MAGNETIC ACTUATION OF LAPAROSCOPIC ATRAUMATIC GRASPER

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EXAMIANTION COMMITTEE

We hereby recommend that the dissertation prepared under our supervision by: Javairia Yousaf Cheema, Reg#NUST2014631611MSMME62414F. Titled: “Magnetic Actuation of Laparoscopic Atraumatic Grasper” be accepted in partial fulfillment of the requirements for the award of MS (Biomedical Sciences) degree with _____ grade.

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DECLARATION

It is hereby declared that this research study has been done for partial fulfillment of requirements for the degree of Master of Sciences in Biomedical Sciences. This work has not been taken from any publication. I hereby also declare that no portion of the work referred to in this thesis has been submitted in support of an application for another degree or qualification in this university or other institute of learning.

Javairia Yousaf Cheema

ABSTRACT

Laparoscopic device incorporating magnetic actuation mechanism has been designed that would provide desired precise grip with minimal risk of tissue damage. To actuate laparoscopic grasper; an external magnet would be coupled with the internal permanent magnet to drive leadscrew mechanism which would further actuate the scissor mechanism to open and close the grasper. The laparoscopic device consisted of multiple parts which were assembled to obtain the final device. In-silico design of laparoscopic device was made on Solid Works and furthermore assembly was done in Inventor 2016. Different parts of device were fabricated by milling and high speed lathe machine. Grasper jaws were fabricated using CNC EDM wire cut machine. The mechanism is voltage driven, the optimal operating requirement was found to be 12 Volts. In proposed device, maximum force grasper applies horizontally is 9.7 N whereas its 4.7 N vertically for a duration of 30 s but now precision is improved. As designed prototype takes 14 revolutions to open the grasper & to close it.

DEDICATION

I dedicate my thesis to my parents for their affection, love, encouragement and prayers.

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ABBREVIATIONS

mm	Millimeter
SS	Stainless Steel
g	Gram
DC	Direct Current
SW	SolidWorks
Dia	Diameter
V	Volts
A	Ampere

INTRODUCTION

Laparoscopic surgery (MIS) modern surgical technique in which operations are performed far from their location through small incisions (usually 0.5–1.5 cm) elsewhere in the body. Several surgical instruments used in a laparoscopic surgery includes forceps, graspers, scissors, probes, dissectors, hooks, retractors and more **(**Eubanks, Swanström, Soper & Leonard 2000). Grasper is one of the commonly used instrument during the laparoscopic surgery. Grasper is of various kinds Laparoscopic surgery is having number of advantages in contrast to open surgery. In laparoscopic surgery there is decreased blood loss pain and discomfort along as the fine instruments are used which usually leads to less tissue trauma. Recovery times are shorter in laparoscopic surgery in comparison to open surgery, as patient is usually discharge from hospital in a day (Agha & Muir, 2003). There are several challenges in laparoscopic surgery faced by surgeons that include reduced degree of freedom, poor depth perception, less grip precision, risk of tissue damage and mechanical coupled actuation. (Lanfranco, Castellanos, Desai, & Meyers, 2004)

So the aim of this thesis was to design a laparoscopic device incorporating magnetic coupled actuation mechanism that would provide desired/precise grip with minimal risk of tissue damage and to actuate laparoscopic grasper using an external magnet that would be coupled with the internal permanent magnet to drive leadscrew mechanism which would further actuate the scissor mechanism to open and close the grasper. The aim behind this research was to design and fabricate a light weight, robust, magnetically coupled device.

CHAPTER 2

LITERATURE REVIEW

Several actuation mechanisms are used in different biomedical devices which include thermal or electric actuation but they are having certain disadvantages which lead to development of some new actuation method. Magnetic actuation mechanism is currently the most widely research area. Actuation mechanism is used in several biomedical devices. Some of the applications of magnetic actuation include laparoscopy surgery, soft capsule endoscope, robotic catheters, arrays of 3D micro tissues, catheter ablation and many more.

Robotic Catheters

Robotic catheters are processed to reach such anatomical sites that are inaccessible. Brewer, Loewke, Duval, & Salisbury, 2008; came up with new technique to monitor robotic catheter i.e. Magnetic actuation. Catheter distal tip is loaded with small magnet and another large magnet that is located outside body. This external magnet provides magnetic force or torque essential for orientation of catheter and its movement. Permanent magnet system lacks one feature i.e. to provide variable force. To counter this problem, we can use either large magnets or shielding materials can be used between magnets to provide variable magnitude of forces. Shielding is done to redirect lines of magnetic flux through itself and away from smaller magnets.

In this setup two shielding plates called Hymu-80 are located at right angles to large magnetic field. To fluctuate amount of forces that is applied on small magnet this setup is connected with some spreading mechanism that deals with opening and closing of plates. To increase the shielding capacity, the plates can be stacked or their thickness can be increased. (Natali, Member, & Buzzi, 2015)

Catheter Ablation

Catheter ablation is medical procedure used for treatment of cardiac arrhythmia. In catheter ablation several catheters are used with electrodes at their tip through which heat is transmitted to damage those tissues that are causing fast heart rate. Robotic assisted catheter ablation is of wide importance as its navigation and precision is easily controlled, and more over it’s less time consuming. Earlier actuation mechanism of catheter ablation involves magnetic field generated by MRI (Magnetic Resonance Imaging) scanner which produces enough magnetic forces on the array of micro coils in which catheter is embedded. Using beam theory different parameters including displacement, deflection and torsion angles are measured. (Lin & Scott, 2012)

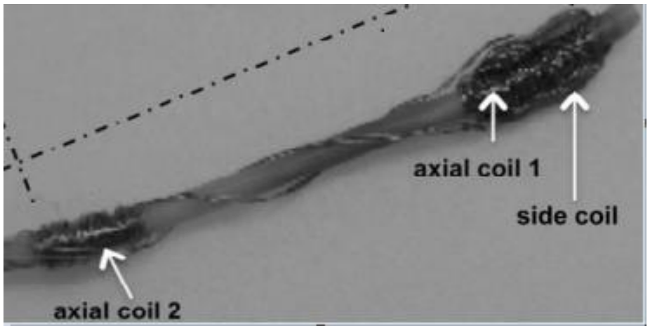

Figure 1. catheter prototype showing arrays of coils

Faddis et al., 2002; evaluated the magnetic guidance system in dogs and pigs to steer ablation catheter to be used in ablation of arrhythmias. In order to navigate intracardiac regions and to perform radiofrequency ablation, a 7F ablation catheter was used whose efficiency was not effected by MGS. The magnetic catheter was steered efficiently among 6 animals across 51 positions all the way through heart. Whereas in 5 animals the steerable catheter was moved to all pulmonary veins. Furthermore, catheter was used to ablate atrioventricular node and linear ablations were also performed and recorded. Thus The MGS suggested precise movement of catheter and its potential to move catheter in any of the desired direction whereas the conventional catheters that are manually controlled has the potential to move in a single plane. The study demonstrated MGS to be safe and responsible for precise catheter movement in all 4 chambers of heart.

Ernst, Ouyang, Linder, Hertting, Stahl, Chun, Hachiya, Bänsch, et al., 2004; performed catheter ablation in patient with AVNRT using magnetic navigation system. The ablation was successfully conducted in slow AV nodal pathway without any complications. The study suggested first generation MNS to be safe and feasible as it provides catheter movement in all direction but it does not allow remote catheter ablation.

Ernst, Ouyang, Linder, Hertting, Stahl, Chun, Hachiya, Krumsdorf, et al., 2004 proposed the use of Niobe magnetic navigation system in combination with motor drive unit to carry out mapping and ablation in patients suffering with both types of atrioventricular nodal reentrant tachycardia (AVNRT) that is Common and Uncommon. The system comprises of 2 permanent magnets mounted on both sides of patient which generates magnetic field of 0.08 T. The mapping catheter is provided a small magnet located at its tip that positioned itself with the changing direction of external magnetic field to facilitate it to be moved efficiently. The position of external magnets was altered resulting in changing the direction of magnetic field and eventually causing deflection of catheter. Furthermore, the addition of motor causes the catheter movement by steps of 1mm in forward and reverse direction. As the external magnet is at location close to patient it results in the limitation of angulation degree of C-arm to 28° as a result septum could not be viewed. Thus a constant and a slow motion catheter position was attained in all patients by remotely controlled catheter steering. Moreover, with the use of radiofrequency current catheter ablation was carried out at monitored temperature. This process carries many advantages for both patients and physicians. With the use of external magnetic field, the catheter maintained steady position even in presence of altering cardiac rhythms. It results in reduction of exposure time of fluoroscope.

In another study Thornton et al., 2006 performed catheter ablation in 20 patients suffering from tachyarrhythmia using magnetic navigation system by Niobe. Magnetic steering in Koch's triangle and ablation of atrioventricular nodal re-entry tachycardia (AVNRT) with a magnetic catheter was performed. A field strength of around 0.08 T was produced via this system. MNS in combination with fluoroscopy system was used to perform navigation whereas, Cardiodrive^{TM} system was used to direct catheter in forward and backward direction. AVNRT was effectively ablated in 18/20 patients with 95% success rate. Results suggested that magnetic navigation performed in Koch's triangle results in more efficient ablation. The results of 1 and 3 magnets catheter were compared and the results suggested no evident difference between ablation conditions in both magnet catheters. In three magnet catheter the distal portion is straighter when compared with single magnet catheter. Thus three magnet catheter would be appropriate in complex anatomies and in difficult to reach areas.

Bruce D. Lindsay (2006) compares the Telstar and Niobe System. Telstar were the first generation of system with enhanced imaging system and consisting of orthogonal array of electro magnets placed on person's chest. The diameter was too small for large patient and causes claustrophobia. Liquid Helium was used to cool down electromagnets. Time required to change vector for navigation purpose is 5-15 sec. There is difference between two designs Niobe system is more reliable over Telstar, alterations in field vector is achieved in 1-3 sec in comparison to Telstar's 5-15 second, absence of helium compressor makes it less silent. Other significant difference between the two is field strength dropped from Telstar 0.15 to Niobe 0.08. This decrease in field strength leads to more steering of catheter.

Moustris et al., 2011 proposes the magnetic catheter. To prevent blood loss, pain and for quick recovery minimally invasive vascular surgery is done by the use of catheters. Catheter and guide wires are commonly used to allow drainage. The maneuverability of catheter is another challenging task. These conventional catheters are difficult to steer along they have unchangeable shapes. Magnetic catheter basically consists of embedding small magnets into its tip and is controlled by external magnet. Magnetic catheter is having many advantages in comparison with active catheter which includes pull wire catheter, smart material actuated catheter and hydraulically driven catheters. Magnetic catheter can be guided by adjusting magnetic field can be drive in desired direction, it’s safer to use as it’s having soft catheter tip.

Magnetically Actuated Soft Capsule Endoscope

Sendoh, Ishiyama, & Arai, 2003 proposed the working of capsule endoscope using the magnetic actuator. As capsule endoscope has been widely used in **g**astrointestinal (GI) endoscopy to determine cancer of stomach and coon in their initial stages. Capsule endoscope is moved via peristalsis of GI tract thus its movement is not monitored and regulated. Capsule endoscope needs controlled movement to prevent missing a disease. The proposed capsule endoscope comprises of magnet along a spiral structure whose movement is regulated by application of rotational magnetic field. Results suggested that the magnet’s essential volume to be used as actuator is 250mm with the strength of external magnetic field 150 Oe. Results suggested that spiral structure of 1 mm could be moved at 5mm/s. Magnet with diameter and length of 11mm and 30mm respectively was used. The proposed actuator lacks the need of wire or battery as a power supple. Moreover, owing to simple structure of actuator the chances of its breakdown lessened.

Swain et al., 2010 proposed a simple and inexpensive method to make tether less capsule endoscope with the use of neodymium-iron-boron magnets that could be easily positioned in the stomach and esophagus for transferring images. A stack of magnets was used and were placed in the capsule. Magnets were placed in a fixed position and magnetic field was provided in such a way that north and south poles were along longitudinal axis of the capsule without altering the geometry and sizes of capsule.

Another external magnet was used with aim to deploy the capsule. The effectiveness of magnetic steering was evaluated by using gastroscope. Capsule images were acquired using software real-time imager. Capsule was observed in esophagus and stomach using another video software. Real times images and reviewed images were compared and reviewed with the capsule images. Capsule was swallowed by the patient and gastroscope was moved into esophagus. An external magnet was controlled behind the back and it was able to manipulate the capsule. Capsule was able to be moved and dragged in all positions of stomach. Specific movements of external magnet like spinning, rotations and particularly somersaulting in long axis show rapid movements. Capsule was not observed to cause any marks or harm gastric surface or esophageal mucosa. Moreover, magnetic compression of esophagus and stomach was not uncomfortable to the patient.

Carpi, Kastelein, Talcott, & Pappone, 2011 reported the illustration of robotic maneuvering along magnetically actuated 3-D localization of video capsule in major parts of GI tract. Wireless capsule endoscopy (WCE) enables video examination of GI tract but WEC carries poor diagnostic efficiency. WEC is driven by phenomena of peristalsis and gravity and thus its movement is not controlled or maneuvered. The proposed approach was verified by using the PillCam device and coaxial magnetic shell adhered to its external surface. The cylindrical shell was made up of neodymium magnets with external and internal diameter of 13mm and 11mm respectively. Shell was 13mm in length and carries diametral magnetization of 9.71 × 105 A/m. A uniform static field of 0.08 T allowed capsule maneuvering only in single direction with accuracy of 1◦. Moreover, the in vivo testing of device was conducted in domestic pigs. Several tests were conducted and for each test animal was placed between the two permanent magnets. Magnetic steering was studied in various parts of the GI tract. Results suggested that no obstacles were observed during and post suggesting safe maneuvering of capsule. The localization of capsule was implemented with regard to X-ray reference system.

Yim & Sitti, 2011 proposed a wireless magnetic capsule robot. The robot has two vital attributes that is it has one extra degree of freedom to execute supplementary tasks like injecting or releasing drug or performing biopsy. Furthermore, the design properties of magnetically deformed capsule robot includes the deformation curve which suggests the deformation behavior. The particular locomotion technique of capsule led to several advantages including that the locomotion is continuous, improved tracking ability, increase control over posture which eventually led to interface between capsule and external magnetic field. The suggested capsule is positioned and rotated on tissue wall by the external magnetic attraction and magnetic torque respectively. This led to stable movement of robot and its position is now manageable during movement. The working of the suggested capsule robot is demonstrated by magnetically actuating it in the synthetic stomach model. The results suggested stable movement of the capsule and the gap between external magnet and capsule was found to be only 20 % of the capsule's length. The drug is discharged because of the preload force of the head as external magnetic field axially compress the capsule. The drug release was completed with the preload force of about 850 mN. Furthermore, for squeezing of the drug chamber an external magnetic field of about 200 G was required. The required magnetic field for the mechanism of drug release can be decoupled from that required for locomotion of capsule. The rotational angle of the capsule and external magnet was found to be proportional suggesting that the two are symmetrical. As the capsule positon is symmetrical to the external magnet so the operator can estimate the positon of capsule so doctor stops the capsule using capsule axial contraction which is magnetically actuated. The presented endoscope carries potential ability to capture entire stomach area in 3D along executing functions like drug delivery and biopsy.

Keller et al., 2012 proposed a new technique for steering and control in Magnetically Guided Capsule Endoscopy (MGCE). A guidance magnet is enclosed in a system with the aim to produce a magnetic field of low intensity to navigate the capsule endoscope along two cameras in human stomach filled with water. For this purpose, the exclusive features of stomach were studied to developed the system which would be able to capture the images of stomach wall along provides control over the system. The proposed method includes 10 functions for capsule movements, mode changes and special maneuvers. The tracking of capsule position was excluded to reduce the complexity of guidance magnet and capsule which results in undesirable capsule movements beyond work space. The drifts were reduced by incorporating the Top-/Bottom-mode to system in order to retain capsule in contact with mucosa and to attain the steadiness. The clinical trials were conducted in 53 cases to test the prototype system which eventually suggested that the functions were adequate enough to stretch to every area of stomach and moreover to attained the close-up images of stomach. In some cases, the view was blocked especially when the stomach was not sufficiently expanded. These problems can be addressed by upgraded control method or by bringing change in patient's preparation. The operator's survey and the statistical study suggested that the functions particular order such that Rotate, Forward/Backward, Tilt followed by Top-/Bottom-mode is important for thorough examination. These functions result in 5+1 DOF such that the magnetic maneuvering can be done in five degrees whereas the other last DOF is achieved by moving the patient in the guidance magnet.

Yim, Member, Sitti, & Member, 2012 proposed a medical device functioning on magnetic actuation is MASCE i.e. magnetically actuated soft capsule endoscope. This robot is capable of performing several functions which include drug releasing into target site, performing biopsy and moving actively in desired location. It’s a small mobile robot used for medical applications. To actuate MASCE two magnets one internal and other large external magnet is required. MASCE is having distinct features that is that its external body is composed of elastomer based structure which deform passively on robot tissue contact. Plus, it can deform actively in axial direction by external magnetic actuation that enables functions like drug release drug injection biopsy. It can navigate in 3D by rolling on inside of stomach surface. To fix small robot in preferred location or to roll it external magnetic force and external magnetic torque is required respectively. Single permanent magnet tends to produce smaller magnetic force in contrast to large permanent magnet similarly magnetic torque produced by single rotating magnet tends to be limited by rotating dipole field generated by magnet in radial or axial position. [8]

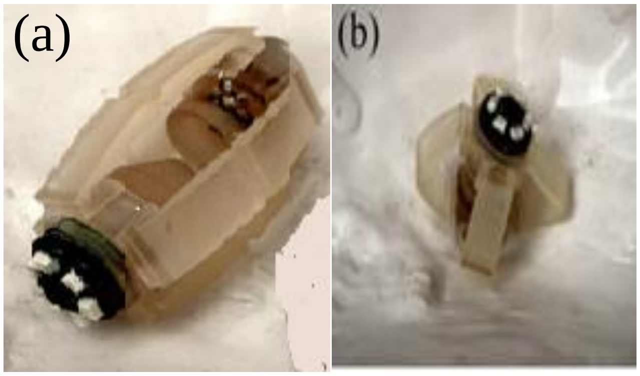

Figure 2. (a) shows magnetically actuated soft endoscope capsule (MASCE), (b) shows compact capsule forms as it’s placed on artificial stomach surface.

X.Wang et al (2007) proposed capsule endoscope using magnetic stereo actuation mechanism considering the requirements of simple internal structure and tether less control. The available capsule endoscope is deficient of self-actuation mechanism and is inefficient for diagnostic purposes. One of the fundamental element defining the practicability of the system is to determine the force essential for driving the capsule in small intestine. In-vitro experiments were conducted in pig to measure the amount of resistance small intestine carries. The results suggested that the capsule size is directly proportional to the amount of force. The force is in the order of 10-1N in case of regular size capsule. A small magnet was embedded in the capsule which is further actuated by several current coils positioned around the area of abdomen and thus is maneuvered in a 3-D space. Magnetic field reduced with three orders of the distance only when the actuation force is small. Using a six-coil method the stereo actuation mechanism is simulated.

Yim, Goyal, & Sitti, 2013 proposed the use of magnetically actuated soft capsule endoscope to be used for the purpose of drug releasing. The capsule comprised of a drug chamber sandwiched between the magnetic heads. The drug is discharged via four slits at the corners by the preloading force of the upper head. The capsule released the drug in the desired location when the magnetic heads were compressed using an external magnetic field. The slits opened only on the application of external load as the chamber is formed of elastomer. The release of drug by capsule occurs in two separate modes. A slight quantity of drug is constantly released by a sequence of pulse type magnetic field (0.01–0.03 T) in the first mode. The analysis of 2-D images of the drug diffusion suggested that the release rate of the drug can be control and regulated by the frequency of the external magnetic pulse. Moreover, it’s suggested that this mode would be suitable where several diseased tissues are observed at various locations during endoscopy. Whereas, in the second mode nearly 800 mm^3 of drug is released by the external magnetic field of 0.07 T. As it produces a strong magnetic attraction than the critical force for capsules collapsing so as a result polymeric coating is formed around the capsule. The area of coating relies on the viscosity of drug. The coated area of about 317mm^2 is formed when the drug viscosity is 0.2 Pa/s. The proposed soft endoscope capsule carries two drawbacks. Firstly, the polymer coatings are formed around the target instead of at the target. Secondly, the suggested mechanism is employed in a swallow-able capsule which occupies the volume of 2300 mm^3 however the experiments suggested that the chamber volume should be at least 800 mm^3 to cover the targeted tissue.

Arrays of 3D Micro-tissues

Xu et al., 2015 proposed that an array of micro-tissues construct that has the ability to measure generated force or contractility of very minute scale model tissues.

Generated force produced by tissues is reported by the deflection of cantilevers. They are like micro-tissue strain gauge (μTUGs) and with them the study of contractility in fibroblast smooth muscle cells and cardiomyocytes is made possible. To improve the results cantilevers are bonded by magnetic microsphere. [9]

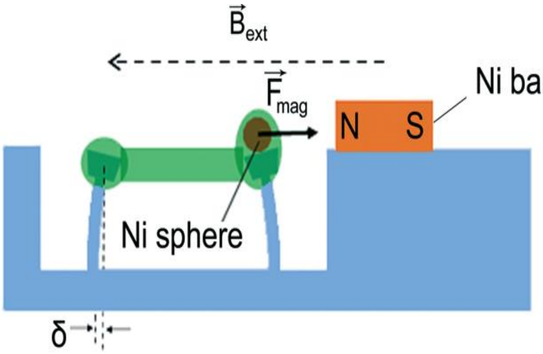

Figure 3. shows magnetic micro-tissue actuation system

Figure 3 shows magnetic micro-tissue actuation system, Micro-tissue (green) deflects flexible micro-pillars on tension. Magnetic field magnetizes the Ni sphere placed on micro-pillars also a Ni bar as a result force is generated between the two resulting in stretching of micro-tissues. The deflection δ of the left pillar reports the tissue's force.

Shape Memory Polymers

Another field incorporating magnetic actuation is in class of shape memory polymers. SMP have ability to change their shape upon application of external stimuli. This external stimulus can be external heating mechanism i.e. photo-thermal or electrical. SMP devices are used widely and among them include micro-actuator for purpose of removing clots in patients of ischemic stroke or stents with drug delivery mechanism or in self-tensioning sutures. Another actuation method includes inductive heating in which ferromagnetic materials are attached into SMP and further alternating magnetic field is used to cause heating. There are several advantages of using magnetic field in SMP as now there is no need of fiber optic wires or power transmission lines. More complex and difficult device design can be achieved. Moreover, now specific areas of device can be loaded with magnetic particles leading to selective heating of device areas. Buckley et al., 2006

Skeletal Deformities

Scoliosis is the curvature of spine either to the left or towards right. Scoliosis is usually treated by inserting rods to uniformly align the spine. Spinal bracing and fusion has been the most common method to treat scoliosis but it carries several limitations as it prevents normal spinal growth also the spinal bracing is ineffective in children. The drawbacks associated with spinal bracing and fusion were overcome by development of growing rod. Implantation of growing rod needs the use of anesthesia and later on distractions of rod to maintain normal spine position by opening the incision point. To overcome the shortenings associated with the rods distraction Cheung et al., 1967 proposed magnetically controlled growing rod (MCGR) system. The MCGR comprised of titanium distractible rod with mid-portion carrying magnetically drive-able mechanism. An external magnetic remote controller was positioned over the internal magnet and thus the rotating mechanism inside the rod results in lengthening of rod and eventually distraction of spine. The extent of curvature of spine was measured using the Cobb angle. Images were captured of both pre- and post-distractions to measure the extent of distractions. The mean change in rod length per distraction was 1·9 mm (0·4 mm). The results proposed that the increment in MCGR length leads to increment in spine length.

Magnetic coupling is also used to correct skeletal deformities. Skeletal deformities like limb lengthening is the most studied area. Limb lengthening methods include extending the length of bones in extremely short limbs. External fixators have been used to rectify limb lengthening but it carries many drawbacks including mechanical collapse of brace, raising possibility of infection and complications due to numerous tuning sessions. So another suitable and better option is internal fixation proposed by Liu, Heller, Kwiat, Fechter, & Harrison, 2015. In internal fixation implantable rods are used which are lengthened gradually. Many processes have been proposed amongst them included ratchet mechanism or electronics but both have disadvantages. Thus a system is suggested that efficiently fixed skeletal deformities via magnetic coupling. The presented system composed of implantable telescoping rod that is implanted inside the body and its monitored using external controller. Two magnets are attached one to implantable rod and the other to controller. This coupled magnet acts as magnetic gear which permits patient to apply torque to weight wirelessly. This system precisely measures the force needed by the controller to elongate the implant as well as distraction distance of the implant. The analog circuitry was used to analyze the progress along identifies the errors like magnetic decoupling. The torque was measured by measuring the current needed by the motor versus the distances between implant and driver. The results suggested that at the minimum current of 114 mA the implant and driver were observed to be coupled. On the other hand, any distance larger than 70mm results in decoupling of implant and driver magnets. As the distance was further increased it eventually results in reduction of the current drawn by the motor. The proposed system suggested that torque as low as 0.12 mN m was required to drive the motor when the distance between the implant and driver was 5mm. Furthermore, the results suggested that proper extensions of the system were achieved but the system performance was affected by several problems. Foremost amongst them was fabrication of implant in unstandardized manner along the implant design.

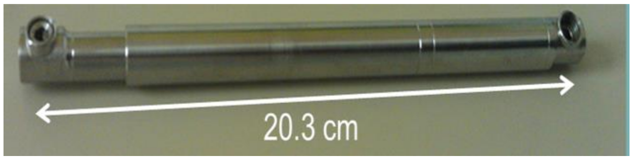

Figure 4. shows prototype of ROBO implant

Child sarcomas are often subjected to limb salvage surgery. The surgery results in removal of the impaired bone along the extraction of epiphyseal growth plates. Thus the patients require such implant that can be extended intermittently. Pollock, Cannon, Briggs, Taylor, & Blunn, 2006 proposed extendable non-invasive prosthesis using magnetically driven mechanism and consisting of motor with a gear-driven telescoping shaft. The motor comprised of rotating magnet that was placed inside the prosthesis and the external device or stator used to elongate the prosthesis as the patient grew. The stator produced magnetic flux leading to lengthening in the implant that was able to overcome the tension force of around 1300N created by the soft tissues during extending process. (left in detail)

Hinged Microstructure

Ramachandran & Mazuruk, 2004 proposed the use of magnetic fluids to be used in hyperthermia therapy to be used in cancer treatment. Hyperthermia is a notable technique to be used in cancer therapy where tumor regions are raised to temperatures between range of 40–46°C. This leads to inactivation of cell regulatory processes resulting in necrosis. Several magnetic fluids possess thermoregulating features. Magnetic particles can be moved into desired targets inside the human body in several ways followed by their activation to act as localized heat sources. Magnetic fluid hyperthermia (MFH) uses very fine 10nm size magnetic particles in dispersions as they carry the ability to selectively adhere to tumor cells. Usual field strengths of 5–30kA/m with a frequency range of 100 to 500kHz were used. Tumor cells can be carefully adhered to magnetic particles and thus tumor cells are killed by alternating magnetic field. The proposed method has advantage to reach those target areas which are unapproachable by other techniques such as those brain tumors.

Laparoscopic Surgery

Laparoscopy involves the abdominal examination and surgeries that are executed through small cuts far away from their sites. This surgery is more pain inflicting and more recovery time is required. In laparoscopic surgery magnetic actuation is used which results in minimal invasiveness, less pain causing and increased recovery time. Onboard actuators meaning controllable actuator embedded inside the magnetic instrument are used to attain controlled and repeatable motion in contact with the tissue. One way of doing this is to use electromagnetic motors. These EM motors are limited in power and lacks ability to perform several other surgical tasks. So tissue retractor working on LMA mechanism is the solution.

LMA i.e. local magnetic actuation is used to drive a laparoscopic robot by magnetic coupling crossways abdominal wall. Magnetic coupling involves the transferring of the torque by use of magnetic field. Technique behind LMA device basically consists of one anchoring unit consisting of internal driven and external driving magnet plus one actuation unit consisting of driving and driven magnet. Driving magnet that can be actuated independently results in actuation of driven magnet which resultantly cause actuation of one degree of freedom of laparoscopic robot Power transferred on driven magnet causes actuation of mechanism. Permanent magnets were selected on the basis of finite element simulations and static modeling. Three tier validations were done to determine the functionality like lifting an organ of retractor was performed.

Using different inter-magnetic distances, the mechanical power transmitted across abdomen was also determined. An average value of 1.5 mNm is transferred at distance of 7cm and when the distance is cutoff to 2cm it increased up to 13.5 mNm. The mechanical power transmitted is used to drive robot to one DoF.

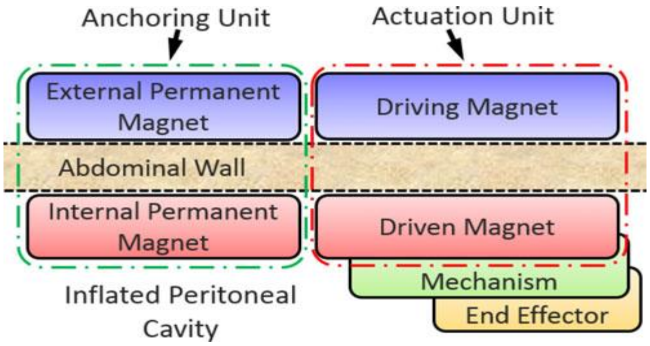

Figure 5. shows the magnetic actuation mechanism in robotic based instrument

J.A. Zeltser et al., 2007 proposed magnetically actuated instruments in case of trocar-less laparoscopy. The design requirement suggested the device to be moved via 12mm diameter trocar into abdomen and moreover would be positioned to desired location using external magnets. The MAGS concept was improved to a prototype which consisted of external magnets, 2 kinds of passive retractors and an internal camera along a hook cautery held via a robotic arm. Moreover, the fabricated design was tested in a porcine nephrectomy model. With the help of fabricated prototype, two laparoscopic nephrectomies were performed successfully without any occurrence of complication. A robotic arm with 3 degree of freedom was fabricated to aid the positioning of hook cautery. The first and second joint of a robot was capable to move in 50 and 45 degree of motion respectively whereas the third joint was able to extend the arm length by 20mm. The robot was deployed and positioned to the abdominal wall by sliding an external magnet. The robotic arm was further activated to perform tissue incision by joystick. The figure shows schematic diagram of the fully deployed device.

Beccani, Natali, Rentschler, & Valdastri, 2013 proposed a wireless method to detect concealed tumors and to identify the hidden blood vessels. In the proposed technique the magnetic palpation device positioned using a standard trocar and is located to target site using laparoscopic grasper. The system comprises of intra body device along a robotic manipulator containing a permanent magnet and a load cell which is located externally. The wireless device comprised of a sensing module, magnet, microcontroller and a battery. The extent of tissue indentation was then measured by varying and controlling the amount of magnetic field. Three different trials were conducted to experimentally validate the wireless palpation in single degree of freedom. The three silicone tissue samples each with varying elastic modulus were indented and eventually compared with the regular indentation. Loading and Unloading experiments were conducted and the results suggested that the indentation depth varied from 0.85mm to 1.26 N in stiffer and softer sample respectively whereas indentation force achieved was 1.26 N. Invivo studies were conducted in which squared lump made using rapid prototyping was introduced in the porcine liver in order to validate whether device detects stiffness in the organ. The positioned lump was used to mimic the concealed malignant tumor that is more firm than nearby tissues. Maximum indentation depth achieved was 3.5 mm whereas indentation force attained was 3 N. The experimental results suggested the efficiency of wireless vertical indentation as an elastic modulus varying from 50 kPa to 93 kPa was detected in three silicone tissue samples suggesting relative error below 3%.

Natali et al., 2015 proposed multi-DOF–LMA to be used as robotic manipulator. The proposed design comprised of 1 anchoring unit along three actuation units. The actuation unit (AcU) was used to provide the required mechanical power to actuate 1DOF of the wrist whereas the anchoring unit (AnU) was used to provide the required support, positioning along the potential to actuate the tilt angle. The AcU comprised of two units – an external driving magnet used to transfer mechanical power from motor to the mechanism incorporated internally among each of the transmission modules. The transmission module comprised of planetary gear train, spur gear and cable reel was positioned across the abdominal wall. The AnU comprised of two axially magnetized magnets where external anchoring magnets (EAMs) magnetically coupled with the internal anchoring magnets (IAMs) provided the sufficient force required to provide the multi-DOF-LMA. The AnU positioned the manipulator tip by actuation of joint. Results suggested an attraction force of around 1-5 N and an actuating torque of around 2mNm - 8mNm was found when the inter-magnetic distance was kept 6cm. A flexible grasper attached at the tip of manipulator performed desired surgical tasks. Grasper was externally actuated to provide 40N grasping force.

CHAPTER 3

METHODOLOGY

In-silico Design

The in-silico design of the laparoscopic actuation device was made using Pro Engineer wildfire 5.0 and Solid Works 2015. The laparoscopic actuation device consists of multiple parts which were assembled to obtain the final device. The overall device consisted of 6 parts.

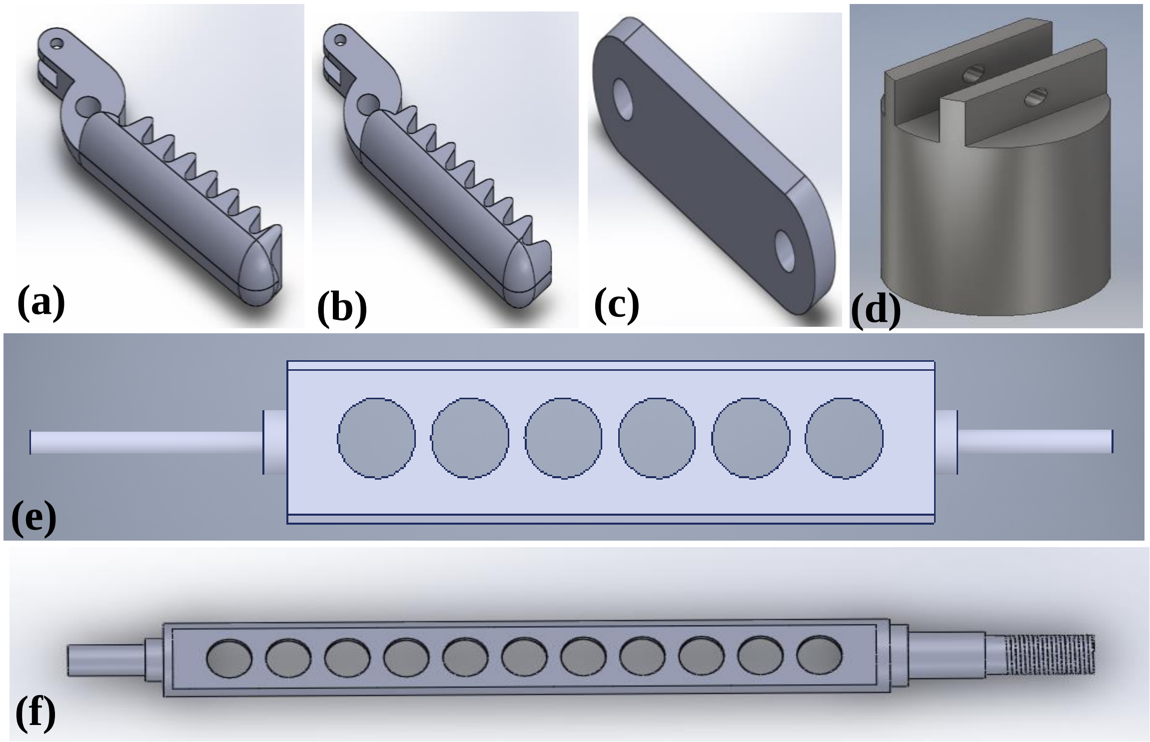

Figure 6. Illustrating different parts of the device; (a) Grasper Jaw A, (b) Grasper Jaw B, (c) Short Bar, (d) Lead Head carrying countersign threading, (e) Primary Magnetic Array (f) Secondary Magnetic Array with leadscrew threading

Fabrication of the Device

The material chosen for fabrication of laparoscopic grasper was mild steel whereas aluminum metal was used for fabricating the secondary magnet shaft. The parts were fabricated using CNC EDM wire cut, high speed lathe, milling machine, drill machine, bench grinder, surface grinder at Manufacturing Resource Centre, NUST (MRC).

Grasper

Fabrication of Grasper Using Laser

Atraumatic grasper was fabricated. The type of atraumatic grasper was bulldog grasper with double action. Initially the prototype of grasper was fabricated using CO_2 laser, Laser cutting equipment Jinan Jinqiang Laser CNC JQ9060-was used. Laser cutting was carried out at a Power 40W and Speed 2 mms^{-1}.

Following jaw designs were tried:

Figure 7. Grasper various designs fabricated using Laser machine

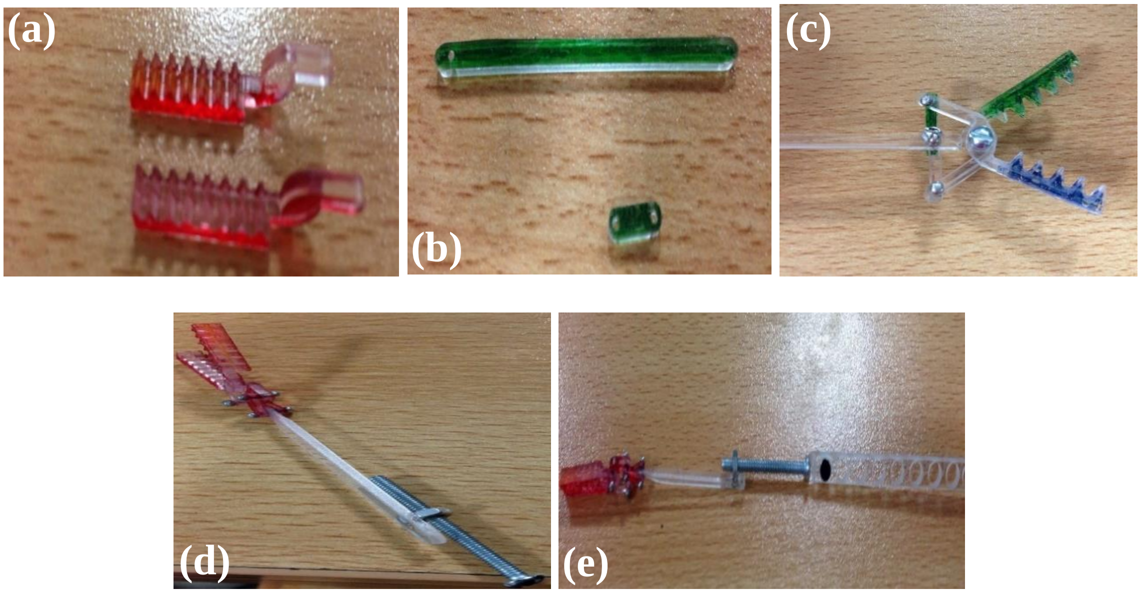

Figure 8. Illustrating different parts of the prototype fabricated using Laser, (a) Grasper Jaws A & B (b) Long bar & short bar, (c) Assembled grasper jaws with scissor link mechanism, (d) Assembled closed Grasper with the lead screw and magnetic array, (e) Opened

But CO_2 laser had some drawbacks as Acrylic is having very brittle nature therefore there were design limitation while using acrylic and also only 2D cutting was available in laser machine therefore the actual device was fabricated using metal and metal cutting machines.

Fabrication of Grasper using Needle File

The material of choice for fabrication of macro model of expansion device was metal. Stainless steel and high grade aluminum metal was used for fabrication. The parts were fabricated using high speed lathe and milling machine at Manufacturing Resource Centre, NUST (MRC). Initially the grasper was made by using needle file but jaws were not precisely made, teeth formed were irregular and they were found to be not interlocking each other hence grasper was then fabricated using EDM wire cut machine.

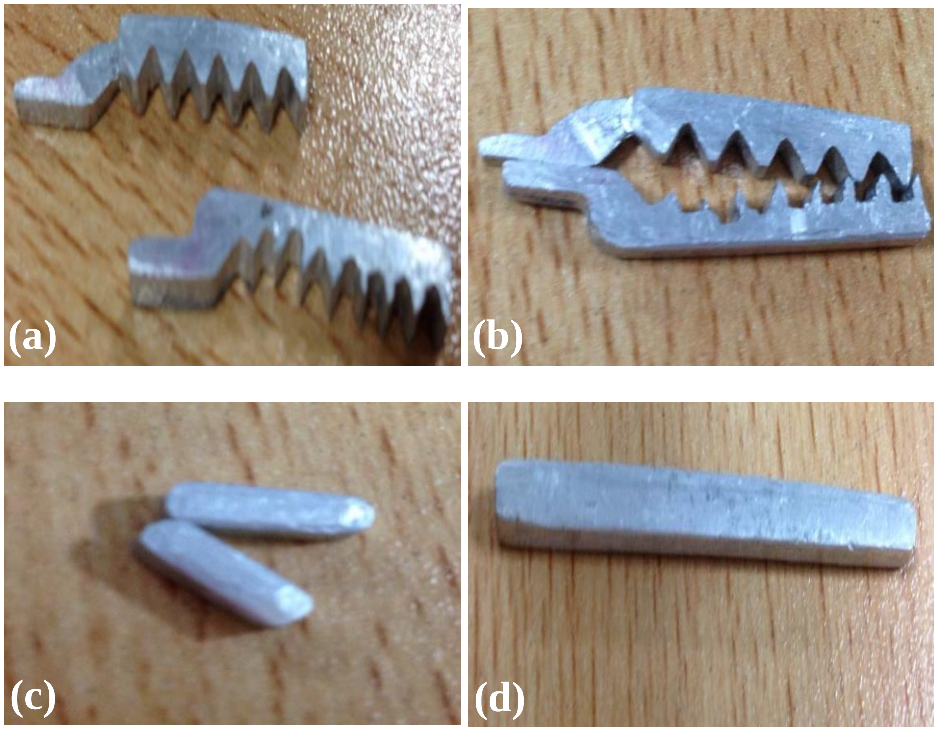

Figure 9. Illustrating different parts of the prototype fabricated using Needle File, (a) Grasper Jaws A & B, (b) Irregular Grasper teeth, (c) Short bars, (d) Long bar

Fabrication of Grasper using EDM Wire Cut Machine

Then the grasper was fabricated using EDM. For this purpose, material selected was mild steel (MS) and stainless steel (SS) sheets. Stainless sheet with thickness of 4mm was used to cut the grasper whereas the sheet with thickness of 2mm was used to cut the short bars. Sheets were firstly milled down to desired thickness using Vertical Milling Machine Model 3S, Serial Number 130507 with specification features of Model 35/34 (X632251/B), Table size 254x 1270mm, 3axis traveling (X 900, Y 450, Z 600) mm. The machine operated at voltage 380 V, frequency 50Hz and power of 2.2Kw. Moreover, the sheets were surface grinded to overcome friction using machine Surface Grinder Model No. MSG818 Serial number 1914 with specification features of Speed 3000rpm, wheel 220mm, center line of the spindle to column maximum 1600, minimum 360mm. Two types of grasper were made containing variant number of waves that are 8 and 11 waves.

Figure 10. Illustrating different parts of the prototype fabricated using EDM Wire Cut Machine, (a) &(b) Grasper Jaws and short bars, (c) CNC EDM Wire Cut machine cutting the CAD design of grasper jaws

Then grasper components that comprised of jaws and short bars were drilled using drill bit of 1.4mm and 2mm. Then the grasper was assembled using nut and bolt of M1.4 mm and M2 mm.

Primary Magnetic Shaft

Aluminum rod was used to fabricate the primary magnetic shaft. For generation of strong magnetic field, cylindrical Neodymium Magnets were used. Strength of Neodymium magnets of various shapes & numbers was determined to select magnets with desired strength. For this purpose, weights were used to measure the force generated.

Figure 11. Primary Magnet

The area covered by magnets of both primary magnetic shaft and the secondary magnetic shaft was kept same and special step size was made on both sides of shaft so that bearing could be mounted to avoid friction while rotation. Neodymium Magnets($Nd_2Fe_{14}B$) were preferred and a total of 6 magnets with following specifications. Magnets used for primary magnetic shaft were of diameter 10mm and height of 10mm. The grade selected of the neodymium magnets was N35. Whereas, the magnetization directional was observed to be axial.

Figure 12. shows the top view of primary magnetic shaft

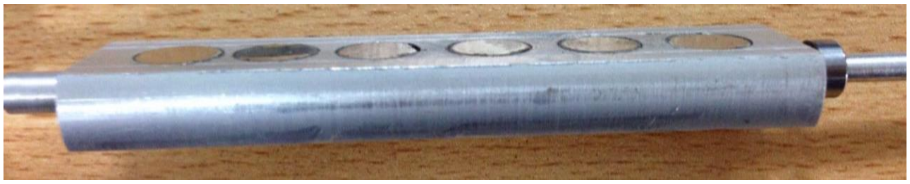

Figure 13. shows the lateral view of the primary magnetic shaft

Secondary Magnetic Shaft with Lead Screw

Aluminum rod was used to fabricate one-part device carrying secondary magnetic array and leadscrew. High Speed Lathe Model Number BLO636B/1000 with a Serial number 122416 was used to fabricate the secondary magnetic shaft. Twelve Neodymium magnets were used in array. Magnets were having specific features among them the diameter and height of the magnets used were 5mm*5mm. N35 Grade was selected among the wide range of magnets grades. Surface of the magnets were Ni-Cu-Ni plated and the magnetization direction of magnets were observed to be in axial direction.

Figure 14. Secondary Magnets

The Magnets were fitted in shaft such that the North pole of magnets directed to one side and South to the other side to increase the magnetic field. The polarity of magnets was determined using handheld navigational compass. Standard M6 tap was used to make thread. Threading were having pitch of 0.8mm. Grasper takes 7 complete turns and 14 half turns of thread to fully open and close each. So the length of lead screw was kept according to requirement that was 10mm.

Figure 15. Shows the Top view of the Secondary Magnetic shaft

Figure 16. Shows the Lateral view of the Secondary Magnetic shaft

Lead Head Containing Countersign Threading

Aluminum rod was used to make cylindrical part using Lathe Machine. The part was 15 mm in length with drill hole of M4.3mm and depth of 10mm in length. The grasper short bars total displacement measured was 2.72mm in length but threading length was kept 10mm region to avoid any inconvenience. Moreover, standard M5 threading was done in the drill hole.

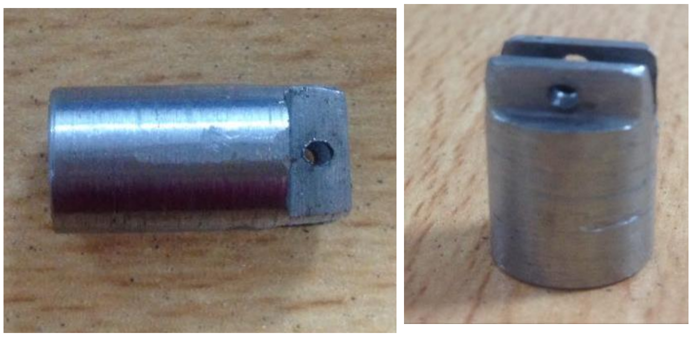

Figure 17. Lead Head

Assembly of the Device

The device was assembled using the fabricated components. In-silico design of the assembled device is shown in the figure 14.

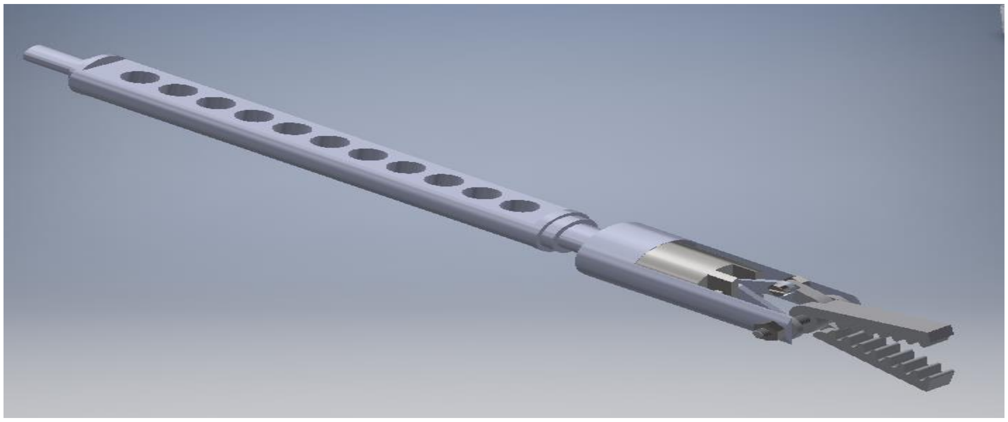

Figure 18. The Assembled Device

Major parts of the device are shown below in Figure 19.

Figure 19. (a) Assembled Grasper with the lead head, (b) Assembled grasper with the outer aluminum pipe, (c) Opened Grasper with the magnetic array, (d) Closed Grasper with the magnetic array

Characteristics of the laparoscopic Device

Following characteristics of the device were measured and are shown in Table 1.

Table 1. Measured Characteristics of the Device

Parameters	Values
Secondary Shaft length	113mm
Secondary Shaft Diameter	10mm
Material	Stainless Steel
Working End Length	30mm
Device Length	160mm
Device Weight	32g
Device Diameter	12.88mm

Device diameter is very much suitable for laparoscopic surgery as trocar with largest inner diameter is dedicated to endoscopic camera i.e 13mm inner diameter for Versaport V2 Covidien Mansfield MA so assuming we use that port we can consider 12.7mm. Stainless steel material is suitable for the medical instruments for its feature to be sterilized again and again along its ability to be non-reactive with the body.

Rig Assembly

Rig was consisting of two vertical slabs and one horizontal slab. Acrylic sheet of 9mm was used to fabricate the slabs. Holes were drilled in vertical slabs at a distance of 2cm from center to center. Bearings were used to avoid friction. Two different bearing sizes were used 4x8x3 and 6x12x3.

Figure 20. Rig Assembly for Testing of Device

Alignments Studs

M6 Alignment studs along washers were mounted in vertical slabs to avoid misalignments between the primary and secondary magnetic shaft.

Figure 21. Aluminum Alignment Studs

Assembly of the Device and Rig

The in-silico design of assembled device and the testing rig are shown in Figure 22.

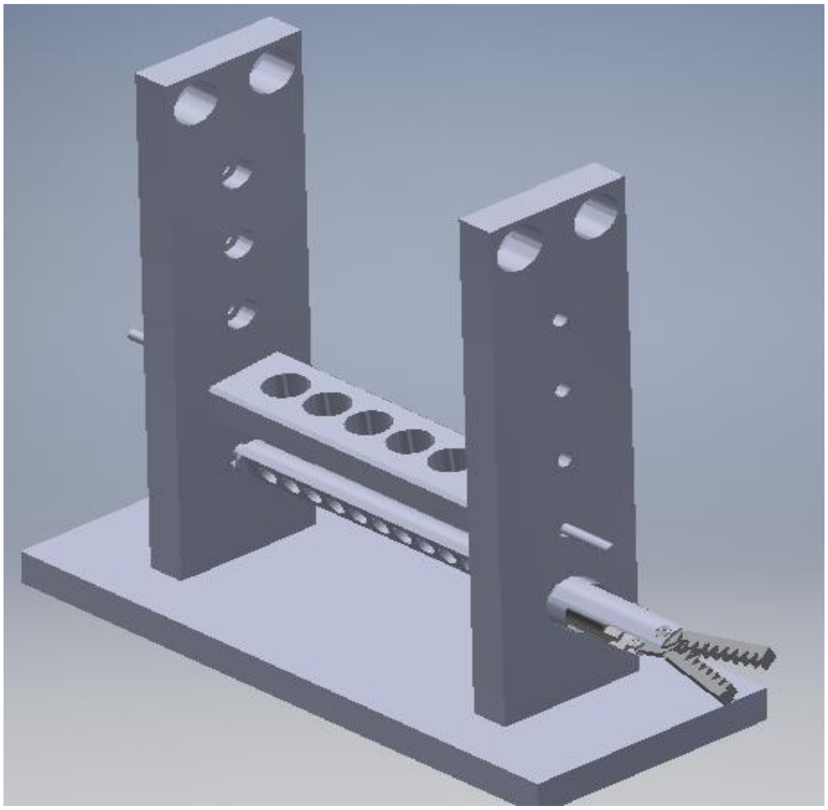

Figure 22. In-silico Design of the Testing Rig and the Assembled Device

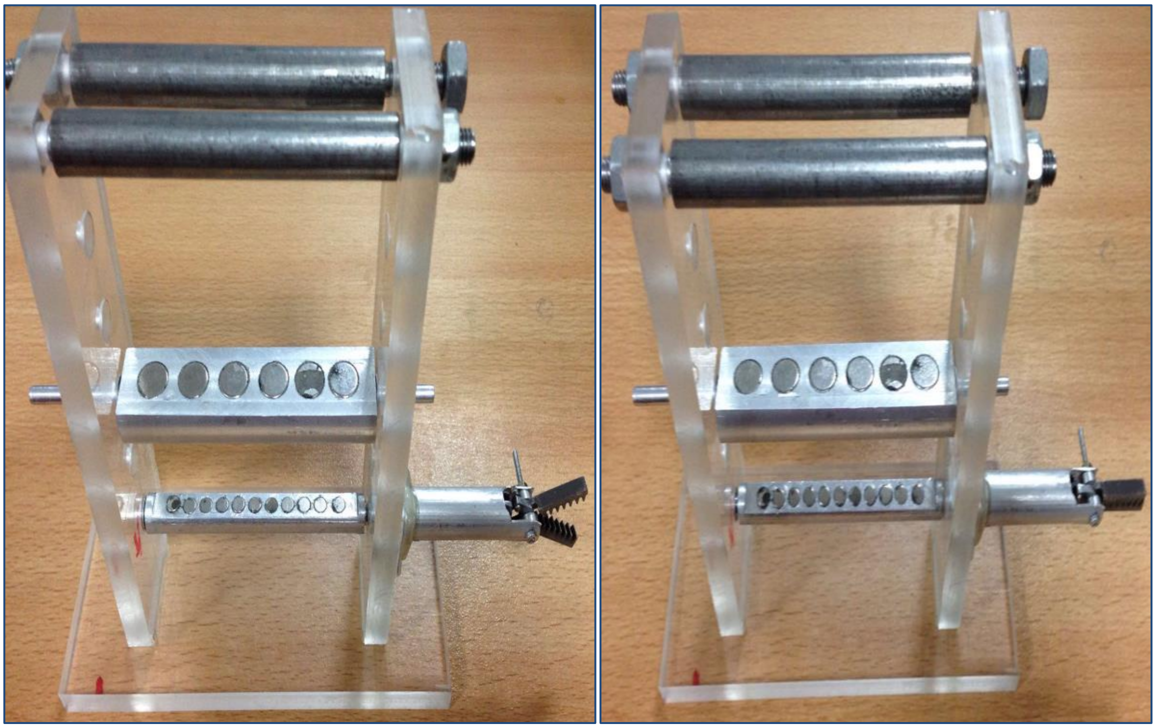

Figure 23. Final Fabricated Testing Rig and the Assembled Device

Fabrication of Parts

Parts were fabricated using following machines and all the fabrication was done at Manufacturing Resource Center (MRC)

Figure 24. Different Machines used during the Fabrication of the Device

Operation of the Device

Primary magnetic shaft was rotated using DC motor. DC motor with following features were used. A DC motor is used in this project. It operates on 9V-15V DC. This motor is selected because it has high torque of 4.5 Kg/cm. The motor has 1665 rpm at no load. The motor has 20mA current at no load. The motor has O-type circular shaft with a diameter of 8mm. The motor can rotate both in forward as well as reverse directions by changing the polarity of DC supply. The motor is shown in Figure 25 below.

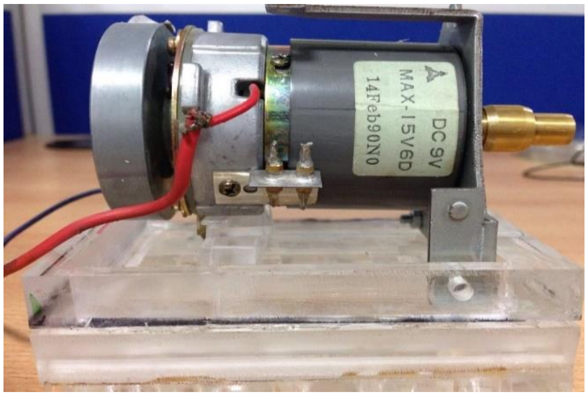

Figure 25. Motor used

Bidirectional control of motor was done by making H-bridge circuit. H bridge circuit was made incorporating two P-channel MOSFETs (IRF9540) and two N-channel MOSFETs (IRF540) with two NPN Bipolar junction transistors (2N3904). 2kohm resistors were used to fully turn on N-MOS and fully turn off P-MOS. Regulator was also used with serial number L7812CV.

Hall effect's sensor was used to determine the strength of magnetic field in the form of revolutions per minute (RPM). The more South Pole approaches the sensor from the front side the lower output in the form of voltage it gives. Similarly, the more North Pole approaches the sensor from the front side more high the output voltage is.

The electronic drive for the laparoscope was developed on an Arduino™ UNO® Board, with the core Atmel™ Atmega328P microcontroller.

The mechanism is voltage driven, the optimal operating requirement was found to be 3 Volts and 0.25 Amperes for the pulley mechanism. The power consumed during grasper opening and grasper closing was also measured using Analog current sensor (ACS712). The average power consumed was found to be 0.5951W whereas the peak power consumed was found to be 1.2605W. The lead screw mechanism had to be configured with NPN transistors in an H-bridge configuration circuit, to satisfy the same voltage requirements without the use of a higher battery voltage.

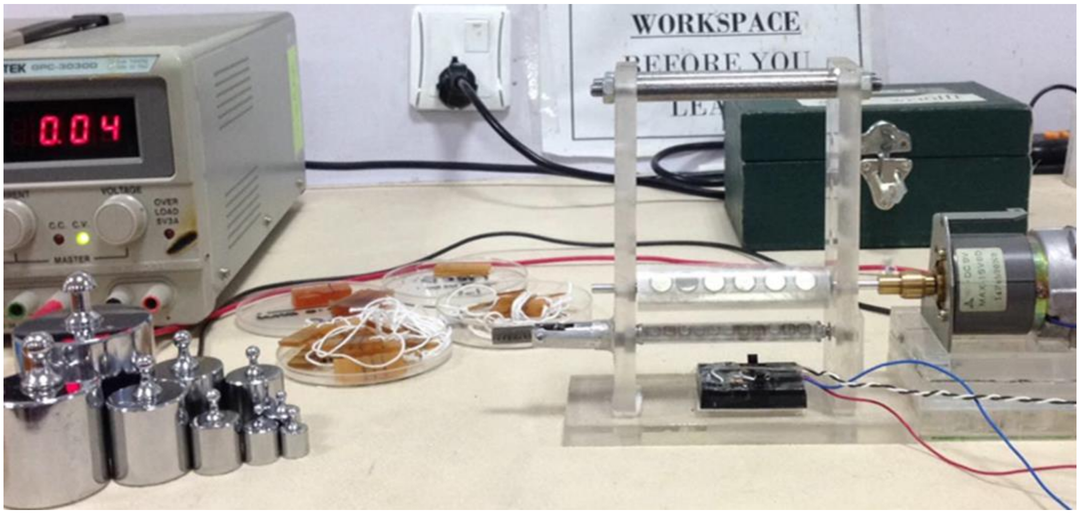

Figure 26. Whole testing setup for device testing with circuitry and testing rig

Testing of Device

After the final assembling, the device was powered ON and was tested both in forward & reverse directions for longer times without any load to assure its operation and reliability. After that the device was tested on different tissue equivalent materials. To test the deployment device three different thicknesses of polyurethane sheets were fabricated. The polyurethane used for the fabrication of sheets was PMC-744 (Smooth-On INC.PA, USA). It consists of two parts A and B which were mixed in 2:1 respectively and then poured into the mold to form sheet of 2mm thickness. Five types of tests were performed which includes slippage test, lifting test, magnetic decoupling test, force/pressure measurement between jaw teeth and precision test.

CHAPTER 4

RESULTS

Slippage Testing

Two types of slippage testing were performed that is Horizontal and Vertical Slippage testing. Polyurethane films with different thicknesses were subjected that is 1.3mm, 2.33mm and 4.5mm. Polyurethane was used as it mimics the mechanical properties of that of skin. Films with these thicknesses were used as mean skin thickness of abdomen was found to be 2.2mm (Gibney, Arce, Byron, & Hirsch, 2010) and 1.55mm to 3.00mm (Jain, Pandey, Lahoti, & Rao, 2013). Tests were conducted across different inter-magnetic distances as 3 holes at a distance of 2cm apart were drilled.

Horizontal Slippage Test

In horizontal slippage test, PU sheets were placed at an angle of 90 degrees to grasper teeth. Results suggested that the PU sheet with minimum thickness was slipped at force of 9.506 N.

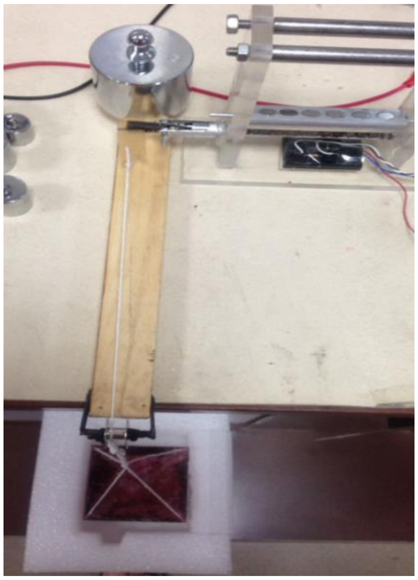

Figure 27. Horizontal Slippage Test Setup

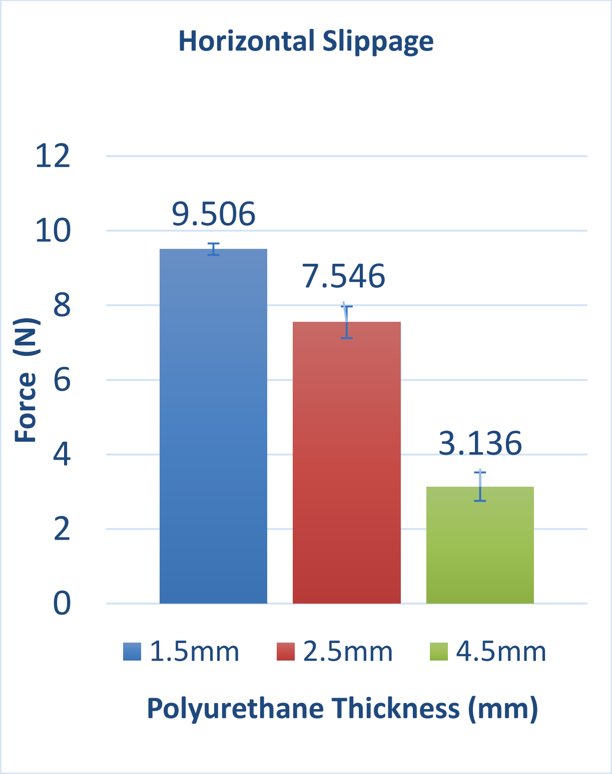

Figure 28. Results of Horizontal Slippage Tests (Bar Plots with Error Bars)

Vertical Slippage Test

In vertical slippage test, PU sheets were placed at an angle of 0 degree to the grasper teeth. Results suggested that PU sheets with mere thickness of 1.5mm was slipped after a force more than 4.606 was applied.

Vertical slippage was observed at a force greater than 4.606 N whereas the horizontal slippage was observed at a force greater than 9.7 N. The difference in the two was because of a reason as the area of contact is greater in horizontal slippage which prevent the motion along the line whereas in vertical grip the area of contact is perpendicular to the application of force so hence very small effective area of contact.

Figure 29. Vertical Slippage Test Setup

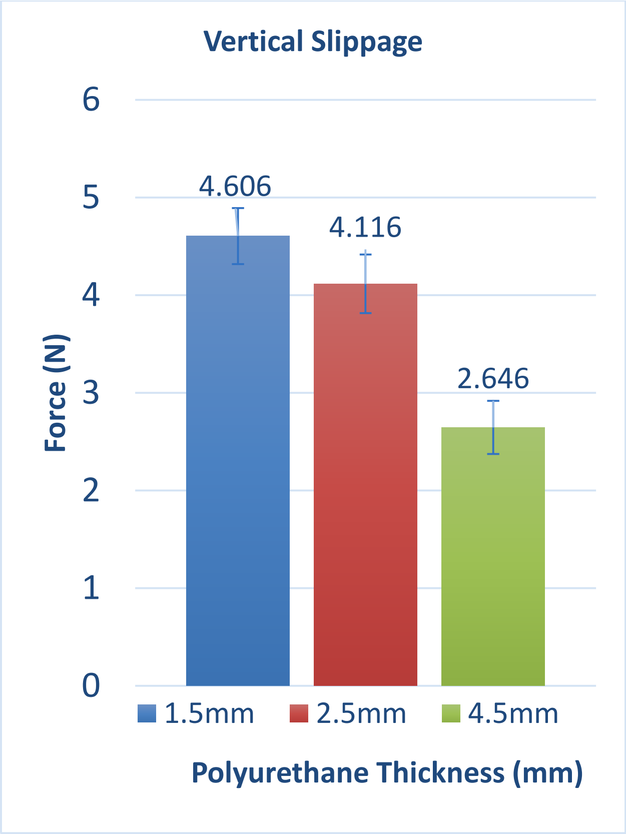

Figure 30. Results of Vertical Slippage Tests (Bar Plots with Error Bars)

Lifting Test

Lifting tests were performed to check the ability of the grasper to lift the weight. The max value of weight successfully lifted up and lowered down was around 520 g. The test was performed at inter-magnetic distances of 2cm and 4cm. Results suggested that at 2cm the weight lifted was found to be 520g or the amount of force pulled was 5.096 N. Whereas at a distance of 4cm the amount of weight lifted was 130g or the amount of force pulled was 1.274 N. Hence the increment in distance was twice so magnetic field decreased four times as magnetic field decrease inversely as the distance is increased.

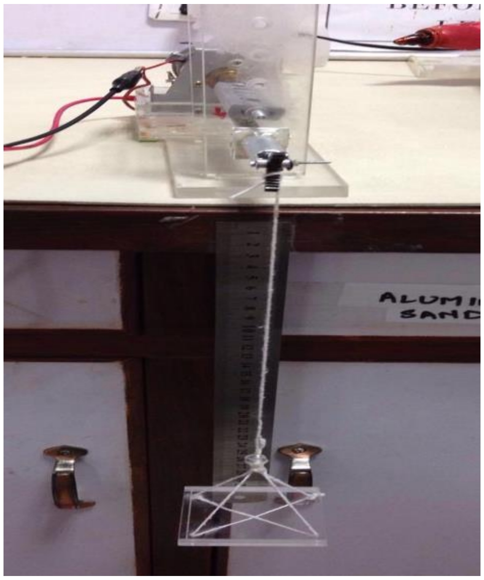

Figure 31. Lifting Test Setup

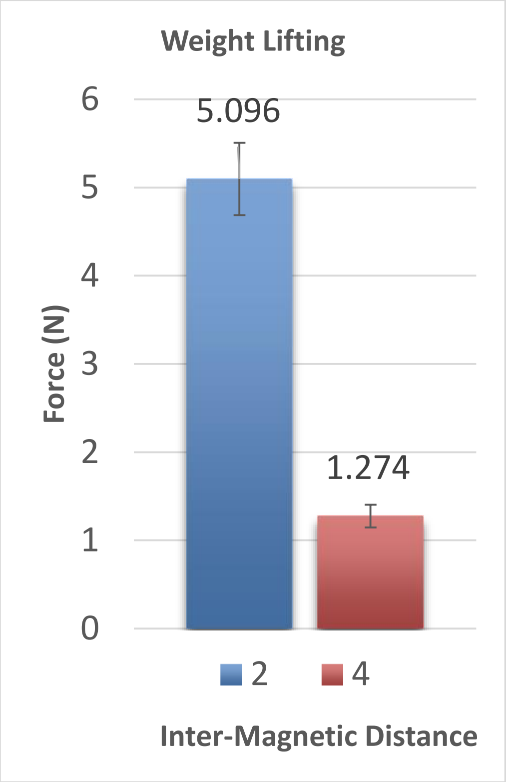

Figure 32. Results of Lifting Tests (Bar Plots with Error Bars)

Magnetic Decoupling Test

Magnetic decoupling test was performed to determine the distance and voltage at which loss of coupling between magnetic shafts was observed and the results are shown in Table 2.

Table 2. Results of Magnetic Decoupling Test

Inter-magnetic Distance	Voltage	Loss of Coupling
2cm	15V	No
4cm	15V	No
6cm	15V	No
8cm	3V & onwards	Yes

To determine the distance and speed at which loss of coupling between magnetic shafts was observed. Results suggested that no loss of coupling was observed at a distance of 2,4 and 6cm when the voltage was increased from 1V to 15V but at a distance of 8cm the loss of coupling was observed at a mere voltage of 3V. So with the use of N35 magnets the magnetic field was observed to be reduced at a distance of 8cm as the magnetic field decreases inversely with the increase in distance. In order to produce the strong magnetic field effect, improve neodymium magnets (<N35) with increased size can also be preferred.

Force/Pressure Measurement

Force and the pressure exerted by jaw teeth was measured using FlexiForce A301 Sensor. Average diameter of sensing area calculated was 8.525mm. Hence, using area dimensions' pressure applied by grasper jaws was measured.

Figure 33. Flexiforce Sensor

Table 3. Results of Force & Pressure Test

Teeth	Net Force	Pressure
1	3.332 N	0.0584 µPa
2	33.0554 N	0.5791 µPa
3	66.662 N	1.0628 µPa
4	48.902 N	0.8567 µPa
5	69.482 N	1.2173 µPa
6	92.022 N	1.6122 µPa

Sensor used is shown in figure 33. The force exerted by the jaws was measured at each 1,2,3,4,5 and 6 teeth number. Results suggested there was general increment in the force and hence the pressure also. An unusual trend was observed at teeth number 4 where the force exerted between at teeth number 4 dramatically decreased.

Figure 34. Sensor held between the grasper teeth

Precision Testing

Precise grip of the laparoscopic device was improved by introducing the concept of intermittent stepping. The proposed device opens and closes in 14 half turns and 7 full turns thus now surgeon would have precise control over grip. Additionally, this feature of precision leads to minimal tissue damage. Figure shows the angles of device at each one of the 14 intermittent steps.

Figure 35. illustrates how angle varies at each of 14 steps

CHAPTER 4

CONCLUSION AND RECOMMENDATION

A laparoscopic atraumatic grasper incorporating magnetic actuation mechanism has been developed with desired/precise grip and minimal risk of tissue damage. The proposed magnetic actuated laparoscopic grasper prototype has the ability to lift weight of 930g in horizontal and in 420g in vertical direction. Testing of the prototype has been done on tissue equivalent material that is polyurethane. Upon testing the results suggested that the device can be used for laparoscopic surgery after further changes and modifications in design as it has the ability to lift the force of 9.7 N in horizontal direction whereas 4.7 N in vertical direction for a duration of 30 s in contrast to conventional laparoscopes generally Surgeons grasp tissue with 7.35 N of force, for durations of 10 s or less (Brown, Rosen, Chang, Sinanan, & Hannaford, 2004). Moreover, precision is improved in proposed design as concept of intermittent stepping is introduced. But now precision is improved in proposed design as concept of intermittent stepping is introduced.

Future Work

The laparoscope grasper fabricated in this research work can be used only with one degree of freedom. In the future degree of freedom of the device can be increased. Someone can perform animal trials with this device to get certifications for regulatory approvals. The device can also be modified to operate on rechargeable batteries. Jaw design can also be modified in order to obtained accurate results. Large Neodymium magnets can be used to increase the force lifted. Electromagnets can also be introduced. In the future the mechanism of lock/antilock can be introduced.

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PUBLICATIONS

Amber Zahoor, **Javairia Yousaf Cheema**, Murtaza Ali, Umar Ansari, Mariam Mir (2016), “Finite Element Analysis of Coronary Stents: A Review”. (Submitted; JABFM)

Maryam Shahid, **Javairia Yousaf Cheema**, Amber Zahoor, Rija Irfan (2016), “Detection of Breast Tumor from Mammogram Images Using Image Processing Techniques”. (Accepted; ICEET)

Javairia Yousaf Cheema, Amber Zahoor, Murtaza Ali, Umar Ansari “Magnetic actuation of medical device: A Review”. (To be Submitted)