Cavatappi Hand

Preliminary Proposal

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2021-2022

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1 BACKGROUND

1.1 Introduction

The Cavatappi Muscle Project focuses on the research of Diego Higueras Ruiz. His research is focused on the field of soft robotics, specifically soft muscle like actuators that unlike most of the comparable existing actuators deliver linear force with little to no radial expansion. Pictured below are the "Cavatappi" actuators, so named after the pasta of the same shape.

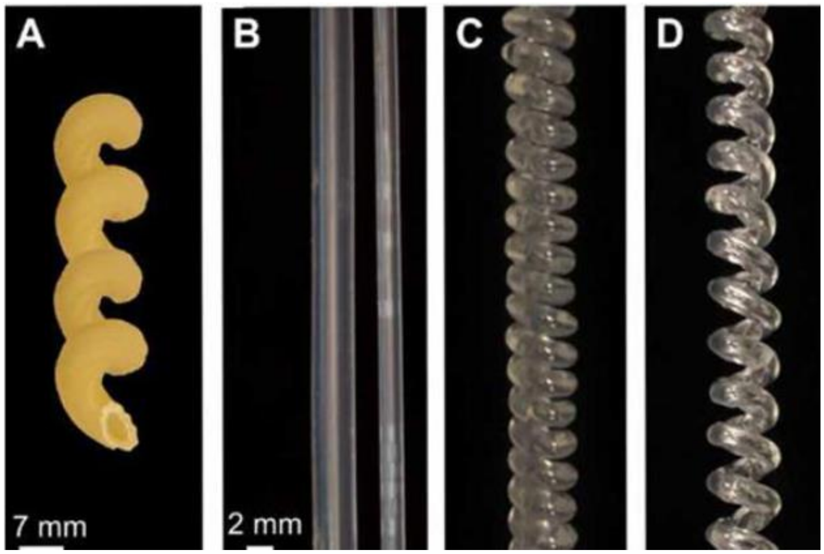

Figure 1: Cavatappi Actuator Comparison [1]

This project is focused mainly on two major points concerning the actuators themselves. Firstly, updating the manufacturing process to better produce actuators both in terms of efficiency and quality. Secondly, once better production is achieved, demonstrating that the base size of the tubing can be scaled down and the actuators set up to run in parallel in order to actuate a hand-like device (1cm x 1cm x 1cm in size) to demonstrate that these actuators can be utilized to perform a more dexterous/delicate task such as picking up a coin off a flat surface.

Soft robotics are going to be a key technology in the future in a variety of sectors, these being robotic systems that directly interface with humans. Soft actuators in that field are going to be critical to making functional objects that be safely used directly with humans. To increase interest in actuators like these for further research and development practical demonstrations to be done to showcase that they have potential. This project may not revolutionize the field or actually directly build a functioning prosthetic limb for an amputee, but it may attract the attention of those with the ability to move the technology forward in a meaningful way so that those things may one day be a reality. Progress is slow but steps like these are necessary to "move the ball down the field".

1.2 Project Description

Below is the original project description given to us by our client Dr. Michael Shafer:
Minimally Invasive Surgery (MIS) represents the gold standard in the majority of abdominal operations. As conventional and standard surgical tools still present fundamental limitations on dexterity and safety, this capstone will aim to address such limitations using emerging robotic solutions. This project will involve the design and fabrication of a tiny robotic hand (1 cm ×1 cm or even smaller) actuated with

artificial muscles (cavatappi) used to increase the dexterity within the body for surgeons. The main idea is based on the exploitation of soft materials or artificial muscles to be intrinsically flexible and safe and enable high dexterity and selective stiffness variability. Such a system will be fully actuated using a hydraulically wearable glove consisting of syringes to generate internal pressurization in the artificial muscles, and in turn, actuation. Each syringe in the glove will allow to individually actuate each finger in the robotic hand. As a result, surgeons will be able to translate their fingers motion into the motion of the tiny hand surgical tool, leading to an increment of the safety level during surgeries

1.2.1 Original System Structure

While no original system exists for the hand itself, this project also encompasses the general manufacture of the actuators themselves and there does exist a system for that already. Using hooks mounted to wooden blocks (hereafter called towers). The hook's center axis is parallel to the work surface and can still rotate freely, secured to the tower by their threads with a nut.

1.2.2 Original System Operation

Both tubing (silicone or pvc) and mandrel (stiff solid plastic round stock of similar size to the tubing) are secured into a small copper clamp at one end. The mandrel is clamped at the other end and both clamps are secured to the hooks. One hook has a slightly loosened nut and can rotate, as it rotates the tubing is twisted along its own center axis and simultaneously coiled around the mandrel. The operator does their best to maintain consistent and uniform coils. Once the coiled length reaches its desired amount, the operator holds the excess material taught so as not to allow the muscle to uncoil or untwist as both are vital to function. The excess tubing is clamped with the mandrel so that both ends of the mandrel and the actuator are clamped. This entire assembly is clamped into a metal rack and placed into a small toaster oven at 170 °F for 30 minutes to anneal. This annealing process allows the actuator to maintain its coiled length without the need for clamps.

1.2.3 Original System Performance

The system as it exists now was designed purely for research purposes. It's not built for producing consistent muscles in larger amounts quickly. While it can produce good muscles, overall, with unpracticed operator the failure rate was around 60% due to various issues within the process. A good actuator takes about 15-20 minutes to twist and coil another 30 minutes to anneal.

1.2.4 Original System Deficiencies

The largest deficiencies in the current process lie in the amount of hands-on interaction with the muscle by the operator. Various inconsistencies in the process lead to introductions of excess force that can cause plastic deformation in the material at different points in the actuator itself. This also means that in limiting the final quality of the muscle that it also increases failures before the actuators themselves can even be tested, causing waste of material and time. Beside the inherent inconsistencies with the operator interaction the process itself is inconsistent in timing even for successful actuators.

2 REQUIREMENTS

The main requirement of the Cavatappi Capstone is to use Cavatappi artificial actuators to produce a laparoscopic surgical tool intended for minimally invasive surgical procedures (MIS). Team Cavatappi is to design and fabricate a small robotic hand that is both dexterous and flexible to make MIS procedures safer and easier. Intended manipulation of the device is to use a glove-like control system with syringes to translate user input into actuation of the hand. Individual “finger” actuation using multiple muscles in parallel is also a necessary design feature. [2] Customer Requirements are developed y Team Cavatappi with the clients. Engineering Requirements are developed by Team Cavatappi based on CRs. Both CRs and ERsused to make a House of Quality to compare CRs and ERs.

2.1 Customer Requirements (CRs)

Team Cavatappi developed customer requirements after meeting with clients Dr. Michael Shafer and Diego Higueras-Ruiz. All CRs were weighted on a scale from one to five, five being the most important. The three most important CRs are minimizing the cross-sectional area of the final design, a glove-like control system, and operation safety. These three have the highest weights because they drive a majority of the final design geometry, with safety being self-explanatory. Controlling the final design with simple inputs like syringes allows for intuitive actuation. A small cross section requirement is because of the intended use in MIS.

The next highest requirements are designing a muscle manufacturing process, ensuring the muscles are scalable, and utilizing muscle systems in parallel. The current manufacturing system is not ideal for smaller muscles, so this needs to be addressed and developed early on in the project. The Cavatappi muscles need to be smaller than they have been in the past, since a small cross-section is required. To build on this, a selling point of the Cavatappi muscle design is their ability to be used in parallel with one another, which saves space compared to other soft robotics actuators. [1]

The less-pertinent requirements are minimizing muscle leaks, staying under budget, and ensuring the design is reliable and durable. While design durability and reliability is important, the other requirements above were deemed top priority by the clients. Because a lot of materials were pre-purchased, staying under budget is also less of a concern. Finally, the current methods of mounting and using Cavatappi muscles can cause leaks, so some testing regarding this issue will be a point of testing along the way.

2.2 Engineering Requirements (ERs)

Based on the CRs, Team Cavatappi developed the following Engineering Requirements (Note: Metrics included below were pulled from supplied literature or come directly from clients): [1] [2]

- Maximize Force Output (>=0.38kJ/kg)
- Minimize Muscle diameter (d<=1.5mm)
- Minimize Manufacturing Cost (Cost < $200.00 USD)
- Mech Input to Hydraulic Output (Wout/Win ~ 0.45)
- Minimize "Hand" Size (<= 1.0 cm^2)
- High Factor Of Safety (1.25 < FS < 3.25)
- Minimize # Muscles per Bundle (2 < N < 4)
- Minimize Muscle Length (L < 90 mm)
- Minimize Pressure Input (100 psi < P < 150 psi)
- Maximize Muscle Efficiency (Efficiency > 20%)

The most notable metrics above are the cost, pressure input, hand size, and the factor of safety. The total budget of the project is $200.00 USD. Despite a large portion of the supplies being pre-purchased, Team Cavatappi should not exceed this amount for new materials, manufacturing, or any other potential charges. [2] Cavatappi muscles are rated to withstand up to 150 psi, so the system cannot apply more than this pressure. [1] The hand size is directly from the client. [1] Finally, the system must be safe to use, so it is the job of Team Cavatappi to prove that the muscles will not fail and cause injury to the user or the patient. Safety factor calculations will need to take place after a manufacturing process is developed.

The force output of a Cavatappi muscle has been measured to be around 0.38 kJ/kg. [1] The muscles created for the final design must be able to output a similar force. The diameter of the muscle depends on the manufacturing process, with a coil diameter of 1.5 mm being average for small Cavatappi. This number must be maintained. When actuated in a system, the Cavatappi muscles exhibit an input-output ratio of around 45%. This metric is based on the mechanical input by the fluid on the muscle and the output work of the muscle. [1] The number of muscles per bundle and maximum muscle length target values were suggested by the client. [2] Finally, human muscle has an efficiency of around 20%. [1] Because of this, clients suggested that ensuring that these muscles are similarly efficient on their own is a good benchmark for future testing.

2.3 House of Quality

For Team Cavatappi, the House of Quality is used to determine which engineering requirements should be the main focus of the prototype development process. By directly comparing the CRs and the ERs with weighted correlations, the most important engineering requirements influence the customer needs. If an ER correlates highly with a CR, it receives a weight of 9. A moderate correlation is a 3 and a low correlation is 1. The sum of these correlations determine which ERs are most important with respect to CRs. A House of Quality based on these CRs and ERs is in Appendix A.

The five highest-rated ERs based on weighted relationships are minimizing muscle diameter, the factor of safety, the number of muscles used in parallel, length of the Cavatappi muscles, and ensuring that the pressure stays within the aforementioned maximum. Essentially, the House of Quality proves that muscle geometry and safety are the most important metrics compared to the CRs.

3 DESIGN SPACE AND RESEARCH

Each member of Team Cavatappi conducted individual literature reviews to find relevant sources to use during the design process. Each member has five sources of value, with explanations of their usefulness to the project and how the information they present is applicable.

3.1 Literature Review

3.1.1 Student 1 (Ann Lester)

Student 1 focused on the properties of various benchmarking systems, including but not limited to TPAs, HANSELs, and McKibben actuators. Student 1 also completed benchmarking various hand models and manifolds.

3.1.1.1 Highly Dexterous Surgical Hand Using Cavatappi Muscles

This source was utilized to provide descriptions for the three artificial muscles that the team would be benchmarking. These muscles are what the proposed design will be compared against when evaluating if the team achieved the project goal.

3.1.1.2 A Novel Biomimetic Torsional Actuator Design Using Twisted Polymer Actuators

This article covered the properties of TPAs. In addition, the article provided information regarding design and fabrication of TPAs. This was important to the project because TPAs are a type of soft muscle actuator that contributed to the design of Cavatappi muscles. It was important for the team to benchmark this actuator and understand the anisotropic nature of TPAs and what can be improved.

3.1.1.3 Index Finger of a Human-Like Robotic Hand Using Thin Soft Muscles

This article described the methods used to design and fabricate an index finger of a human-like robotic hand with McKibben artificial muscles. Student 1 used the article to identify the benefits and drawbacks of McKibben actuators in a design setting. Previous resources provided a brief explanation of these aspects, but it was important for the team to identify how these artificial muscles behaved in a real-world environment. This information will be utilized to improve future designs.

3.1.1.4 Robotics for Chemists

This resource provides various real-world applications of robotics in the field of science and technology. The resource highlights the benefits of soft robotics vs hard robotics. This article provided a benchmarking subsystem for the mechanical hand.

3.1.1.5 Soft Robotics

This resource described the process of designing and manufacturing a lightweight soft robotic arm using pneumatic artificial muscles. This article provided a benchmarking subsystem for the mechanical hand and an example of artificial muscles rigged to a mechanical hand.

3.1.1.6 Manifolds

Manifolds are a machine element that are used to combine fluids via pipes, channels, and tubes. This website summarized the benefits of using manifolds for design purposes and provided descriptions/applications of the three different types of manifolds. This resource was important because the team will be utilizing a manifold to attach the Cavatappi muscles to the mechanical hand.

3.1.2 Student 2 (James Bennett)

Student 2 focused on Cavatappi muscle material properties and current laparoscopic tool designs and their drawbacks. Possible cyclic testing procedures were also a focus of literature research.

3.1.2.1 eMurdock on Tygon Material

The tubing used to produce Cavatappi muscles is known as "Tygon." According to the website *eMurdock*, Tygon is a brand of tubing owned and manufactured by the company known as Saint-Goblain Performance Plastics. The most common materials used to make Tygon are flexible PVC and silicone rubber. However, thermoplastics and polyurethane are also common materials, especially in the food and beverage industries. Medical devices such as pumps, IV units and prosthetics also make use of Tygon tubing because of is flexibility and made-to-order manufacturing options offered by Saint-Goblain. [8] Knowing that Tygon tubing can be multiple materials is important because if one type of tubing is not suitable for making artificial muscles, a different kind of Tygon may be usable.

3.1.2.2 Tygon ND 100-65 Medical Tubing

In a material properties document available directly from Saint-Goblain, their medical-use Tygon (ND 100-65) tubing can handle a number of different temperatures and fluids. ND 100-65 is resistant to temperatures up to 165 °F (74 °C), it can handle corrosive fluids like light acids and fuel, and it is sterilizable using an autoclave, gas or radiation up to 2.5 mRad. [9]

Tygon tubing is a great material choice for making a laparoscopic tool, since Saint-Goblain designed a number of tubing types specifically for the medical field. Different sizes of tubing handle different maximum pressures, so sourcing Tygon for specific pressures is simple. A table of sample sizes and properties is available in Appendix B.

3.1.2.3 Pressure Pipe Cyclic Testing

Different testing methods of the Tygon will be necessary since the Cavatappi muscles will require pressure to actuate them and reducing leak failures is one of the CRs of the project. For large-scale water pipes, research centers such as the Borouge Innovation Centre use a method of testing known as cyclic fatigue testing to estimate the life cycle of PVC pipes. By repeatedly pressurizing the pipe and monitoring stresses, an estimate of how long a pipe is usable for can help predict when a pipe needs replacement. [10]

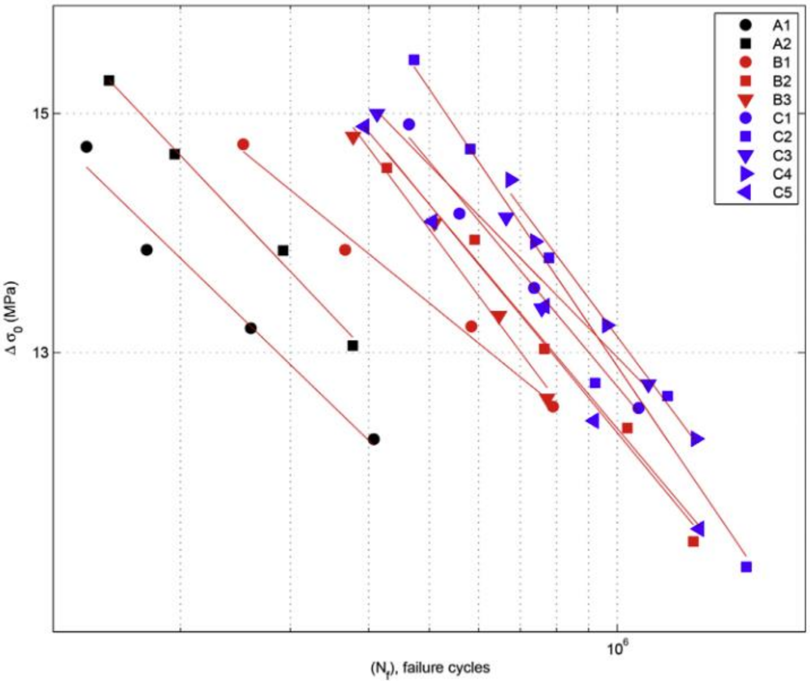

Figure 2: Sample Stress-Failure graph for multiple pipes tested by BIC [10]

While Cavatappi muscles are much smaller than pipes used for transporting water, a similar cyclic testing procedure may prove useful, once the muscles are producible at a regular rate. Knowing how long a muscle can last will help estimate how often our final design may need to be replaced in the future, which will factor into the final product cost.

3.1.2.4 Original Forceps Patent

As the current go-to tool of most modern MIS procedures, forceps have been around since the creation of their patent in 1976. They're designed with a simple scissor-like control for actuation with one range of motion. A long arm made of steel moves back and force during use, which actuates the tip of the forceps during surgery. [11]

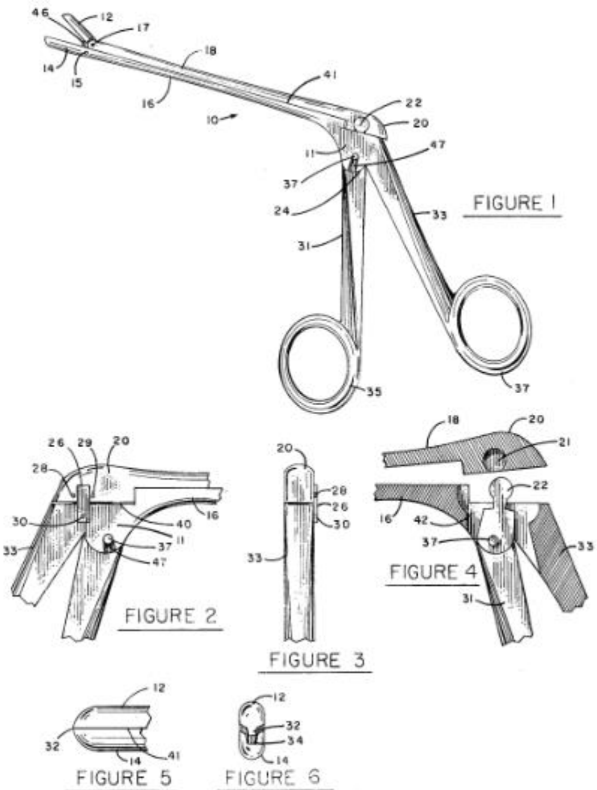

Figure 3: Original forceps patent drawings [11]

Forceps are common tools in surgeries and have seen little design updating in the past forty years. This is because of their reliability and ease of manufacture. However, their lack of complex actuation is a notable place for improvement. During the device design phase, using forceps as a baseline for current laparoscopic surgical instruments may prove useful.

3.1.2.5 Current Forceps Drawbacks

Despite their widespread use, there have been a few attempts to design more ergonomic surgical tools. In a prototype test conducted by the University of Nebraska, practicing doctors and nurses were asked to evaluate forceps based on their ease-of-use, comfort and any problems experienced during testing. From the sample interviewed, just over 50% of the interviewees experienced both wrist and hand pain, with 60% experiencing both shoulder pain and difficulty manipulating the forceps accurately. [12] For a table of more interview statistics, see Appendix C.

Prototype tests such as this provide some evidence that current forceps designs are not ideal for their users. If over half the doctors in this test using forceps experienced some difficulty during use, it's possible that mistakes during surgery can take place because of an inadequate tool design.

3.1.3 Student 3: Ryn Shuster

3.1.3.1 Fluid Mechanics Fundamentals and Applications, Yunus Çengel, John M. Cimbala

This was the book NAU Mechanical Engineering students used for Fluids I. [13] Since the muscles are most responsive when actuated using an incompressible fluid, having a text around that explores the mathematics used to quantify that seemed prudent to the team. Since these actuators have very little data that indicates how they will perform in parallel having some ways to potentially quantify that force being transferred through the hydraulic fluid to predict potential scalability will be a key deliverable to our client.

3.1.3.2 The Toyota Way, Jeffrey Liker

This is a book that takes an in depth look at the Toyota Production System or TPS. It discusses the finer philosophical and technical aspects of the system. [14] Since a huge component of the project is redesigning and improving the manufacturing component of the actuators looking at the gold standard for production systems the world over was going to be important. Concepts like heijunka were key to our redesign, it's the idea minimizing waste through maximizing equipment use and optimizing production levels by not over producing. The team's excess materials budget is limited so making sure we do not over use material will also be important.

3.1.3.3 Laparoscopic Multifunctional Instruments: Design and Testing of Initial Prototypes, Frecker, Schadler, Haluck, Culkar, Dziedzic

This study looked into the various testing methods of testing different laparoscopic surgical tools. The goal was to test various types of end effectors (the actual grasping tool at the end of the surgical device) performing more than one task with a single reusable end actuator. [15] While their ultimate results did not demonstrate more effective performance than disposable tools their testing methods could be useful for the project to prototype an effect end effector.

3.1.3.4 Flexible Robotics in Medicine: A Design Journey of Motion Generation Mechanisms and Biorobotic System Development, Chapter 13: Design of a flexible robotic bending end-effector for transluminal explorations, U-Jin Joshua Cheah, Pin Rong Tan, Zhongren Thaddaeus Ong, Angelique Huan, Muhammad Amzar Bin Mohd Faisal, Zion Tsz Ho-Tse, Chwee Ming Lim, Hongliang Ren,

This chapter of this book goes into in depth analysis of end effectors specifically in biorobotics and medicine. Specifically the kinematics involved in delivering mechanical power to the end effector and translating that into usable directional force in order to accomplish a task and the mechanical kinematic chains involved in that process. [16] This is a significant design task within the project as the team will need to develop and deploy a way to translate the hydraulic force applied to the muscles efficiently to the end actuator in order to minimize and losses and increase efficiencies. Since the end goal is to demonstrate a delicate and dexterous action any losses will be easily felt by the operator.

3.1.3.5 Advanced Theory of Constraint and Motion Analysis for Robot Mechanisms, Chatper 4: Free Motion of the End Effector of a Robot Mechanism, Jingshan Zhao, Zhijing Feng, Fulei Chu, Ning Ma

This paper explores the idea of flexible end effector in the context of a nasal exploratory surgery. The team involved designed an end effector that had flexible components to better navigate a humans narrow sinus cavities. [17] The design constraints for this project limit us to a 1cm^3 volume for our end effector so the results of this study were a good benchmark to pull design philosophies from to better understand designing small mechanical objects that also have to perform delicate grasping and holding tasks.

3.2 Benchmarking

3.2.1 System Level Benchmarking

Artificial muscles systems have the potential to impact many areas of scientific advancement including advanced prosthetics and robotics. Soft muscle actuators can increase the human machine interface, increase the potential for solving automation challenges in both healthcare and defense, etc. Below are some examples of soft muscle actuators that have been developed, tested, and used in real world applications.

Let it be noted that Cavatappi muscles utilize a hybrid mechanism that combines the properties of TPAs and McKibben actuators. [1]

3.2.1.1 *Existing Design #1: TPAs (Thermally Activated Twisted Polymers)*

Thermally activated twisted polymers are a type of biomimetic thermally activated torsional actuator, that consist of twisted drawn polymer monofilaments. The polymer expands radially and contracts axially and this is thought to produce untwisting of the fiber and subsequent actuation. [3]

The main benefit of this design is that TPAs are capable of torsional actuation. Previous technologies have been tested and developed for linear actuation. Additional benefits are that the manufacturing of TPAs is relatively low-cost in comparison to other torsional actuators in the market. Aspects that contribute to the low-cost design are that TPAs are simple to manufacture, consisting of a nylon fiber, a twisting rig, and an oven. Examples of a twisting rig utilized by the DASL lab can be found in Appendix D. This design is also lightweight and produces actuation with a reasonably high torques per unit volume. [3]

The main drawback of this system is that because TPAs are thermally activated they can be very inconsistent. Therefore, TPAs may not be suitable for all applications.

3.2.1.2 *Existing Design #2: Mckibben Actuators*

McKibben actuators are pneumatically, or hydraulically driven artificial muscles (PAMs or HAMs) widely used in robotics. They change length by inflating a bladder that is surrounded by a counter double-helix–braided sheath. The macroscopically developed anisotropy allows the device to contract in length and expand radially. [1]

The benefits of this system are that they can be designed to mimic biological muscles with contraction ratios like some vertebrae muscles. McKibben actuators perform well in the areas of robustness, simplicity, and high specific force to weight ratio for a given input pressure [4]. Conversely, the main drawbacks of McKibben actuators are that the radial expansion that drives actuation make parallel operation difficult to achieve.

3.2.1.3 *Existing Design #3: HASELs (Hydraulically Amp. Self-Healing Electrostatic Actuator)*

HASELs are electrohydraulically activated rather than thermally or fluid activated like the previously mentioned artificial muscles. HASELs are fabricated from an elastomeric shell partially covered by a pair of opposing electrodes and filled with dielectric fluid. Muscle actuation is achieved by applying a voltage that will induce an electric field. This process generates an electrostatic Maxwell stress that displaces the dielectric fluid and causes the muscle to contract. [1] Although HASELs have the potential to be high performing and self-sensing, they are not suited for all applications because they require a high voltage input (>5kV).

3.2.2 Subsystem Level Benchmarking

3.2.2.1 *Subsystem #1: Laparoscopic Tools*

Laparoscopic tools have created a means of conducting noninvasive surgery on patients and have decreased the potential for infection. These tools, while simple in nature, have been key in revolutionizing the way that surgeries are performed. These tools will be used a starting point for design and fabrication of the mechanical hand, where the team will focus on improving upon existing designs.

3.2.2.1.1 Existing Design #1: Forceps (Patent)

As previously mentioned, forceps are the standard tool utilized in most modern MIS procedures. The scissor-like design was patented in 1976 and is only capable of a single range of motion. Actuation is completed by opening and closing the handles of the forceps and positioning is achieved by readjusting the long steel arm of the forceps. This design is reliable, cost effective, and easily manufactured and will be used as a baseline for all concept generation. The drawbacks of the design are rooted in simplicity and the need for more complex actuation and increased range of motion. [11]

3.2.2.1.2 Existing Design #2: Modern Forceps

Little has been done to improve the original forceps design, some areas that have improved are material selection, weight, and length. The function and benefits of forceps remain the same, however the drawbacks are that modern forceps are not ergonomic and customer friendly. [12]

3.2.2.1.3 Existing Design #3: Mechanical Scissors-Grasperarticulator

Designing and manufacturing various aspects of current laparoscopic tools increases the potential for multifunctional instruments in surgical settings. This design is focused on the end effectors of laparoscopic tools and creating a more dexterous and robust design. The main drawback of this design is that it does not contribute to improvement in ergonomics. This design can be implemented in future concept generation to improve functionality. [16]

3.2.2.2 Subsystem #2: Soft Muscle Robotics/Mechanical Hand Design

Soft muscle robotics serve to replace conventional designs constructed with metal structural elements and joints, actuated by electrical or hydraulically powered systems. The importance of this research and development becomes apparent when considering the handling of fragile objects like internal organs, which can easily be damaged by hard structural elements. Below are some designs that the team drew inspiration from when generating ideas for the design of the mechanical hand.

3.2.2.2.1 Existing Design #1: Starfish Gripper

The gripper below incorporates a starfish-like structure that bends, extends, or contracts to a pre-programmed shape. This design, while simple, has the potential to fit various needs by changing the length, width, thickness, and structure of each finger. Layering and combining Pneunets, as picture in Figure __a, have the potential to create a structure capable of complex movement. [5] This design inspired the team to consider structures that might be less humanoid in nature that combined elements into a single structure.

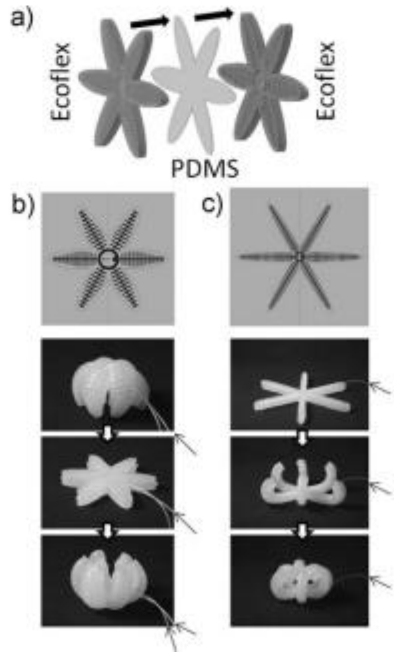

Figure 4: Soft muscle robotics starfish gripper comprising of layers of Pneunets. [5]

3.2.2.2.2 Existing Design #2: Mechanical Arm

The mechanical arm in Figure 4 features a three-fingered robotic hand. The hand was 3D-printed from a rigid plastic material and was covered in soft silicone skin. The process of 3D printing material served to replace the use of heavy metals that were structurally unnecessary. The team found this design to be interesting because it opened the possibility of using rigid materials to provide structural stability for the design of the hand, while maintaining the potential to be used for more delicate applications. In addition, the team noted that reducing the number of fingers in the design to three might simplify the design while meeting all necessary customer needs/requirements.

The muscles of this mechanical arm are also actuated by PAMs, a type of McKibben actuator, which the team may revisit when attaching Cavatappi muscles to the mechanical hand.

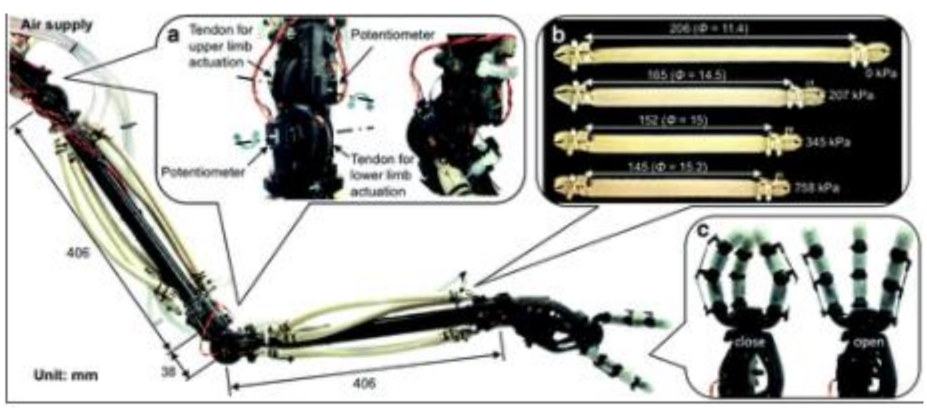

Figure 5: Mechanical arm with 3D printed hand. [6]

3.2.2.3 Subsystem #3: Manifold

Manifolds are a machine element that are used to combine fluids via pipes, channels, and tubes. Benefits of utilizing manifolds in design are lower cost, simplification of design, reduced leakage, and simplification of maintenance. The team will be utilizing a manifold to attach Cavatappi muscles to the mechanical hand, which will deliver fluid through the muscles and actuate movement in the hand.

3.2.2.3.1 Existing Design #1: Laminar

Laminar manifolds are single-piece manifolds that consist of several layers of metal that have been machined or milled through. Laminar manifolds usually consist of stacked steel plates that are brazed together. The fluid paths are determined by the shape of overlapping passages of the steel plates. The benefits of this design are that passages can be designed to accommodate any flow rate and can be built to unique specifications. The drawbacks of this design are that the flow passages are permanent due to manufacturing processes and cannot be modified as necessary. [7]

3.2.2.3.2 Existing Design #2: Drilled Block

Drilled block manifolds are single-piece manifolds that consist of a slab of steel, aluminum, or cast-iron blocks with passages drilled through the block. The benefits of this design are that they can be custom designed to fit various project needs and that valves can be located as desired. The main drawback of this design is that the drilled passages must be straight. [7]

3.2.2.3.3 Existing Design #3: Modular

Modular manifold systems are comprised of directional, sequence, and relief valves, plus other control components. Modular manifolds can be easily manipulated, they can be bench-assembled horizontally and/or stacked. They are usually comprised of cast iron, aluminum, or steel blocks and allow the user to design and build a manifold that fits unique needs. These manifolds can also be color coded to identify certain fluid flows of a system. The main drawback of this design is that construction is significantly more complicated than a single-piece manifold system. [7]

3.3 Functional Decomposition

3.3.1 Black Box Model

A black box model is a design tool used to determine the overall function of a device and express it in verb-object form. Black box models are also used to determine the input and output flows of a device. The team identified that a black box model would simplify the task of identifying which design aspects of the project to target.

The team began by identifying the overall function as being muscle actuation and the input flows for the materials, energy, and signal. It was determined that a signal was not necessary for the design of the project and that input/output flow was omitted for the model. Next, the team identified that the materials that would be inputted were hand and fluid, these materials were taken from simulations done with test muscles produced in the lab. The team noted that input from a human hand and an incompressible fluid were key to producing muscle actuation. The coincident energy inputs were identified as mechanical energy and human energy, which were also necessary to produce muscle actuation. The team then identified the remaining material and energy flows as outputs for the system. That output for the material flow was the incompressible fluid, which remained after muscle actuation, and kinetic energy for the energy flow. The team utilized kinetic energy for this flow because the client proposed utilizing water for the incompressible fluid.

Utilizing the black box model, the team was able to identify that manufacturing reliable muscles was a key aspect to success for the project. Reliable muscles will ensure proper delivery of fluid to the system and maximize the energy output of the system. The black box model can be found in Appendix E.

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

A functional model visually describes the methods used to transform input flows to desired output flows. Functional models can be utilized to emphasize what needs to accomplish to achieve a desired output rather than how to achieve a desired output, which the team used to determine what subfunctions proposed designs needed to achieve.

The team determined that the material inputs were primarily used to input, store, and guide the fluid through the muscle. This was achieved by inputting and converting mechanical energy into kinetic energy that could be transferred to the fluid. The fluid was then guided through the muscle and exported from the system, expelling both kinetic energy and fluid. This model was helpful in determining that the team should focus on the energy output as that was one of the functional requirements that was determined to be of high importance in the house of quality. In addition, the team determined that other important design aspects that should be kept in mind are consistent production quality, reduction of leaks in muscle, muscle diameter, and the mechanical input to hydraulic output ratio that were also identified in the house of quality. The functional model can be found in Appendix F.

4 CONCEPT GENERATION

4.1 *Full System Concepts*

4.1.1 Full System Design #1: Spooling Method

The Spooling Method concept relies on a mandrel suspended between two free-rotating bearing surfaces. A motor attached to one end of the mandrel and clamps attach a length of Tygon to the mandrel during the coiling process. As the motor twists the mandrel, the Tygon coils around the mandrel, forming a Cavatappi muscle. After finishing the coiling process, a clamp secures the other end of the Cavatappi muscle to the mandrel as well. Removing the mandrel from the bearing surfaces readies the Cavatappi muscle for annealing.

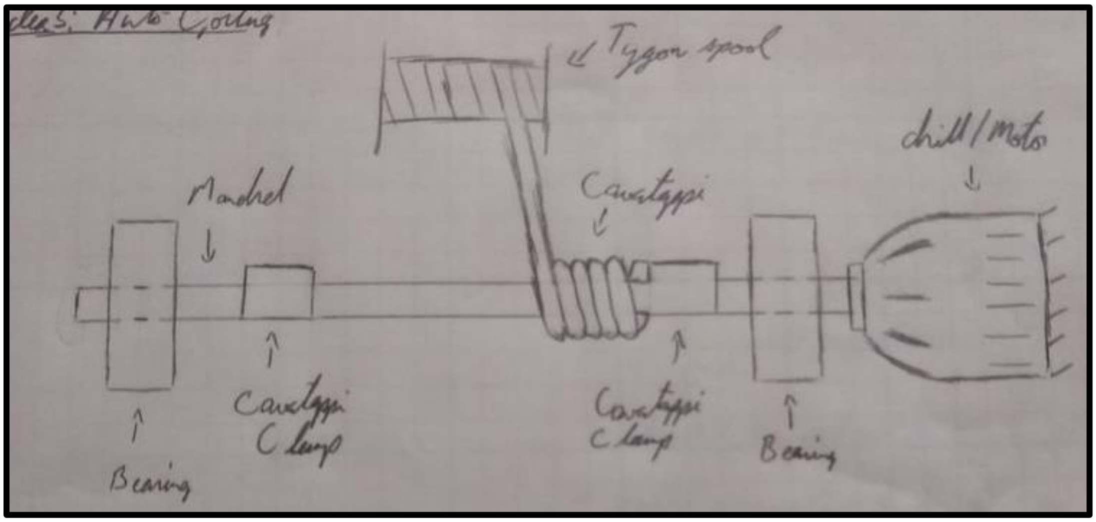

Figure 6: Drawing of Spooling Method

Pros: Compared to the datum, consistent coiling with this method is much easier to achieve. Instead of running the Tygon parallel with the mandrel, having it perpendicularly spooled increases coil consistency. This design would be simple to make, since it's essentially two bearings on posts, a motor, some clamps and a spool of Tygon. A low part count means cheap construction, as well.

Cons: However, this design has more moving parts than the datum, making it a more complex design. The clamps would also have to be fixed to the mandrel permanently, meaning they would have to withstand annealing as well as being a fixed length apart. Multiple mandrels are necessary for muscles of different lengths.

4.1.2 Full System Design #2: Carrier Method

The carrier method follows the same core idea of the spooling method, namely coiling pre twisted Tygon onto a mandrel from a spool, the biggest differences being that the mandrel moves around a stationary length of the pre-twisted Tygon, and both share the same center axis rather than the Tygon being perpendicular to the mandrel. The mandrel is held in a carrier on a circular track on one end and then in a free spinning clamp in a tower on the other. The Tygon runs through a hole in the carrier tower to the a non-free spinning clamp in the opposite tower as the mandrel's carrier moves through it's circular track it coils the Tygon around the mandrel itself. The carriers movement could be driven by a series of gears and a motor of some kind (a hand drill most likely) or rotated by hand.

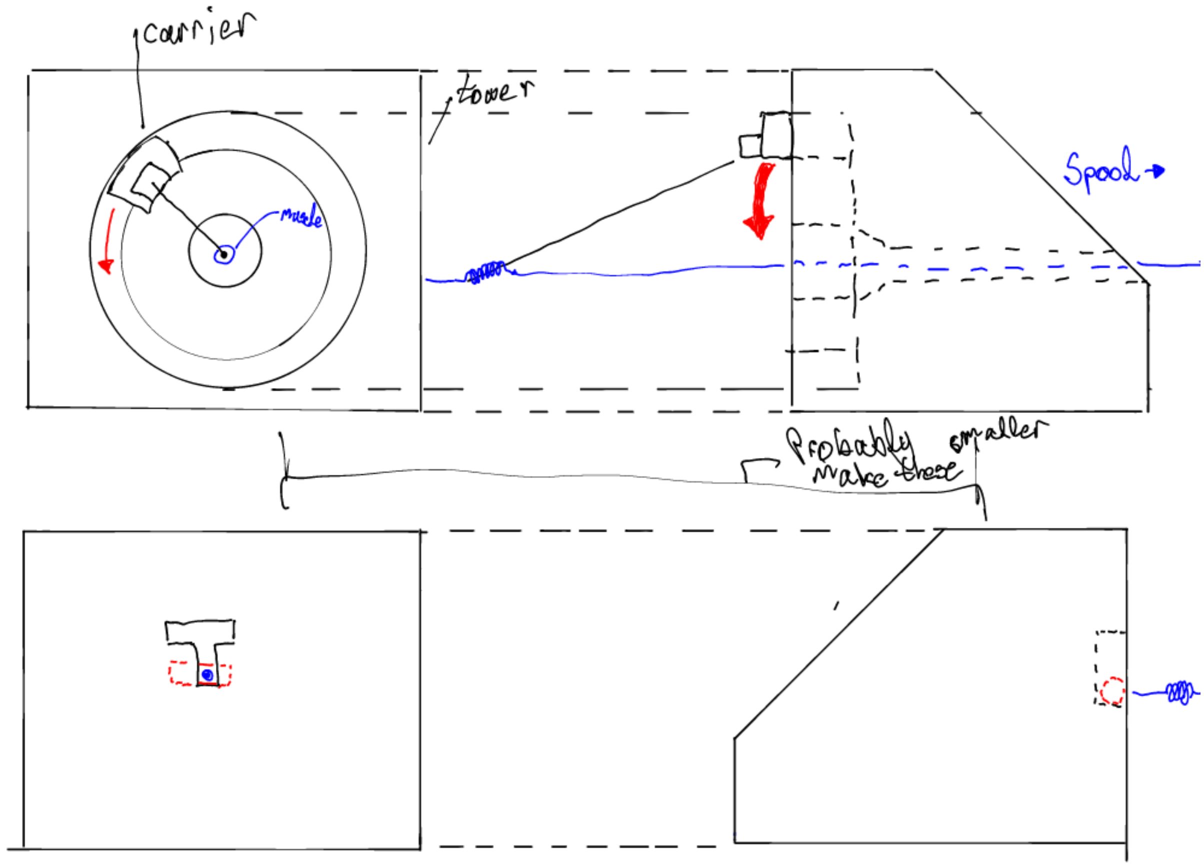

Figure 7: Carrier Manufacturing Method, Carrier Tower (Top) Clamp Tower (Bottom)

Pros: This system was designed in such a way that it could be developed into individual cells, with the ultimate goal being to have four running simultaneously. From preliminary testing it goes the furthest to replicate the best techniques performed by a human operator in a more automated fashion, hopefully increasing efficiency by decreasing inconsistent force application and other operator errors.

Cons: This design was ultimately far more complex than was necessary for the needs of the project or the client in the context of the stated design goals. The number of moving parts and points of failure in the mechanisms was also, relative to the other design ideas, much higher than the team had wanted.

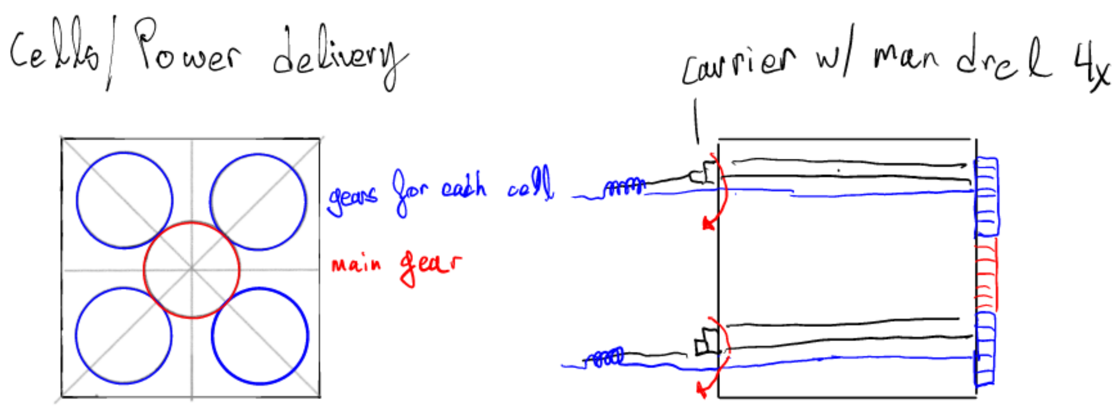

Figure 8: Carrier Manufacturing Method, Potential Cell Configurations

4.1.3 Full System Design #3: Potential Hand Design

As of the writing of this report the team is leaning towards a design that does not mimic the human hand for a multitude of reasons. The most significant of these being that in order to have the functionality of a human hand multiple complex degrees of freedom are required. This could change as the project moves more into the hand design phase but as of now our analysis is looking at a more claw like structure where input from the operator is delivered in a comfortable position using a series of syringes in an trumpet-like assembly that allows the operator to actuate each individual “finger” of the claw individually. The claws themselves will be designed in such a way that they can securely hold a coin for a reasonable amount of time. Early forms of this idea range from a “fingernail” tip design, to a groove at the mid point of the finger that coin settles into, to coating the fingers in a malleable “flesh-like” polymer that allows for more biomimetic properties in gripping a small object. Design for the end effector has not been finalized as of yet and is subject to future change based on the progression of the muscle bundles and feedback from the client.

4.2 Subsystem Concepts

4.2.1 Subsystem #1: Annealing Methods

4.2.1.1 Design #1: Updated use of current oven

Using the same method and oven available to the team now, a new rack that is oven safe would be designed and manufactured to hold multiple coiled muscles at once, rather than just anneal one muscle at a time. Each twisted and coiled muscle strand would be clipped into the rack and the rack would be placed into the oven to anneal the actuators at 170 °F for 30 minutes.

Pros: Would require very little in terms of design, and the annealing method has already been confirmed to be working to produce muscles of similar quality to the research that created them. This method would also not require us to provide any new source of sustained heat.

Cons: Consistent timing is not easy to achieve with the oven mainly because it is a consumer toaster oven and therefore is not made for precise timing and heating. This leads to inconsistencies that do not appear to be causing the failures found in testing but until those inconsistencies are removed that cannot be proven.

4.2.1.2 Design #2: Sous Vide

As the name indicates the sous vide method will utilize a water heater called a Sous Vide normally used to indirectly cook food in a kitchen. Keeping the coiled and twisted actuator strand on the mandrel and clamped the entire assembly will be put into a bag that has most of the air removed and placed in the 170 °F water for 30 minutes.

Pros: The pros for the water bath in cooking are mostly the same for the pros for the water bath in annealing. The operator can maintain a very consistent temperature for the entirety of the annealing process within fractions of a degree. Also heat transfer into the actuator being submerged in circulating water should be far more consistent than in an open-air oven not utilizing any sort of fan to increase convection. The team also has access to a high-end Sous Vide, no additional purchases would need to be made.

Cons: While heating is consistent getting the water to the correct temperature does take double or triple the time it takes to get the current heating method to temperature. Water levels also have to be maintained if long term manufacturing is to be done in a single session as liquid will evaporate over time. This factor is largely dependent on the size of the container used.

4.2.1.3 Design #3: Air Fryer

Again the name of the design more or less denotes its function. This would be a step up from the current oven design as the modern air fryer is essentially a desktop convection oven. A convection oven utilizes a series of fans to move air through out the interior of the oven during cooking, helping to maintain a significantly more consistent annealing temperature through out the process. This method would also require the rack redesign from Design #1: Updated use of current oven.

Pros: Along with maintaining a more consistent temperature than the current oven, the air fryer the team would have access to has controls that would make consistent annealing times much easier to maintain. Also being new it would be more consistent in maintaining its internal temperature due to the seals and insulating materials being new. The heated area of the air fryer in question also has easier access for safe removal of heated specimens by the operator.

Cons: This method would still require the rack redesign and though the convection capabilities of something like an air fryer are greater than that of a standard toaster oven (the current method) they still would not be as consistent as a heated water bath.

4.2.1.4 Design #4: Mandrel Stand

The current manufacturing method requires individually annealing Cavatappi tubes. Clamping the muscles horizontally takes up a lot of space in the toaster oven. This is time-consuming, lowering the potential Cavatappi muscle production rate. By standing mandrels vertically in rows and columns, more mandrels with muscles can go through the annealing process at the same time.

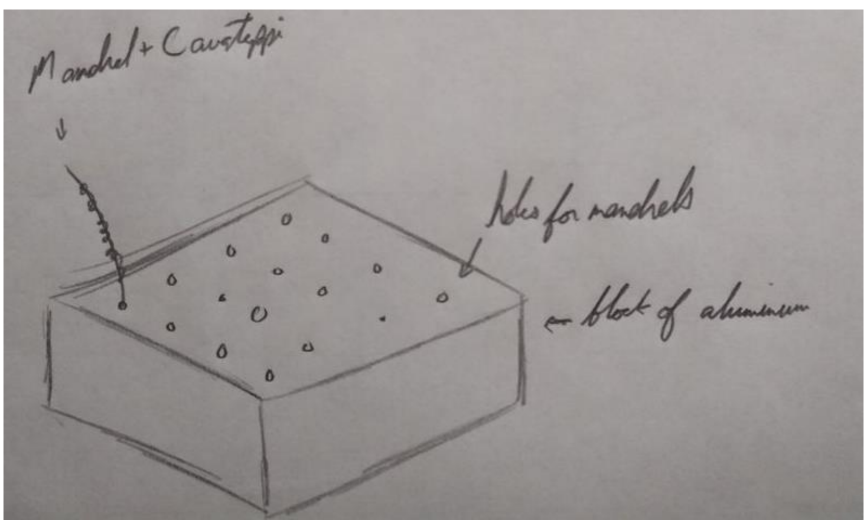

Figure 9: Potential Mandrel Stand

Pros: This method means that many Cavatappi muscles may be produced at a time, with consistent heating between muscles baked at the same time. This would also be easy to manufacture, since this idea could be as simple as drilling holes in a stock piece of aluminum to stand them upright.

Cons: If the heating element is too close to the top of the vertical mandrel, this could cause melting. And, if the Sous-Vide Method is applied, water currents could pull the Cavatappi mandrels out of the stand, which would result in possible uneven heating.

4.2.2 Subsystem #2: Coiling Methods

4.2.2.1 Design #1: Pre-spooled, Pre-coiled Tygon

To manufacture Cavatappi muscles, Tygon has to be drawn, twisted and coiled. When doing this right before making a muscle, it adds time to the manufacturing process and may result in inconsistent coiling and drawing lengths between each Cavatappi tube.

Pros: If the Tygon is stretched and twisted beforehand and spooled onto a spindle, it would simply be a matter of twisting the tube around a mandrel to make a muscle. This would result in consistent muscle fabrication and speed up the coiling process.

Cons: However, only one direction of coiling would be achievable, since the twist direction must match the coil direction. Varying the ratio of twist to length of Cavatappi muscle would also be impossible without having multiple spools with different twisting ratios.

4.2.2.2 Design #2: Reusable Mandrels

The current mandrels used to make Cavatappi muscles are not well-kept. They are often discarded after annealing. This is wasteful, since there is currently a limited number of mandrels at our disposal.

Pros: By integrating a clamping system directly into the mandrel, they would become more vital parts of the manufacturing process, making them less likely to be thrown away.

Cons: However, the clamps would have to be made of a material resistant to heat, since they'd have to be used during the annealing process. Multiple mandrels would need to be produced for varying muscle lengths, as well.

4.2.2.3 Design #3: Double-Motor Method

In the current datum of muscle manufacture, a drill is used to twist the Cavatappi from one end. One issue that arises from this is that if the Tygon tubing kinks in an unexpected place, it could crimp and ruin the coils. By having two motors at each end of the mandrel, consistent rotation could help the coils form more neatly.

Pros: Using two motors prevents the mandrel from twisting, which could cause inconsistencies in the coils. It also means that the supports for the mandrels would be much more stable since they have to accommodate a motor on each end.

Cons: This method requires an additional motor, which would drive up device costs. The motors would also likely need to be wired to the same switch and capable of operating in opposing directions, making this design more complicated than necessary.

4.2.3 Subsystem #3: Clamping Methods

4.2.3.1 Design #1: Plumber's Tape

One possible clamping improvement is using plumber's tape to secure the Cavatappi tube to the mandrel during coiling. Plumber's tape has a naturally grippy surface that makes impermanent bonds with plastics and rubbers.

Pros: Plumber's tape is inexpensive and readily available. In the event that a Cavatappi muscle requires adhesion to a mandrel with minimal warping, Plumber's tape could easily do the job.

Cons: This clamping method would produce waste, since the plumber's tape is not reusable. It's also unclear if the tape would hold up under heat and wet environments, meaning that it would not be ideal for annealing.

4.2.3.2 Design #2: Alligator Clamp

A simple clamp design where the jaws are clamped onto both mandrel and tubing by tightening a bolt that runs into a threaded hole on one side of the jaw where the head of said bolt provides pressure that pulls both jaws together when it makes contact with the non-threaded side.

Pros: Very simple design, few points of failure, easy to make a large quantity, easily scalable to varying sizes, could hold multiple actuators at once.

Cons: Potential for high force concentrations and damage to the actuators at those force concentrations. Breakage and failure of the clamp easier due to over tightening of the bolt.

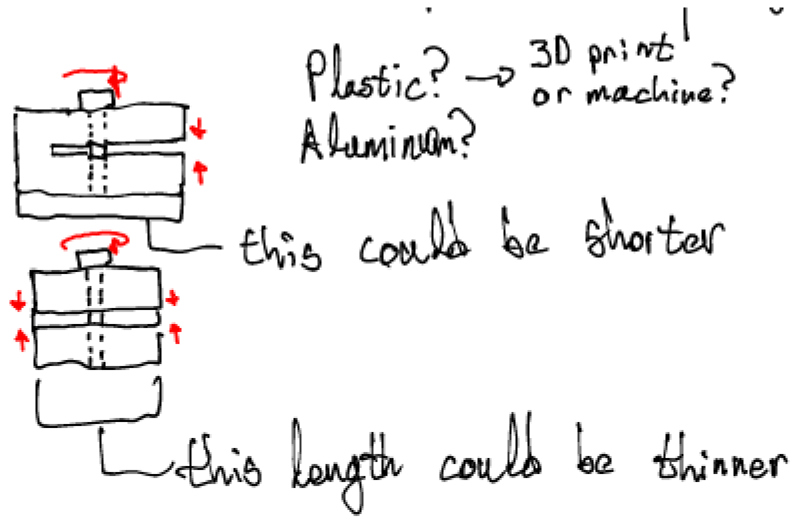

Figure 10: Alligator Clamp Concept Sketch

4.2.4 Subsystem #4: Hand Designs

4.2.4.1 Design #1: Trumpet Actuation

Common forceps are unwieldy and uncomfortable to use. They only offer one range of motion, making them imprecise. To offer a wider range of motion and a more comfortable way to actuate forceps, having a set of "trumpet" keys to actuate individual fingers hydraulically would make device use much more comfortable. Pressing down on a key compresses the fluid inside, forcing the Cavatappi muscles to actuate.

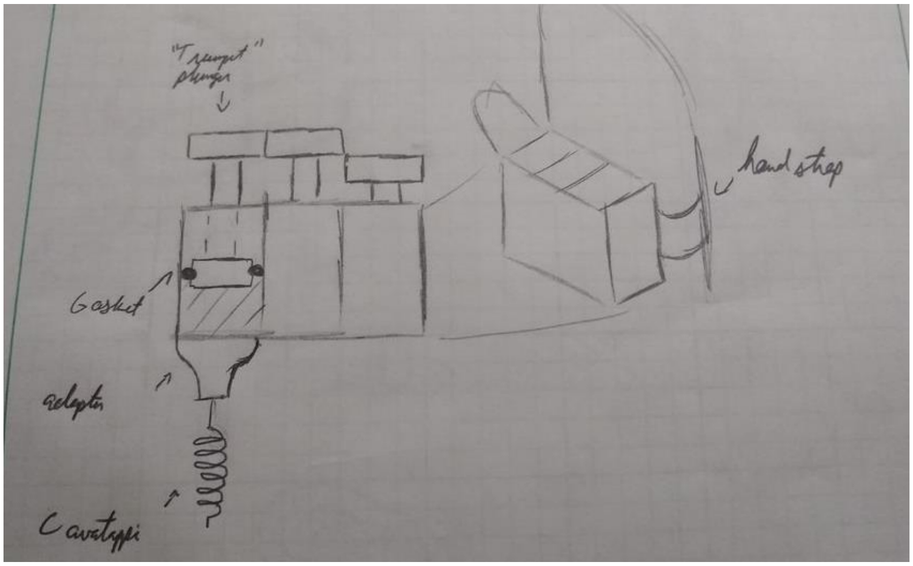

Figure 11: Drawing of possible "trumpet" actuator

Pros: This design would be much simpler to use than a scissor actuator. Pressing keys is a simple motion, making actuation relatively intuitive. The arm of the laparoscopic tool can be mounted anywhere on the actuator, meaning that optimal angles for the user could be custom-made.

Cons: Actuation in this way may require a little more getting used to, since pressing down on a "trumpet key" would actuate in the opposite direction of finger motion. This concept is also quite complicated and may need calibration before use.

4.2.4.2 Design #2: Rounded Fingers

Because the laparoscopic hand will be used for MIS, having a rounded tip would prevent scraping or damage to inner tissues. Modern forceps already employ a rounded tip, making this design compliant with normal laparoscopic designs.

Pros: A capsule shape with the fingers designed to close any gaps between them before actuation would also help prevent unnecessary damage.

Cons: This shape would not be easy to print, since the curves of each finger would have to meet closely, and tight tolerances would be necessary to achieve a smooth exterior.

4.2.4.3 Design #3: Biomimetic Claw Design

In order to grasp a small object looking to nature seemed prudent, this particular end effector component mimics the shape of a bird of preys talon, in order to better get underneath something like a coin. As the coin moves up into the grasp of the talon it finds a grove that it is forced into as the pressure from the operator increases. This grooves is mirrored on not less than three other "claws" equally spaced around a center hub so as to provide equal pressure and restriction of movement once the coin is extracted from the flat surface.

Pros: The fine point has a good chance of getting underneath something like a coin, and the groove would do a good job of holding the coin in place while being moved.

Cons: Since this would likely be 3D printed, concentrating the force at the tip against a metal object like a coin could cause breakage. The design is also very focused towards the singular task of picking up a coin, leaving no room for other demonstrations.

5 DESIGNS SELECTED – First Semester

Included below is a comprehensive explanation of the design criteria used to evaluate the Cavatappi manufacturing process. Technical criteria are explained, then applied to the concepts generated in section 4 through Pugh charts and a Decision Matrix. The final design for manufacturing Cavatappi muscles is modelled as well.

5.1 Technical Selection Criteria

[Identify the technical criteria you will use for comparing the designs in Chapter 4 and explain why they are significant in your design selection. These should be key customer and engineering requirements and must be quantifiable in nature. Describe how these criteria are used in the Pugh Chart versus Decision Matrix, i.e. why were they chosen for each particular selection method.]

Technical Criteria for design selection within the manufacturing process are as follows:

- Scalability of Muscle Length (mm) – Different muscle lengths are going to be critical for testing muscle bundles for most effective force delivery and reliability over a multitude of force cycles.
- Reliability of the System (% Failure) – Currently about 40% of attempts succeed in producing an annealable actuator. This number will have to be increased to ensure a good enough stock of muscles to test various bundling methods and then eventually producing muscles for use with the end effector.
- Flexibility of System (Range of the # of coils & coil diam.) – testing may reveal the need for larger diameter coils or increases/decreases in the overall number of coils. The eventual manufacturing setup needs to be able to adjust for these factors.
- Quality of Muscle (<50% failure during use) – Not only does the muscle strand need to make it out of the twisting/coiling stage the process needs to produce muscles that do not fail under expected use after annealing.
- Simplicity of Design (# of Parts) – Time from design to muscle production needs to be as short as possible so the team can move on to manifold design and end effector design. Iterative changes can be made as production moves forward but a simple design that could be put into practice sooner rather than later was important to our client.
- Heating Consistency (Holding 170 °F) – The heating system within the manufacturing process has to be consistent in heat transfer. The current method has too many points of potential inconsistencies, whichever method takes its place will be selected based on its ability to mitigate those inconsistencies and hold the actuator at 170 °F consistently for a 30 minute period.
- Expected Additional Cost ($) – as our ancillary costs budget is only $200 the designs that utilize the available resources in the lab will be ranked higher.

All the above listed criteria arose after discussions with the client about what was desired from a redesigned manufacturing process. Part of those discussions led to the idea of iterative design being important, therefore design simplicity arose as a more important factor when Pugh Charts and Decision Matrices were utilized as simpler designs shorten the time from design generation to implementation and testing. Ultimately the manufacturing redesign needed to be able to begin producing muscles to test bundling techniques and application as soon as possible.

5.2 *Rationale for Design Selection*

Pugh charts for both manufacturing Cavatappi muscles and a general design of a laparoscopic hand are based on the aforementioned selection criteria. Because the main focus of Team Cavatappi is manufacturing the artificial muscles this semester, the Pugh Chart for manufacturing processes is below, while the hand Pugh Chart is in Appendix G.

		Annealing				Coiling							Clamping		
Criteria	**Datum Values**	**Resistive Heating Element**	**Heating Method with Larger Rack**	**Sous-Vide Heating**	**Annealing Mandrel Stand**	**Respool Precoiled Tubing**	**Reusable Mandrel Design**	**Perpendicular Spooling Method**	**Double-Motor Method**	**Auto-Adjusting Mandrel**	**Navajo String-Coil Method**	**Carrier Held Mandrel**	**Updated Clamp Ideas**	**Workout Clamp**	**Alligator Clamp**
A-Scalability of Muscle	10 - 90 mm	Exceeds	Exceeds	Same	Same	Same	Exceeds	Exceeds	Same	Inferior	Exceeds	Exceeds	Exceeds	Same	Exceeds
B-Reliabity of System	40%	Exceeds	Same	Exceeds	Same	Exceeds	Exceeds	Exceeds	Inferior	Exceeds	Same	Same	Exceeds	Same	Exceeds
C-Flexibility of System	#coils /cm, coil diam.	Exceeds	Exceeds	Exceeds	Exceeds	Inferior	Same	Exceeds	Inferior	Inferior	Same	Exceeds	Same	Same	Same
D-Quality of Muscle	50%	Exceeds	Same	Exceeds	Same	Exceeds	Exceeds	Exceeds	Same	Exceeds	Same	Exceeds	Same	Same	Exceeds
E-Simplicity of Design	# of Parts	Inferior	Exceeds	Exceeds	Exceeds	Exceeds	Exceeds	Exceeds	Inferior	Inferior	Inferior	Inferior	Exceeds	Inferior	Exceeds
F-Heating Consistency	170 °F	Exceeds	Same	Exceeds	Exceeds	Same	Same	Same	Same	Same	Same	Same	Same	Same	Same
G-Expected Additional Cost	~$130.00	Exceeds	Inferior	Exceeds	Exceeds	Inferior	Exceeds	Exceeds	Inferior	Inferior	Inferior	Inferior	Exceeds	Inferior	Exceeds
SUM Exceeds	0	6	3	6	4	3	5	6	0	2	1	3	4	0	5
SUM Inferior	0	1	1	0	0	2	0	0	5	4	2	2	0	2	0
SUM Same	7	0	3	1	3	2	2	1	2	1	4	2	3	5	2

Figure 12: Cavatappi Manufacturing Pugh Chart. Note: Designs marked with yellow were top selections

Both the Carrier Method and the Spooling Method were the designs that made it past the Pugh Chart to the Decision Matrix. Other designs in the Pugh Chart were either subsystems used to develop the complete designs or were too incomplete to move on. The “Reusable Mandrel Design” is already inherently part of the Spooling Method as a sub-system. Therefore, despite being part of a final design, it did not move on to the Decision Matrix. Both annealing ideas deemed top selections will work relatively similarly. Both are capable of maintaining a temperature of 170 °F. Because of this, Team Cavatappi decided that testing the Sous-Vide Method would be the easiest option, since the Resistive Heating Element Method would require more construction. If the Sous-Vide Method is deemed inadequate, the Resistive Heating Element is a good fallback.

In the Decision Matrix, weights of each criteria are based on CRs. The final muscle manufacturing Decision Matrix is included below:

Decision Matrix: Muscle Production					
Criterion	Weight	Carrier Method		Spooling Method	
A-Scalability of Muscle Length	10.00%	80	8	80	8
B-Reliabity of system	30.00%	70	21	85	25.5
C-Flexibility of system	5.00%	80	4	85	4.25
D-Quality of Muscle	25.00%	90	22.5	90	22.5
E-Simplicity of Design	15.00%	60	9	85	12.75
F-Ease of Construction	15.00%	55	8.25	85	12.75
Totals	**100%**		**72.75**		**85.75**
Relative Rank	1st/2nd	2nd		1st	

Figure 13: Muscle Production Decision Matrix

The final design chosen for prototyping is the Spooling Method. While both methods would work, the Carrier Method is more challenging to implement and manufacture. Both scalability and quality of the muscles earned similar scores, sine either design could accommodate a muscle length of 90 mm. However, the Spooling Method is simpler to operate and would be easier make. While potentially requiring more parts, the Spooling Method design has simpler mechanisms than the Carrier Method, which brings up concerns regarding system reliability.

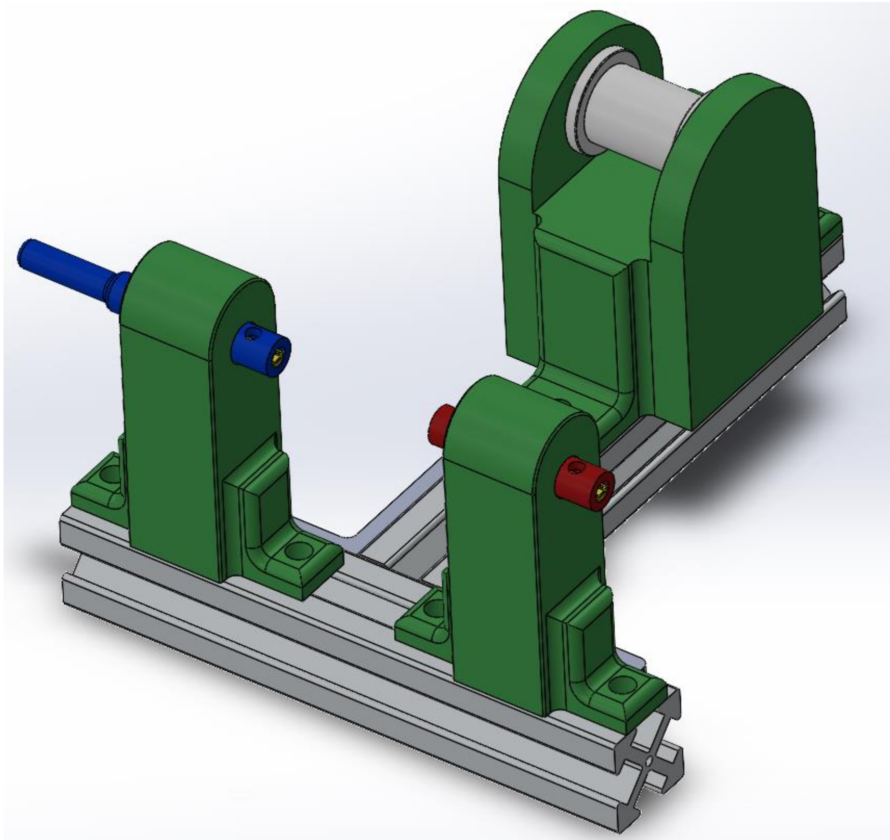

Figure 14: Spooling Method CAD Model

The above image shows the most current form of the manufacturing design. It is the most realized version of the spooling method of manufacturing. any of the towers can be moved along the extruded rails allowing for the needed scalability requested by the client. The clamps take advantage of a jaw like apparatus to clamp down on both the mandrel and the spool thus limiting potential force concentrations by distributing the force all over the interior surface of the clamp. The bolts that apply the force to the clamp hold the clamps themselves in their respective towers, while removing just the outside bolt allows them to be removed without loosening the pressure on the mandrel and coiled actuator. The blue one in the image has an additional extrusion to be clamped onto by a simple electric hand drill, giving the operator a consistent rotation input to control the speed at which the Tygon coils onto the mandrel.

While this is by no means our final design for the manufacturing setup, the majority of the work moving forward will be in focusing on consistent muscle production for the sake of developing a functional bundle design by the end of the semester so that next semester can be focused on “design à prototype àtest” cycle of the end effector and arm.

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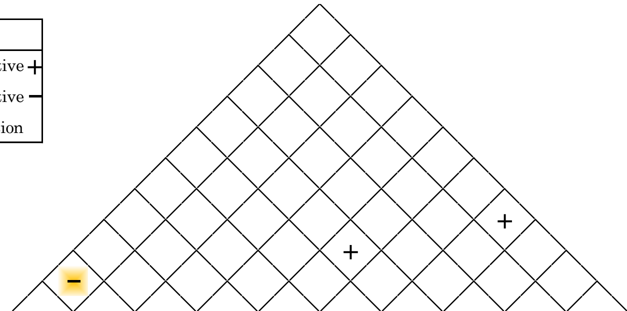
7 APPENDICES

7.1 *Appendix A: House of Quality*

Relationships	
Strong	●
Moderate	○
Weak	▽

Correlations	
Positive	+
Negative	−
No Correlation	

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



					Column #	1	2	3	4	5	6	7	8	9	10
					Direction of Improvement	▲	▼	◇	◇	▼	▲	▼	▼	▼	▲
Row #	Weight Chart	Relative Weight	Customer Importance (rating 1 - 5)	Maximum Relationship	Functional Requirements / Customer Requirements (Explicit and Implicit)	Maximize Force Output	Minimize Muscle diamerer (d)	Minimize Manufacturing Cost (USD)	Mech Input to Hydraulic Output (ratio)	Minimize "Hand" Size	High Factor Of Safety (FS)	Minimize # Muscles per Bundle (N)	Minimize Muscle Length (L)	Minimize Pressure Input (P)	Maximize Muscle Efficiency (%)
1		11%	4	9	Design System For Muslce Fabrication	○	○	●	○	○	●	▽	○	▽	▽
2		11%	4	9	Muscle Scalability	●	○	○	●	●	▽	●	○	○	○
3		8%	3	9	Reliable	▽	▽	○	▽	○	●	○	▽	○	●
4		14%	5	9	Safe to Operate	▽	▽	▽	○	▽	●	▽	▽	○	▽
5		14%	5	9	Acuated in a "glove-like" mechansim	▽	●	▽	○	○	▽	▽	●	●	○
6		11%	4	9	Utilize bundled muscles in paralell	●	●	○	●	▽	▽	●	●	○	●
7		14%	5	9	1cm x 1cm maximum size of "hand"	○	●	▽	▽	●	▽	●	●	●	○
8		8%	3	9	Flexible/ Durable	○	▽	▽	○	▽	▽	●	▽	○	●
9		8%	3	9	Reduce leaks in muscle	○	▽	▽	○	▽	●	▽	▽	○	○
10		3%	1	9	Cost Within Budget	▽	▽	●	▽	○	▽	▽	○	▽	▽
					Target	>=0.38kJ/kg	d<=1.5mm	Cost < $200.00 USD	Win/Wout = 1	<=1cm^3	1.25 < FS < 3.25	2 < N < 4	L < 50 mm	120 psi < P < 150 psi	Efficiency = ~ 20%
					Max Relationship	9	9	9	9	9	9	9	9	9	9
					Technical Importance Rating	361.11	455.56	250	388.89	366.67	433.33	472.22	455.56	444.44	416.67
					Relative Weight	9%	11%	6%	10%	9%	11%	12%	11%	11%	10%

7.2 *Appendix B: ND 100-65 Pressure Table*

TYGON® ND 100-65 Manufactured Sizes and Pressures

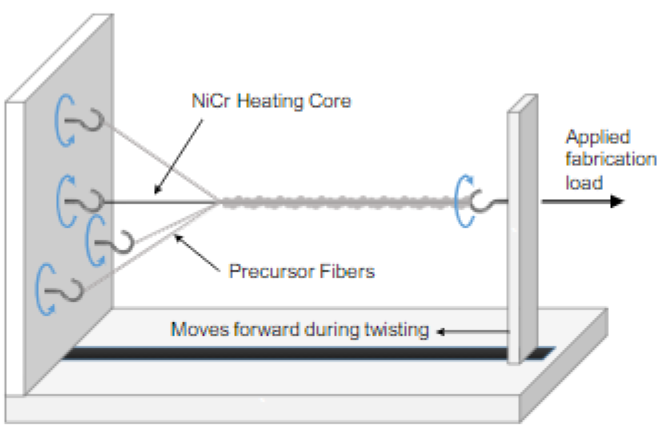
Part Number	I.D. (inches)	O.D. inches (inches)	Wall Thickness (inches)	Length (feet)	Minimum Bend Radius (inches)	Max. Suggested Working Pressure at 73°F (psi)*	Vacuum Rating In. of Mercury at 73°F
ADF00001	1/32	3/32	1/32	50	1/8	100	29.9
ADF00002	1/16	1/8	1/32	50	1/4	55	29.9
ADF00003	1/16	3/16	1/16	50	1/8	100	29.9
ADF00004	3/32	5/32	1/32	50	3/8	40	29.9
ADF00005	3/32	7/32	1/16	50	1/4	70	29.9
ADF00006	1/8	3/16	1/32	50	1/2	30	25
ADF00007	1/8	1/4	1/16	50	3/8	55	29.9
ADF00009	5/32	7/32	1/32	50	3/4	25	15
ADF00010	5/32	9/32	1/16	50	1/2	45	29.9
ADF00011	3/16	1/4	1/32	50	1	20	10
ADF00012	3/16	5/16	1/16	50	5/8	40	29.9
ADF00013	3/16	3/8	3/32	50	1/8	55	29.9
ADF00014	3/16	7/16	1/8	50	3/8	70	29.9
ADF00016	1/4	5/16	1/32	50	1-5/8	18	5
ADF00017	1/4	3/8	1/16	50	1	30	25
ADF00018	1/4	7/16	3/32	50	3/4	45	29.9
ADF00019	1/4	1/2	1/8	50	5/8	55	29.9
ADF00022	5/16	7/16	1/16	50	1-3/8	25	15
ADF00023	5/16	1/2	3/32	50	1	35	29.9
ADF00024	5/16	9/16	1/8	50	7/8	45	29.9
ADF00027	3/8	1/2	1/16	50	1-3/4	20	10
ADF00028	3/8	9/16	3/32	50	1-3/8	30	25
ADF00029	3/8	5/8	1/8	50	1-1/8	40	29.9
ADF00032	7/16	9/16	1/16	50	2-1/4	20	8
ADF00033	7/16	5/8	3/32	50	1-3/4	25	18
ADF00034	7/16	11/16	1/8	50	1-3/8	35	29.9
ADF00036	1/2	5/8	1/16	50	2-7/8	18	6
ADF00037	1/2	11/16	3/32	50	2-1/8	25	15
ADF00038	1/2	3/4	1/8	50	1-3/4	30	25
ADF00041	9/16	3/4	3/32	50	2-1/2	20	10
ADF00045	5/8	13/16	3/32	50	3	20	9
ADF00046	5/8	7/8	1/8	50	2-3/8	25	15

7.3 *Appendix C: Table of Forceps Interview Responses*

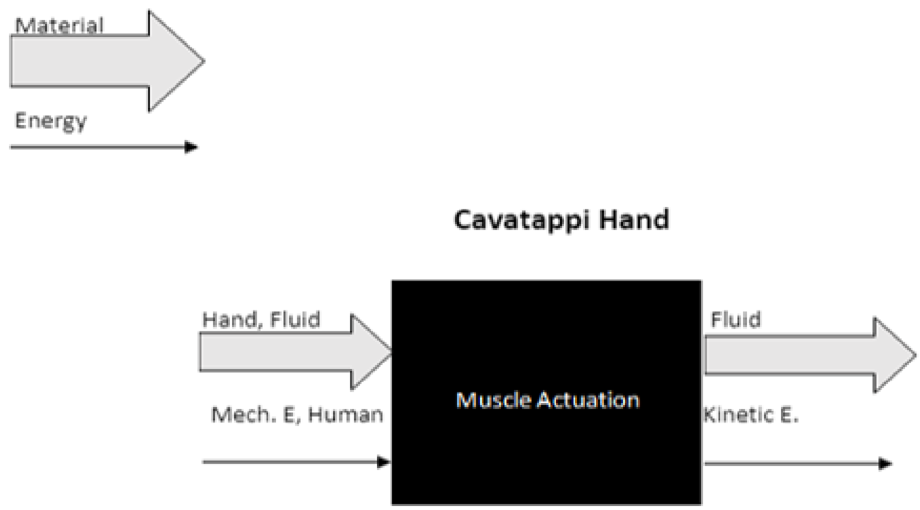
Table 1: Problems experienced by Interviewees during Forceps testing [12]

Problem experienced	%
Neck pain	47%
Neck stiffness	47%
Shoulder/arm pain	59%
Shoulder/arm stiffness	50%
Hand/wrist pain	53%
Hand/wrist stiffness	50%
Back pain	29%
Back stiffness	29%
Headaches	7%
Mental fatigue, irritability, exhaustion	47%
Excessive tachycardia/sweating/tremors	0%
Instruments awkward to manipulate	60%
Not able to perform fine or precision motions	47%

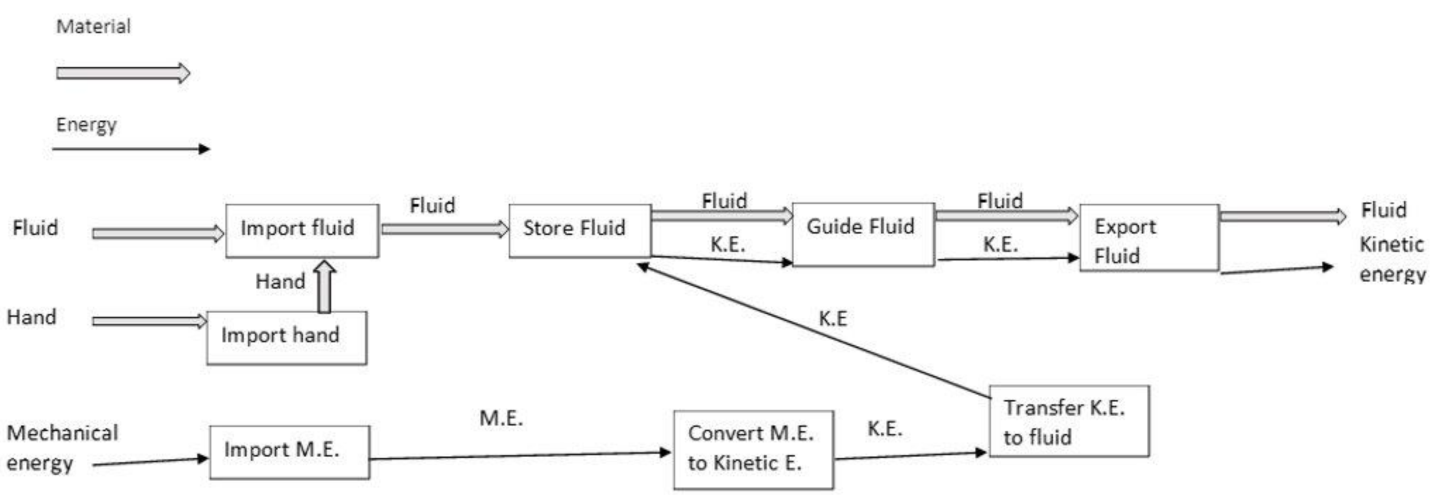
7.4 *Appendix D: TPA Twisting Rig*



7.5 Appendix E: Black Box Model



7.6 Appendix F: Functional Model



7.7 *Appendix G: Hand Pugh Chart*

Criteria	Datum (Forcep	Finger nails	Finger Tip grip:	Trumpet	Capsule	Spring Loaded Fingers	Rubber Finger Tips	Fleshy Hand	Pincer	Flexible Joints	Thumb muscle pattern
A-Aesthetic	Same	Inferior	Exceeds	Exceeds	Exceeds	Inferior	Same	Exceeds	Same	Same	Inferior
B-Reliability	Same	Exceeds	Exceeds	Inferior	Same	Inferior	Exceeds	Exceeds	Exceeds	Inferior	Exceeds
C-Degrees of freedom	Same	Same	Same	Exceeds	Same	Same	Same	Same	Same	Exceeds	Exceeds
D-Ease of Construction	Same	Exceeds	Inferior	Inferior	Same	Inferior	Exceeds	Inferior	Same	Inferior	Inferior
SUM Exceeds	0	2	2	2	1	0	2	2	1	1	2
SUM Inferior	0	1	1	2	0	3	0	1	0	2	2
SUM Same	4	1	1	0	3	1	2	1	3	1	0