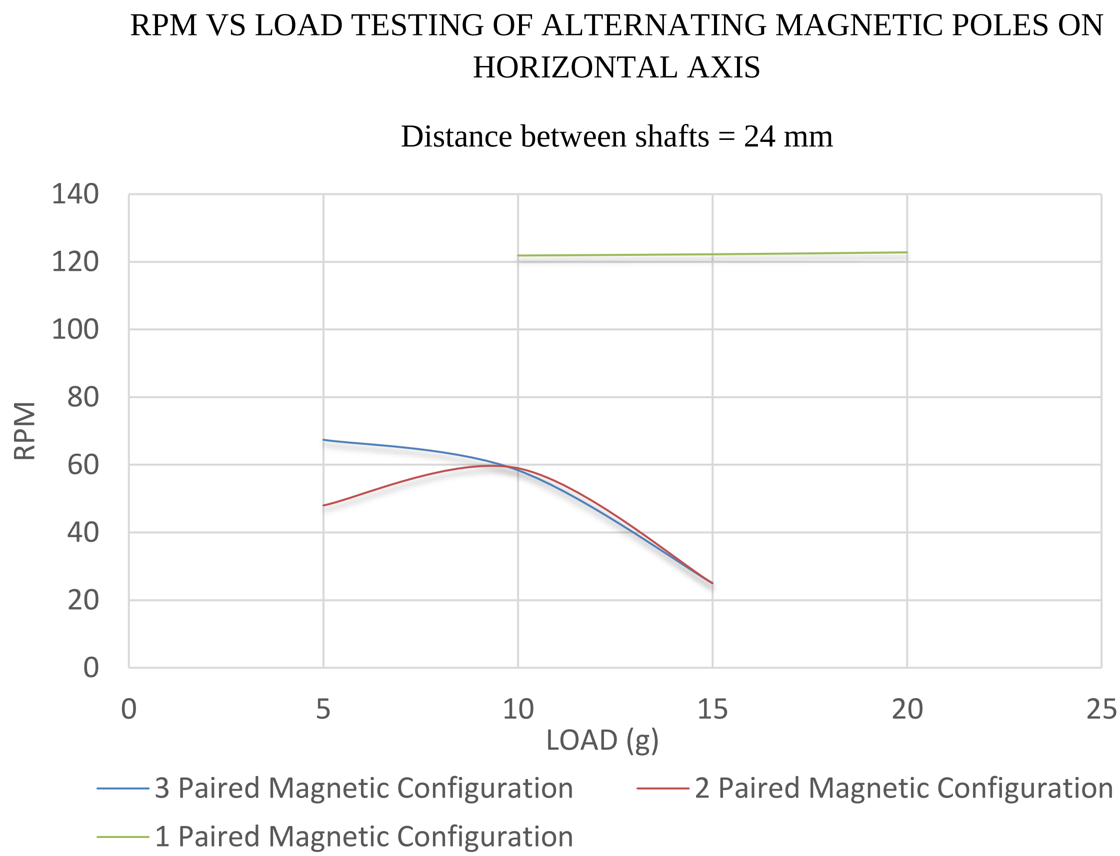

***Figure 4.4** Demonstration of RPM vs load testing of alternating magnetic poles on horizontal axis*

Distance between shafts = 24 mm

These results show that the weight lifting capability of single magnetic ball is better than double and triple magnetic balls on each shaft i.e. with the addition of magnetic balls on horizontal axis, the weight lifting ability of the system did not improve. And the load lifting capability of this system decreased when the distance was increased up to 24 mm between the PDM and SDM. By looking at these results, it was hypothesized that the magnetic fields of consecutive magnets might be interfering with each other resulting in weak coupling between the 2 shafts. Therefore in order to improve the results, separations of varying sizes i.e. 4 mm, 8 mm and 12 mm were introduced between the magnetic balls on horizontal axis of each shaft. (**Figure 4.5**)

Figure 4.5 *Illustration of separation of varying sizes between the magnetic balls on horizontal axis of each shaft*

4.1.2 RPM VS. LOAD TESTING OF ALTERNATING POLES WITH VARYING SEPARATION BETWEEN MAGNETS

As a result of added separations between 3 paired configurations, the results of the system improved dramatically. Here we can see that in comparison to 4 & 8 mm separation, 12 mm separation between consecutive magnetic balls made the system lift loads up to 500 grams.

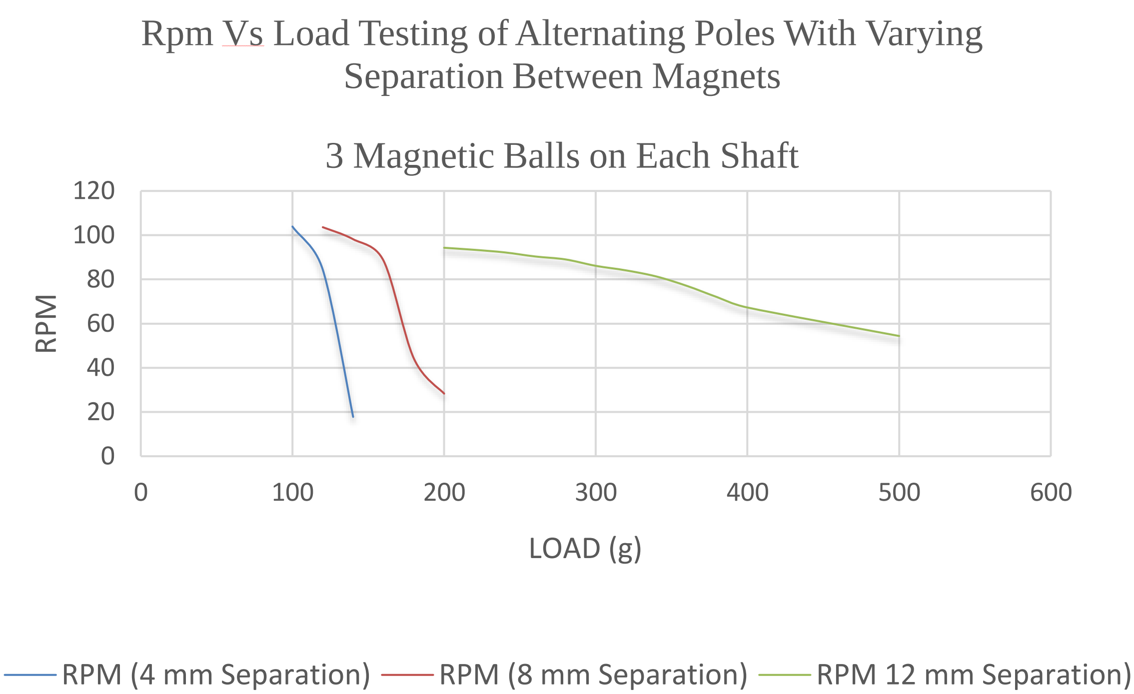

Figure 4.6 *Demonstration of Rpm Vs Load Testing of Alternating Poles with Varying Separation between Magnets (3 Magnetic Balls on Each Shaft)*

4.1.3 RPM VS. LOAD TESTING OF MAGNETIC SHAFTS WITH SAME MAGNETIC POLES ON HORIZONTAL AXIS

The magnetic testing of this system was conducted first with 2 paired magnetic configurations and then with 3 paired magnetic configuration. The results of a 2 paired magnetic configuration with varying separations between the magnets showed that this system was able to lift loads up to 500 grams at 4 mm separation between magnets. The system showed better results at 4 mm rather than at 12 mm separation (**Figure 4.7**). Likewise in 3 paired magnetic configuration, when the separations were introduced the results showed that this system also showed better results at 4 mm separation rather than 12 mm (**Figure 4.8**). If compared to the previous system in which alternating magnetic poles were introduced on x axis, the weight lifting capability of that system increased with increasing separations between magnets on x axis however in this system with increased separations on x axis, the weight lifting capability of the system decreased. From this behavior of the 2 systems, we can conclude that in latter the magnetic fields added up on horizontal axis making it a stronger one.

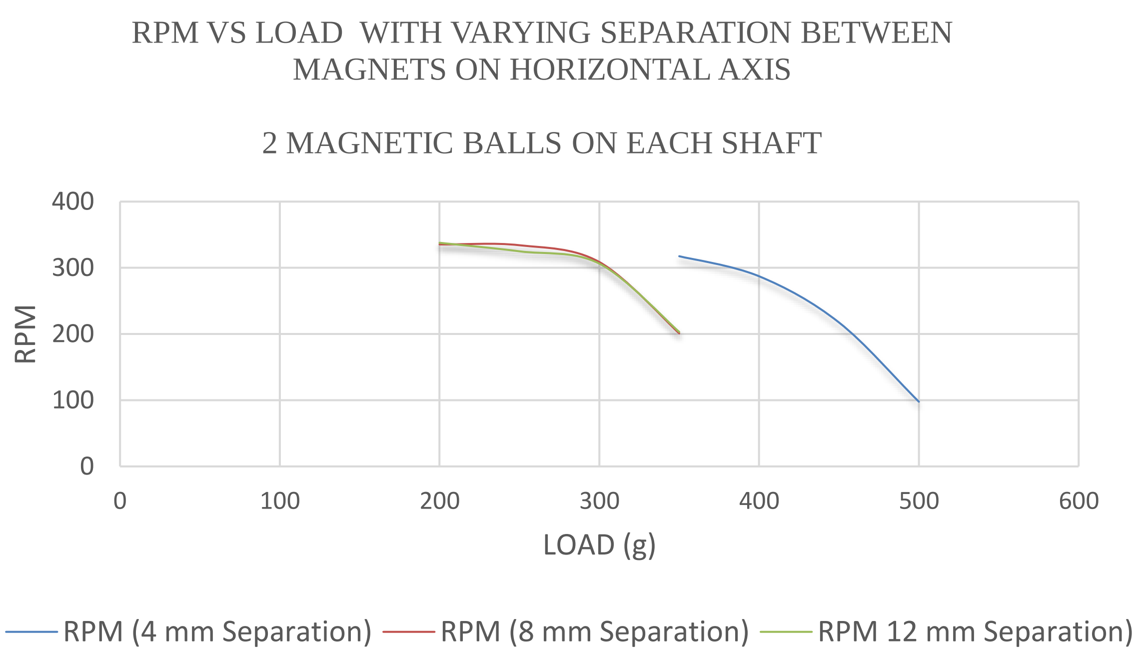

Figure 4.7 *Demonstration of RPM vs load with varying separation between magnets on horizontal axis (2 magnetic balls on each shaft)*

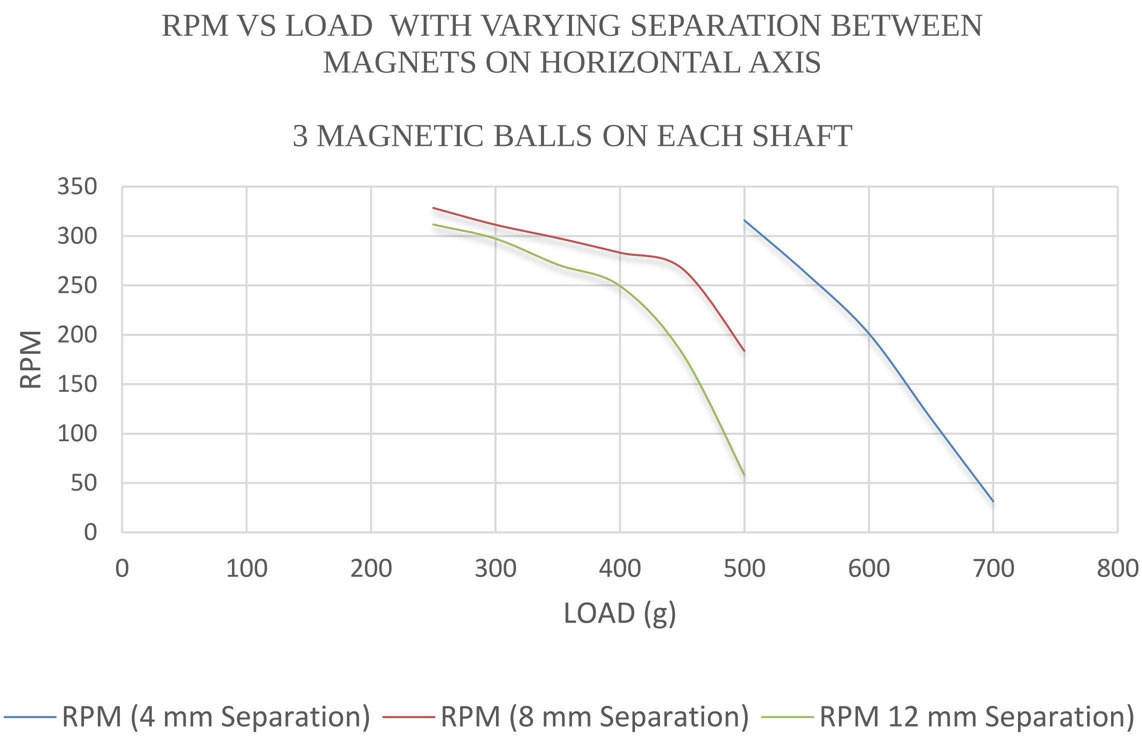

Figure 4.8 *Demonstration of RPM vs load with varying separation between magnets on horizontal axis (3 magnetic balls on each shaft)*

When the results of 1, 2 & 3 paired magnetic configurations were compared, it was observed that by increasing the number of magnets on each shaft, the weight lifting capability of the system improved dramatically (**Figure 4.9**).The system with 3 paired magnetic configurations was able to lift loads up to 700 grams whereas the system with 1 paired magnetic configuration could lift loads only up to 100 grams only.

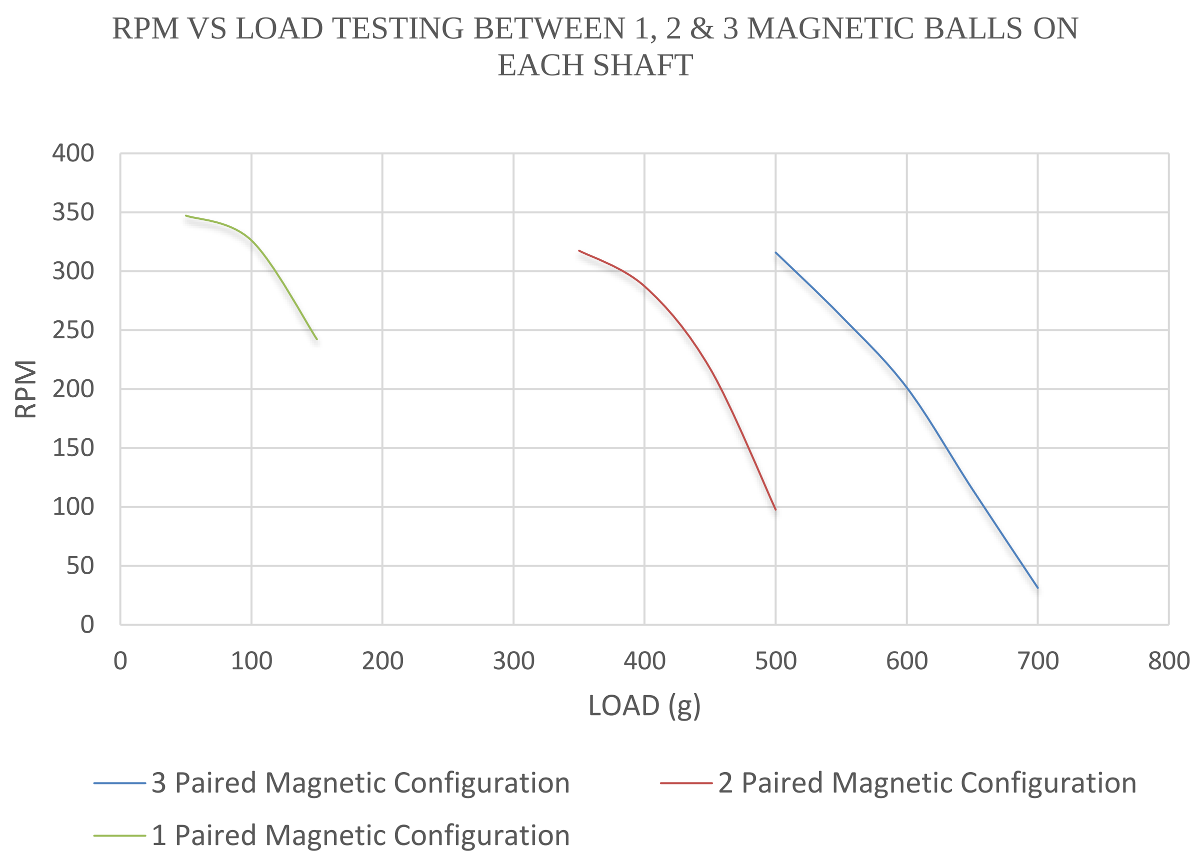

Figure 4.9 *Demonstration of RPM vs load testing between 1, 2 & 3 magnetic balls on each shaft*

These results clearly show that the best results have been given by a system in which 3 magnetic balls with same poles were introduced in each shaft. The separations between the magnets were of 4 mm and the distance between primary & secondary shafts was 12 mm. So considering in mind the specifications of this system, a final muscle model was assembled and tested for force velocity and force time curves.

4.2 FORCE VELOCITY RELATIONSHIP

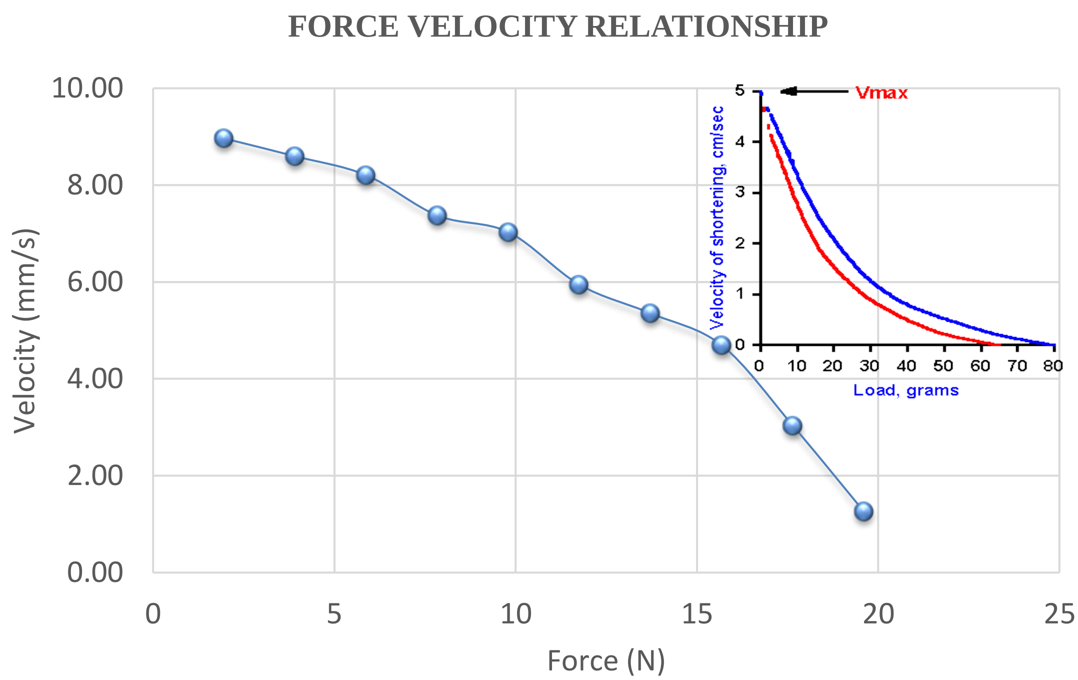

Figure 4.10 *Demonstration of relationship between two parameters i.e. Force and Velocity of designed muscle model*

This **Figure 4.10** represents the Force Velocity Curve of the muscle model which depicts that as the Force is increased, the velocity of Contraction decreases. These results are similar to force velocity curves of a physiological muscle. At Max RPM of around 300, full contraction of the system is achieved in approx. 3 sec i.e. it covers distance of 6 cm in 3 secs.

The Right corner graph has been taken from literature which shows that my results are in accordance with literature. As far as the shape of the graph is concerned, it is less important that the fact that as the force increases the shortening velocity decreases.

4.3 FORCE TIME RELATIONSHIP

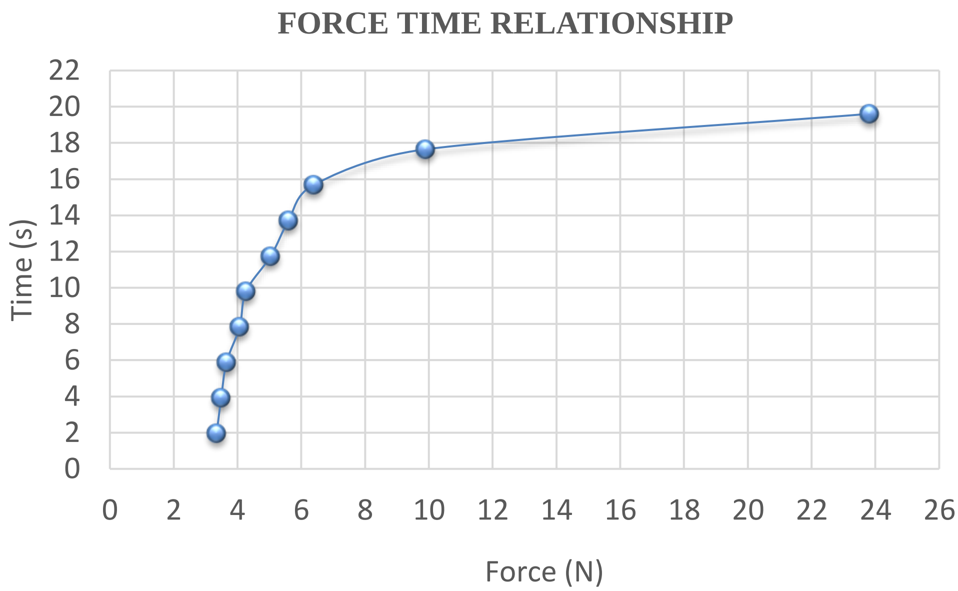

Figure 4.11 *Demonstration of relationship between Force and time of designed muscle model*

As the force increases the time for contraction of the muscle model also increases showing a direct relationship between the two factors.

CHAPTER 5 CONCLUSION & RECOMMENDATION

CONCLUSION

A mechanical muscle model incorporating magnetic actuation has been developed. This muscle model shows promising results to be used as an implantable muscle in future as it is actuated through magnetic coupling. The system is strong and can generate force up to 20 N with 3 paired magnetic configurations. The Force Velocity & Force Time curves generated by this model show similarity to the actual muscle model, hence we can consider this model as a promising one.

FUTURE WORK

In order to further improve the force generating capability of this system, magnets of more strength can be incorporated as well as the number of magnets on each shaft could also be increased. Further more muscle like characteristics can be obtained by the addition of Viscoelastic effect through the incorporation of springs in this system. Incorporation of series and parallel elastic elements could also be done followed by its parametric testing.

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