Final Design Package

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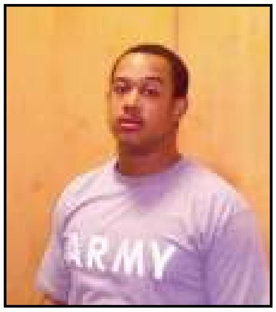
FAMU/FSU College of Engineering

ABOUT TEAM FILLAUER…



Mr. Larry Jones, Senior B.S. Mechanical Engineering
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Mr. Jones is a proud native of Tallahassee, Florida. Larry was enrolled in the Naval Academy in Annapolis, Maryland for two years. He has interned with Pratt & Whitney in West Palm Beach, Florida. Mr. Jones is the active Parliamentarian for the American Society of Mechanical Engineers. He is currently enrolled in the Officer Candidate Program working towards a 2nd Lieutenant Commission.

Mr. Rajiva Rampersad, Senior B.S. Mechanical Engineering
Florida State University
Mr. Rampersad was born and raised in Northern California and has lived in south Florida for the last nine years. Mr. Rampersad has owned and operated an automotive performance shop in Palm Beach Florida for the last five years. In addition to operating his performance shop in South Florida Rajiva has worked for RMF Engineers and Kenico construction. Upon graduation Rajiva plans on moving back to south Florida to resume operation of his business.

Ms. Giselle Rojas, 4th year B.S./M.S. Mechanical Engineering
Florida State University
Ms. Rojas was born in Queens, New York but raised in West Palm Beach, Florida, with a Honduran background. Giselle is the active Treasurer for the American Society of Mechanical Engineers. She currently researches for Dr. Namas Chandra and Dr. Peter Kalu in the area of superplasticity. Giselle has acquired two prior internships with Cargill and Proctor & Gamble, and will intern with BP in the Summer of 2006.

Ms. Donna Nicole Wright, Senior B.S. Mechanical Engineering
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Ms. Wright was born and raised in Atlanta Georgia. Donna is the Community Outreach Chairperson for the American Society of Mechanical Engineers. She has interned with AGL Resources (a natural gas company) and Eli Lilly & Co (pharmaceuticals), as a project engineer. Donna's intended future education includes law school with a concentration in Intellectual Property/Patent Law. She is currently employed part-time with Bryant Miller and Olive, a local law firm.

ABOUT THE CUSTOMER…

The Fillauer Companies have a long history of providing innovative orthotic and prosthetic solutions. Together Fillauer, Inc, Hosmer, Motion Control, Center for Orthotics Design and Centri manufacture, distribute and custom fabricate a wide range of O&P products including; RGOs, the MightyMite Endoskeletal Line, the Utah Arm, and Micro Coated Gloves, and the King Pin Lock. Fillauer LLC is the Specialist in Specialty Products including Custom Fabrication Items, Special Modifications, and Technical Support. Innovative technologies, along with tried and true techniques are utilized just as they have been for more than 60 years. The Hosmer Dorrance Corporation produces many Lower Extremity Prosthetics and is a leader in Upper Extremity Prosthetics. Hosmer continues to focus on strength, quality, and the independence of the wearer.
Motion Control and the Myo-Electric Arms and Hands have made a mark as a favorite among patients. With Cutting Edge Technology and Patient Focused Designs, Motion Control products will continue to be a favorite among their wearers. The Center for Orthotics Design and its creative founder, Wally Motloch, CO, are best known for the Isocentric RGO, and have long been recognized as being on the leading edge of orthotic innovation. Centri® manufactures and distributes a variety of products for upper and lower extremity prosthetics and Orthotics. Centri provides a much needed off-the-shelf thermo formable locking liner with a custom fit, as well as a Micro Coated Glove with unique qualities to benefit the patient. Please visit the website www.fillauer.com, for further information, questions, comments, concerns and/or contact information.

THE FILLAUER COMPANIES

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ABSTRACT

A leading manufacturer and distributor of prosthetics, Fillauer, would like to design and fabricate an incremental motion knee joint for assisting patients in walking and standing. The project is to be supervised by a Fillauer engineer. After researching and analyzing several incremental motion mechanisms, a pawl and ratchet mechanism was chosen using 17-4 Stainless Steel HT 1150°F. The design includes a pawl and ratchet clutch mechanism that contains 123 degrees flexion with increments of 11.25 degrees. Since Fillauer currently produces a free motion joint, the new design interfaces with the KingPin bars, as well as the housing for the knee joint. A stress analysis was done for the joint utilizing two different methods. The first method included a cantilever beam analysis in Mathcad; the second method included an Algor analysis. Both methods verified the teeth would not fail. The housing of the knee joint along with the release mechanism was machined on-site at Fillauer, while the Senior Design team machined the inner workings, i.e. gear, pawl, and backing, at FSU-FAMU College of Engineering and the FSU Physics Lab. The gear and pawl were machined using a process called Electrical Discharging Method (EDM). The working prototype was assembled and inspected by both the Design Team and Fillauer and design changes were discussed and noted. Upon complete assembly the first prototype was found to ratchet and lock successfully. However, before initial testing began it was discovered that the first prototype ratcheted both ways, rendering testing unnecessary. The mechanisms problems were corrected by design alterations and confirmed using a Working Model Simulation.

1.0 INTRODUCTION

1.1 Problem Definition

Fillauer, a leading manufacture of prosthetics and orthotics in the world, would like an incremental motion orthotic knee joint. Fillauer currently manufactures a free motion orthotic knee joint called the KingPin Lock. This device does not allow the incremental motion desired. The new design of an incremental device would allow the patient more knee stability and control to the user through an incremental range of knee flexion while transitioning from the sitting position to the standing position.

1.2 Motivation/ Objective

This medical device helps patients with conditions such as Post Polio, Spinal Cord Injuries, Cerebral Palsy, and Multiple Sclerosis. This device is on the company's priority list along with one of their European partners. Once several concepts are explored, Fillauer would like to discuss the most promising concepts and possibly prototype two designs. Ideally a second iteration could be fully developed to have a prototype. The project should meet discussed deadlines so parts can be scheduled with R&D machinist. The goal is to have a device ready for patient trials by the end of Spring semester, 2006.

1.3 Requirements and Specifications

The needs specified in this project are to design, develop and test an incremental motion orthotic knee joint, which extends freely. The existing knee joints on the market all have certain problems that the new design should address and overcome. The main specification states the design of a joint that provide locking positions allowing users to have their leg fully extended at 0 degrees, to negative 130 degrees, when fully bent backwards. It may have an infinite number of locking positions but the threshold (maximum) increments should be15 degrees with 10 degree increments be the objective. Since Fillauer currently manufactures the King Ping Lock, the joint must interface with all existing Fillauer King-Pin Bars. The joint must also provide a free motion joint setting, providing the same motion as the currently manufactured King Pin Lock. Fillauer works with federal healthcare programs such as Medicare, so the design must ensure that the chosen materials and procedures used in the design conform to all pricing guidelines, which include a $\$40^{\underline{00}}$ ceiling on the joint. The joint should be cost effective under the expected volumes. While considering the design, it must conform to the International Organization for Standardization (ISO) standards, specifically, ISO/TC 168/WG 3.

2.0 BACKGROUND RESEARCH

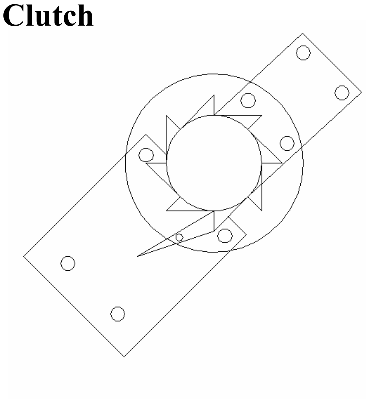
2.1 Theory

There are various methods and mechanisms used to design and develop incremental motion devices. These mechanisms include a combination of gear sets, ratchets, springs, clutches, pawls and actuators. The most familiar and most utilized method is a ratchet and pawl. A ratchet and pawl is a mechanical device that permits motion in one direction only. The ratchet is usually a wheel with slanting teeth. The pawl is a lever tangential to the wheel with one end resting on the teeth. As the wheel rotates in one direction, the pawl slides over the teeth, thus providing free motion; when the wheel rotates the other direction, the pawl catches in the teeth, thus providing incremental motion. This theory is the basis for most design concepts of incremental motion devices.

2.1.1 Internal Ratchet and Spring Loaded Pawls

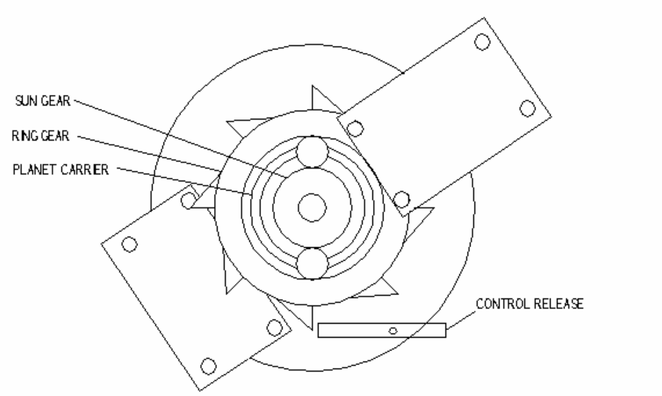
The pawls are compressed and rotated clockwise to create incremental motion, and to create free motion the pawl is rotated counterclockwise. The springs compress to allow pawls to disengage and allow incremental motion as well as free motion in the opposite direction. The increment size will depend on the number of teeth on the outer member.

2.1.2 Pawl and Ratchet Clutch



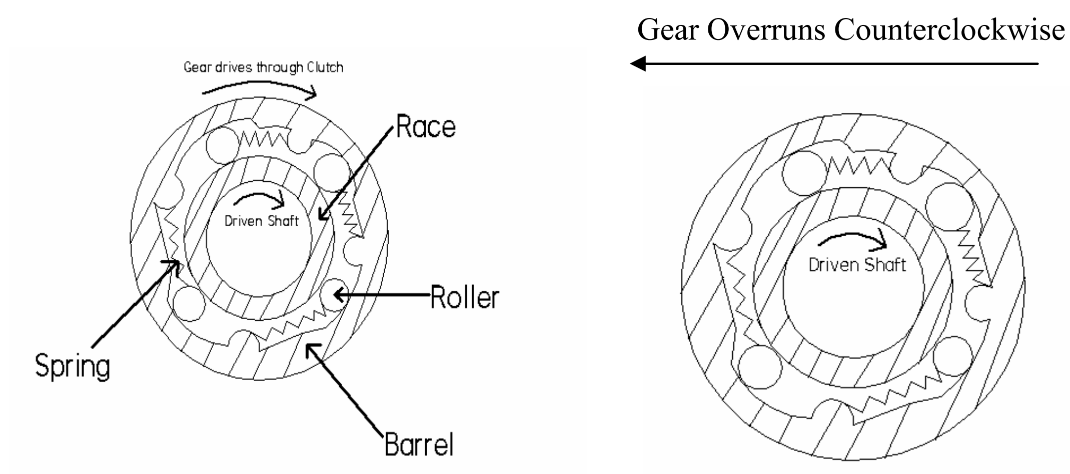
The driving ratchet of this clutch is keyed to the driving shaft, and the pawl is pinned to the driven gear which can rotate freely. When the user raises the control arm, the spring will disengage the pawl, allowing the ratchet and drive gear to rotate freely. To engage the pawl, the user will lower the control arm, allowing incremental motion.

2.1.3. Planetary Transmission Clutch



Planetary gear sets inherently possess two degrees of freedom. By taking advantage of this fact, this mechanism may be used to transmit power or to freewheel. In this case, may be set to the incremental motion or free motion setting. The sun gear is the driving gear and the carrier is the driven member. When the control lever is in the lowered position as shown, both the ring gear and the planetary gears are free to rotate. The sun gear will drive the two planetary gears in equal but opposite directions of rotation. Since the ring gear is free to rotate, this rotation of the planetary gears will cause the ring gear to idle counterclockwise. When the control lever is in the raised position, it prevents the ring gear from rotating. As the sun gear rotates, both the planet gears and carrier will rotate. The increment size will depend on the number of teeth on the gears.

2.1.4 Roller Clutch



This device transmits torque load in one direction, and overruns freely in opposite direction. Either shaft or housing can be the driving member. Rollers wedge between shaft and outer race. Positive wedging forces prevent slipping. Springs position rollers for instantaneous lock-up. It is a light weight device, ideal for indexing, backstopping, or overrunning operations. The roller clutch wrench operates using rollers connected with springs installed between concentric cylindrical races as shown in the first figure. The pins disengage one set of rollers, which allows its engaged partner roller to roll up the wedge surface of the hub when the wrench is turned in one direction. Rotation in the other direction causes the roller to roll down the wedge surface, disengaging the clutch for overrunning. This action allows the wrench to apply torque in one direction and free spin in the other like a traditional ratchet wrench. Moving the pins clockwise so that they engage neither roller will cause the wrench to become a rigid bar, allowing the wrench to apply torque in both directions. Rotating the pins further clockwise will cause them to disengage the rollers that were previously engaged, allowing the wrench to apply torque in the opposite direction as before. The clutch can be actuated selectively to prevent undesired flexion when weight is applied or to allow both flexion and extension when weight is not applied or when it is desired to exercise leg muscles.

2.2 Existing Products

There are currently four to five incremental knee joints on the market. While these joints have been marketed successfully, many have design flaws that prevent them from being ideal. For example one knee joint made by OTS, which is known as the Step Lock joint is sold for $100.00. The Step Lock has 9 locking positions with increments of 10 degrees and 135 degrees of flexion. One of the main problems with the Step Lock is that under load, the joint is hard to unlock. This can make the joint difficult to use for some of the weaker patients due to lack of muscle control. Additionally, the teeth of the gear may break off, creating a dangerous situation for the user.

Figure 2.2.1 OTS Step Lock

Another manufacturer, Becker, makes an incremental knee joint, known as Ratchet Lock Model 1014. Like the OTS the Becker sells for $100.00, however this joint is new on the market and its flaws and problems are yet known.

Figure 2.2.2 Becker Ratchet Lock Model 1014

3.0 DESIGN CONCEPT SELECTION

3.1 Concept Comparison

The pawl and ratchet clutch mechanism was chosen over the other mechanisms for several reasons. This mechanism would be the easiest to manufacture in terms of manufacturability and replacement of parts. Other mechanisms scored poorly in the manufacturability category due to excessive number of parts and complex parts to be machined, i.e. planetary transmission clutch has a lot of parts to fit within the specified dimensions and the roller clutch has complex shaped parts. Using the pawl and ratchet clutch, the existing housing used for the currently Fillauer manufactured KingPin Lock could be utilized. Using the same housing, thus the same process would inherently save money in producing the joint. Keeping the cost minimal was a specification high in importance, as discussed earlier, due to the involvement of federal healthcare programs. This mechanism also embodies a function to not only provide the main objective of incremental motion , but just as easily could provide a free motion setting as specified. The patients using the device have muscle diseases that include weakened muscles and limited muscle control. The device must be easy for the patient to understand and use. Other mechanisms would require a lot of force to operate under a certain load. The pawl and ratchet clutch also easily interfaces with the KingPin bars already designed and in use by patients. This means the housing should be suitable for the KingPin bars. This interface would be more difficult for the other mechanisms such as the planetary transmission clutch and the roller clutch. Based on the discussed rational, two design concepts, the internal ratchet with spring loaded pawls, and the pawl and ratchet clutch, were chosen to go into further analysis. See figure 3.2.1 below.

3.2 Mechanism Decision Matrix

	Manufacturability	Cost	Range of Motion	Ease of Use	KingPin Interface	Total
Internal Ratchet w/ spring loaded pawls	4	5	5	3	3	**20**
Pawl & Ratchet Clutch	5	4	5	5	4	**23**
Roller Clutch	3	2	5	4	3	**17**
Planetary Transmission Clutch	3	3	5	2	2	**15**

1= unacceptable 2= poor 3= good 4= better 5= best

Figure 3.2.1

3.3 Preliminary Design Concepts

3.3.1 Internal Ratchet with Spring Loaded Pawls

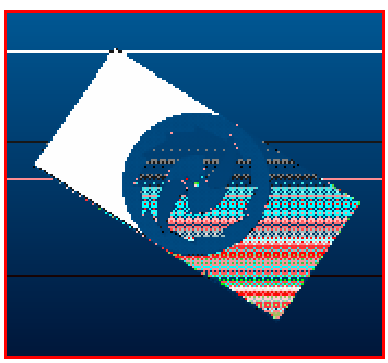


Figure 3.3.1.1 Prototype of Internal Ratchet with Spring Loaded Pawls

This design concept includes two pawls, two springs, an actuator and an internal ratchet. The two pawls is an advantage because it distributes the force on the teeth. The two springs is a disadvantage due to an increase in parts and the necessary spring constant to withstand the force on the mechanism. By inspection it was determined that the spring constant would be too great for the patients to use comfortably. The actuating device proved difficult to adjoin with the basic design. It was challenging to obtain proper placement of bushings and feasibility.

3.3.2 Pawl & Ratchet Clutch

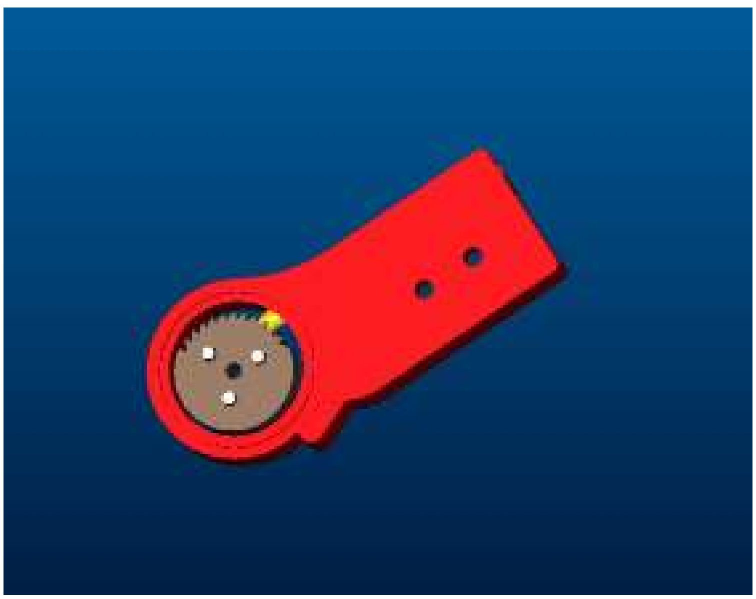


Figure 3.3.1.2 Prototype of Pawl and Ratchet Clutch

This design involves an external ratchet with one pawl that engages the teeth. Since there is only one pawl, the pawl and teeth must be able to withstand the applied force. The pawl location was unclear in the first prototype. There more options in the placement of the pawl and the bushings. This design was chosen for further design details and analysis to prototype.

4.0 FIRST ITERATION DESIGN CONCEPT DETAILS AND ANALYSES

4.1 Pawl and Ratchet Mechanism/Integration

Integration of the pawl and ratchet mechanism with the joint as a complete design concept involved making sure the mechanism itself could function properly. That meant ensuring the teeth were designed at the correct angle so the pawl could engage properly. The number of teeth was determined by the angle of the increment which was 11.25 degrees, thus allowing for eleven teeth on the ratchet. The pawl extends into the housing. The pawl is engaged and disengaged with a spring and actuator. The actuator is placed on the side of the housing, see figure 4.1.1 and 4.1.2.

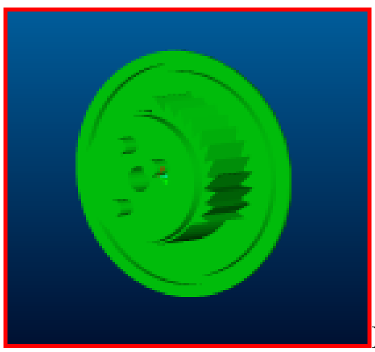


Figure 4.1.1


Figure 4.1.2

4.2 Housing

The housing was based off the current housing for the KingPin Lock, thus able to interface with the KingPin bars. Modifications were made for bushing placement. The housing consists of three main components. The middle housing (figure 4.2.1) accommodates the pawl and spring. The lever for actuation is on the side. It interfaces with one bushing for the outer housing (figure 4.2.2), and a second bushing for the gear hub (figure 4.2.3). The outer housing is an enclosure for the ratchet and contains three holes for the gear hub to be pressed in it. The gear hub consists of one piece with an enclosure and the ratchet. There is also an indentation for the bushing. The three pins that protrude from the gear hub are pressed into the outer housing. This connection ensures any unwanted movement from the housings.

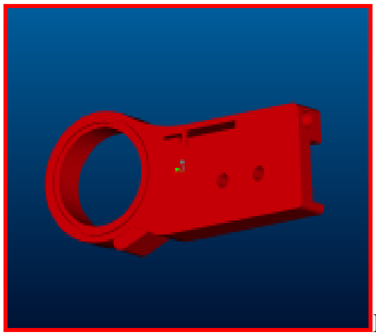


Figure 4.2.1


Figure 4.2.2

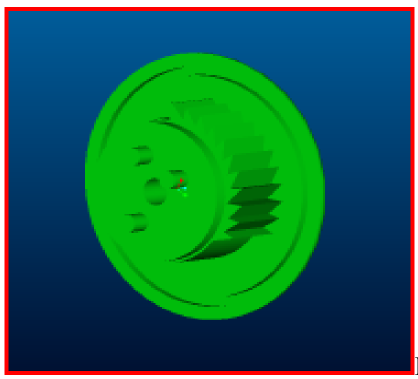


Figure 4.2.3

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4.3 Bushing Type and Placement

The design includes three thin, plastic bushings, which are incorporated to avoid all metal to metal contact (figure 4.3.1). The bushings are also necessary to prevent any axial and radial motion within the joint. One bushing is located between the ratchet and the middle housing. The second bushing is preventing contact between the middle and the outer housing. The last bushing is located between the ratchet and the outer housing. These bushings will be custom fabricated by Fillauer, to suit the design. Plastic bushings comparable to those that Fillauer uses in the free motion knee joint will be utilized for the final design. The bushings are currently manufactured by injecting the plastic into a custom designed mold.

Figure 4.3.1

The successful integration of all the parts encompasses a total thickness of 0.5 inches for the joint; approximately the same thickness as the KingPin Lock and the dimension preferred by Fillauer. All specifications and concerns are addressed in the design concept.

4.4 Materials Selection

The current material used for Fillauer's King Pin Lock was also suggested by Fillauer as the new design's material. Based on this material, research and calculations were made to validate its integrity. 17-4 Stainless Steel HT 1150°F is used for both the housing and hub. 17-4 stainless steel is used throughout industrial and mechanical fields for its high strength, toughness, and low cost. It is also easily cast and machined allowing for easy manufacturability and multiple uses. The housing will be cast and machined, while the gear hub will be completely machined, similar to Fillauer's current fabrication process.

Figure 4.4.1 Material Properties for AK Steel Precipitation Hardening Stainless Steel 17-4 PH, Condition H 1150

Component	Wt. %	Component	Wt. %	Component	Wt. %
C	Max 0.07	Mn	Max 1	P	Max 0.04
Cr	15 - 17.5	Nb + Ta	0.15 - 0.45	S	Max 0.03
Cu	3 - 5	Ni	3 - 5	Si	Max 1
Fe	69.91 - 78.85				

Physical Properties	Metric	English	Comments
Density	7.82 g/cc	0.283 lb/in³	
Mechanical Properties			
Hardness, Rockwell C	35	35	
Tensile Strength, Ultimate	1103 MPa	160000 psi	
Tensile Strength, Yield	1034 MPa	150000 psi	0.2% YS
Elongation at Break	11 %	11 %	in 2 inches
Thermal Properties			
CTE, linear 20°C	11.9 µm/m-°C	6.61 µin/in-°F	21 to 93°C
CTE, linear 20°C	13 µm/m-°C	7.22 µin/in-°F	to 427°C

4.5 Design Analyses

The most important part of the design to be analyzed was the teeth on the ratchet. This is a major concern of the joints currently on the market. The force of the pawl was assumed to act as a point load at the center of the tooth. Although the tooth will experience a distributed load from the pawl, assuming a point load is worst case scenario. The joint should be able to withstand a moment of 80 Nm on the test machine for 1 million cycles. Therefore an equivalent force of 1416 pounds was used for the evaluations.

One method use to analyze the teeth was to define one tooth, with true 3-D dimensions, of the ratchet into Algor, a finite element analysis computer software. This program provides an accurate analysis of the situation. This program was able to obtain numerical values for the stress analysis. The axial stress calculation was 1538.63 lbf/in^2. The bending moment value is 1.36 lbf in. The beam has a bending stress of 222.812 lbf/in^2. The displacement was found to be 2.04e^{-5} inches.

Mathcad, a general, engineering/mathematical calculation software was also used for additional analysis. To analyze the teeth, each tooth was assumed as a very thin and short cantilever beam. See figure 4.5.1. The length of the tooth or “beam” is 0.07 inches and a height of 0.01 inches.

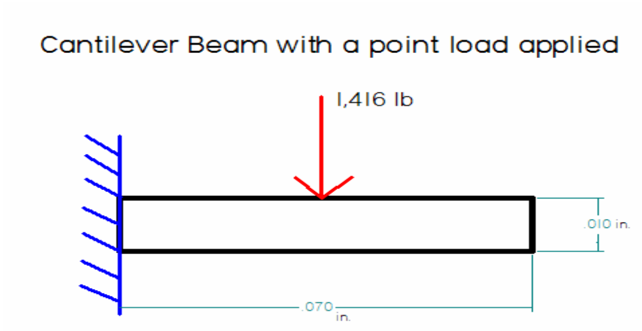


Figure 4.5.1

Using the cantilever beam method, the maximum shear stress is 1416 lbf/in^2 . Figure 4.5.2 shows a graphical representation of the shear stress along the beam.

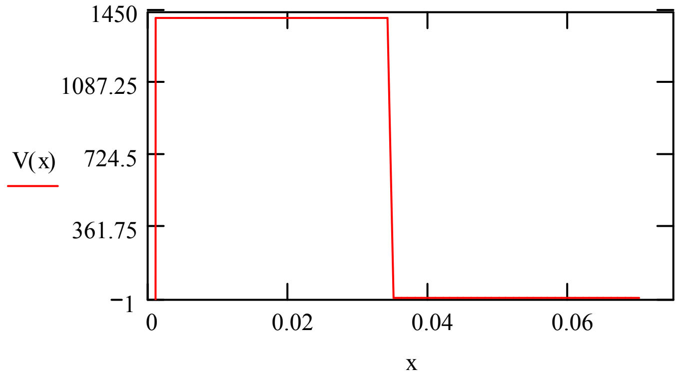


Figure 4.5.2

Figure 4.5.3 is a graphical representation of the deflection of the beam. The maximum deflection occurs at the end of the beam and is approximately $3.15e^{-05}$ inches.

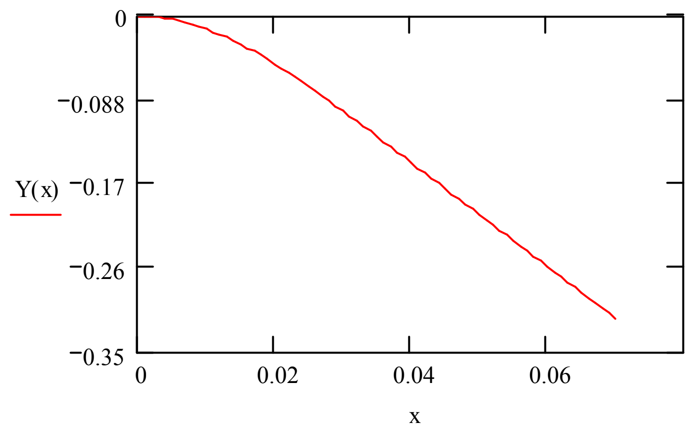


Figure 4.5.3

The values of the Mathcad and the Algor programs, compliment each other. The values are not the same and will not be the same due to the "cantilever beam" assumption. The values do verify the integrity of the tooth design because the calculated stress does not exceed the ultimate tensile strength of the material.

5.0 DESIGN MODIFICATIONS

No major changes were made to the initial design developed, however the design underwent quite a few minor modifications. Most modifications were made an order to accommodate for machining of the components of the knee joint. The actual mechanism concept remained the same throughout the design process. Components were modified as needed when problems were encountered.

Ratchet Gear and Backing

Initially, the ratchet gear and backing were integrated to avoid lateral movement of the gear. Machining became an issue in trying to integrate the two parts. In solution to this problem, it was decided to separate the two parts and make them their own identity. To prevent lateral motion the two parts were bolted and pinned together along with the outer housing. This allowed for the middle housing and the pawl to be the only parts that move in the assembly.

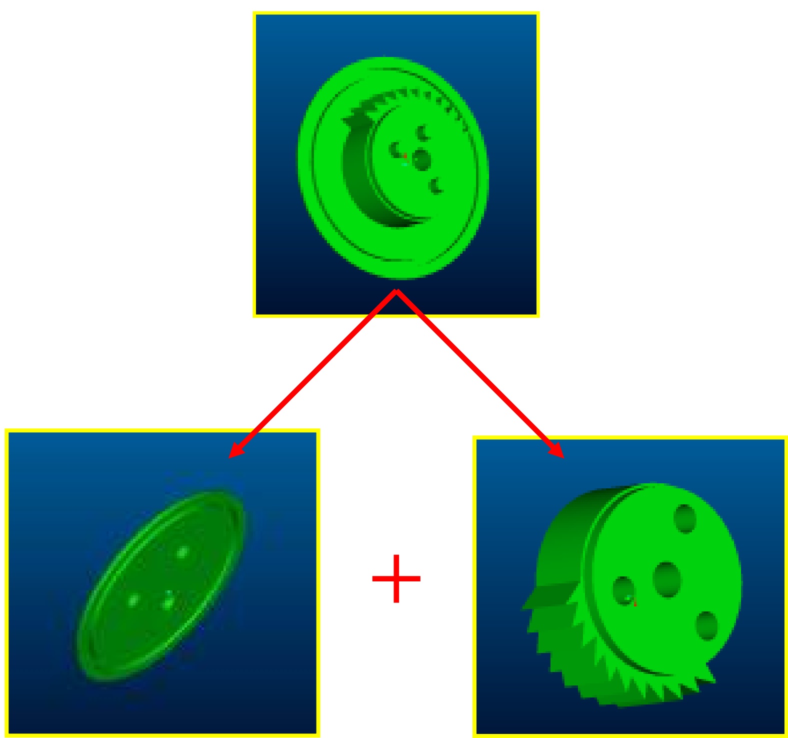


Figure 5.1

Fabricated Parts:

Figure 5.2

Pawl

The pawl was another component that had to be altered in order to accommodate for machining. Originally, the pawl had a squared geometry; however it was found that it was impossible to machine a square whole in the outer housing, which is where the pawl was going to be sitting. Therefore, the pawl was changed to a circular geometry, in order to have a flush fit into the outer housing, without any extreme movement of the pawl.

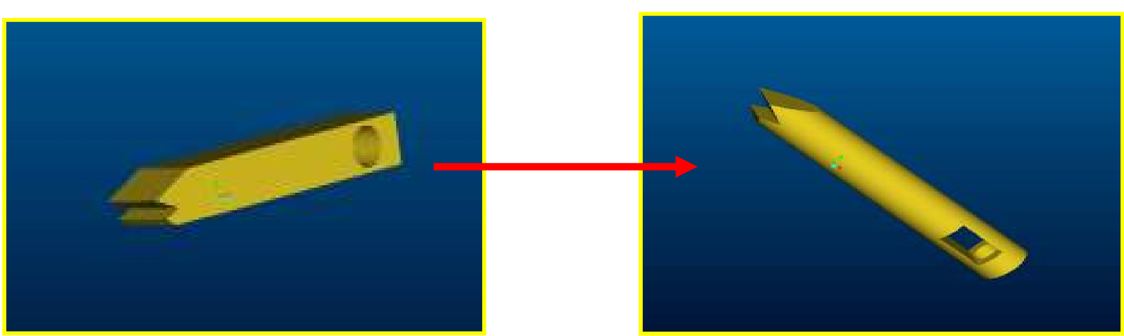


Figure 5.3

Fabricated Part:

Figure 5.4

Actuation System:

The lever that was designed to actuate the incremental knee joint, was completely eliminated, in order to have a more generic actuation system. It was also desired by Fillauer to have an actuation system that the patient can access closer to the hip, instead of right on the knee joint. The group was asked to make necessary changes to the housing to allow for a standard actuator to be attached. The lever was removed, and a threaded hole was added on the back of the middle housing.

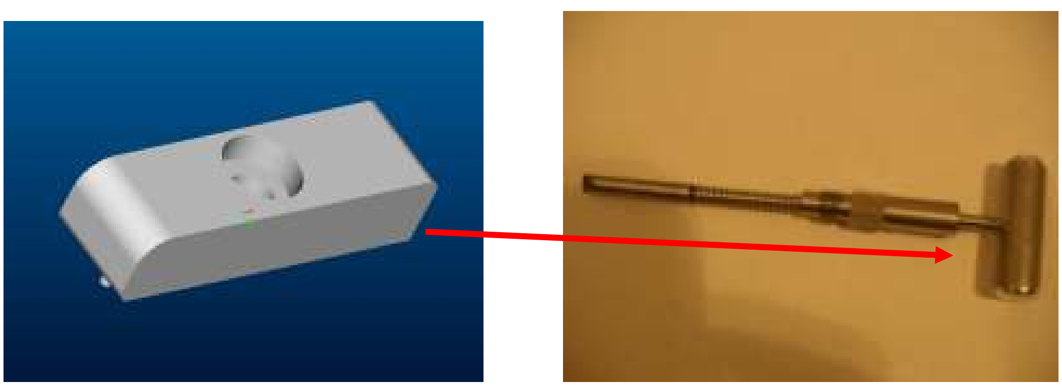


Figure 5.5

Middle Housing:

The middle housing changes came along with the modifications of the pawl and the actuation system. The middle housing was altered to accommodate for the circular pawl, and all the openings that were meant for the attachment of the lever, were removed and a threaded hole on the back of the part was added. Another minor modification made to the middle housing was making the part shorter in length in order to accommodate for the King Pin bars that Fillauer currently has.

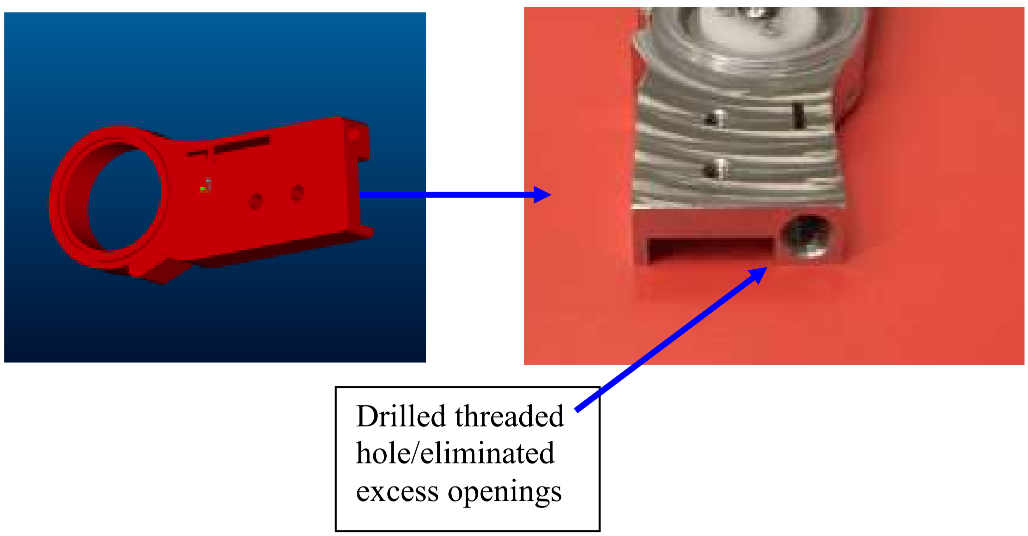


Figure 5.6

<u>Bushings</u>:

To reduce the fabrication of different parts, as well as the cost of machining three custom made bearings, only one type of bearing was kept. The three bearings that were originally going to be used had different diameters and thicknesses. All grooves and protrusions on the ratchet gear backing and the outer housing were altered to house the one bearing chosen.

<u>Outer Housing</u>:

The outer housing length was modified like the middle housing. It was made shorter to accommodate for the King Pin bars. Also, the groove that houses the bearing was altered to fit the one bearing chosen. These modifications were all made in reference to the changes made to the other parts of the knee joint.

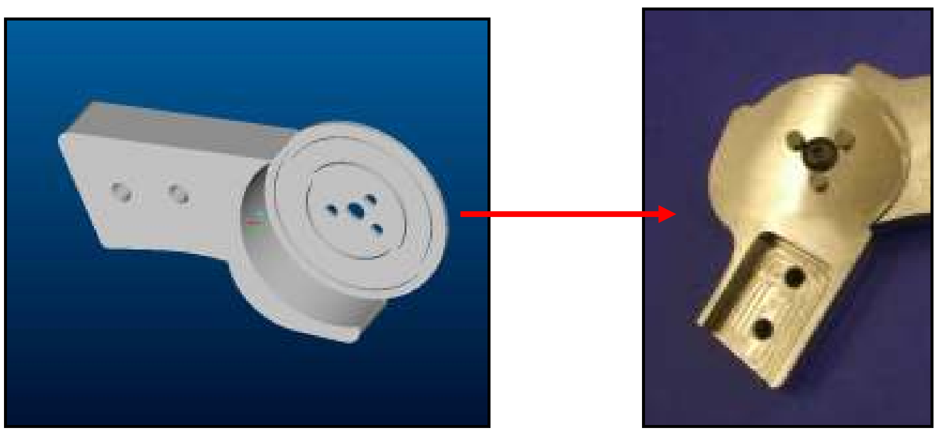


Figure 5.8

Prototype Assembly

With all the modifications made to the individual components of the knee joint prior to machining, it made it easier to assemble the joint with all parts fitted. For the purpose of demonstration, a plexi-glass backing was also machined so that the ratchet and pawl mechanism can be seen in motion.

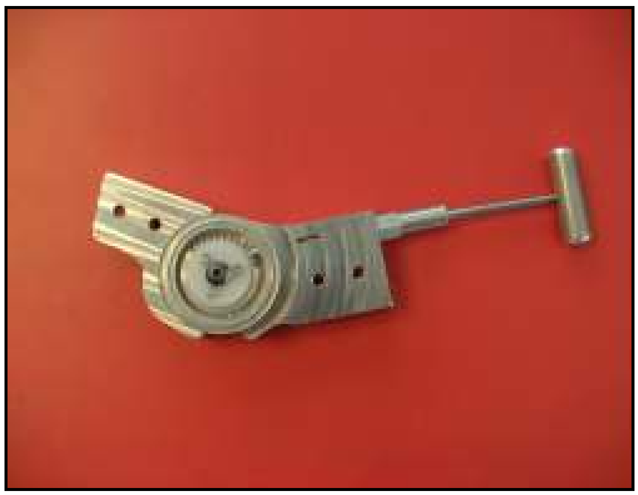


Figure 5.9

Figure 5.10

6.0 MATERIALS/COST ANALYSIS

Part Number	Material Description (Bulk)	Unit Price	Total Price	Knee Joint Part
87205K141	Type 17-4 PH Hardened Stainless Steel Rod 1-1/8" Diameter, 1" Length (Same as 87205K14)	$34.89 Each	$34.89	**Ratchet Gear** 1" Diameter 0.36" Length
89095K323	Type 416 Stainless Steel Rod 1-1/2" Diameter, 1" Length (Same as 89095K32)	$41.19 Each	$41.19	**Ratchet Gear Backing** 1-1/2" Diameter 0.0625" Length
88955K252	Type 416 Steel Precision Ground Rod ¼" Diameter, 3' Length (Same as 88955K25)	$14.19 Each	$14.19	**Pawl** 0.25" Diameter 1.24" Length
8546K27	Virgin Electrical Grade Rod of Teflon PTFE 1-3/8" Diameter	$30.33 Each	$30.33	**Bearing** 1.34" Diameter
98380A471	Type 416 Ss Dowel Pin 1/8" Diameter, ½" Length, MIL Spec 16555-627, Packs of 50	$10.46 Each	$10.46	**Pins** 1/8" Diameter ½" Length

The materials used to build the first prototype were provided to the team by the sponsor Fillauer. The above chart depicts the cost of the raw materials necessary to construct the knee joint prototype. The group was given a budget of no more than $40.00 in material cost per knee joint. The team met this mark because the total cost for manufacturing the parts is less than the monies allocated. It can easily be shown that the complete assembly met the financial limits set forth to us due to the fact that with the supplied materials a total of five complete knee joints are able to be fabricated. The total spent on the materials for the pieces was $131.06, thus, approximately $26.22 per joint.

The machining process was done using both the physics lab at Florida State University and Fillauer's on site machine lab. It took a total of approximately 20 hours to machine the inner mechanism using the EDM process at Florida State. It took Fillauer 1 week to machine the knee joint housings to complete the device.

7.0 MANUFACTURING PROCESS

There were five main components of the incremental knee joint that needed machining: the ratchet gear, pawl, middle housing, outer housing, and the ratchet gear backing. Most of these parts were machined using the traditional lathe and mill. However, when machining the ratchet gear and the pawl a process called Electrical Discharge Machining was necessary, because of the complex geometry and the angles of the gear teeth. All other minor part, such as the pins, the spring, and the actuation system were off the shelf parts.

7.1 Tolerances

When composing the drawings for machining of the parts, tolerances played an imperative role in assuring that the components would be machined to fit together. Given that the overall knee joint is relatively a small and compact device, the process of tolerancing each dimension on the individual components was necessary to achieve a successful assembly. The geometric tolerance is defined as the total amount that the dimension of a manufactured part can vary. The tolerenaces calculated for most of the dimensions on the components are as follows:

.x±0.03

.xx±0.01

.xx±0.005

There were a few dimensions that varied in tolerances, and those particular tolerances were noted on the pro-engineering drawings next to the relative dimension. The diagram below depicts the cyclic cycle of how tolerancing affects the development of a prototype or product that is being manufactured. Tolerances ultimately starts and ends with the customer.

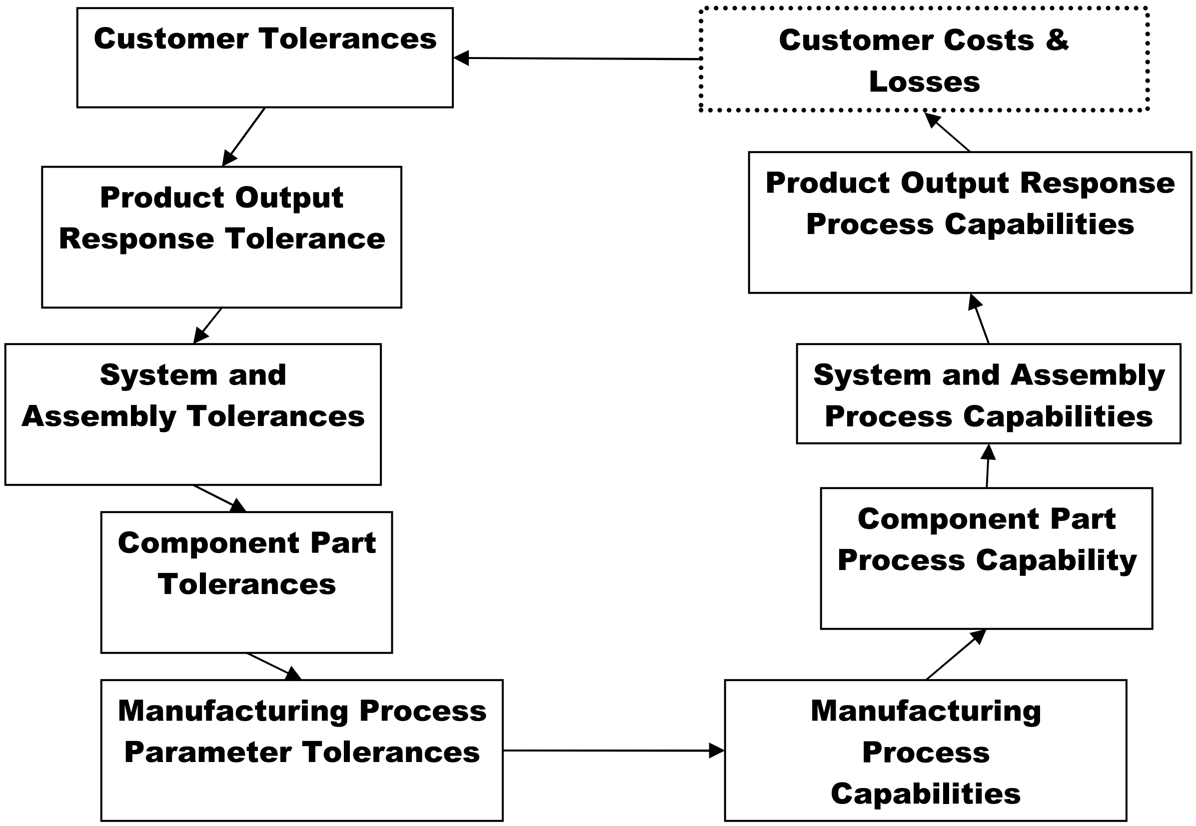


Figure 7.1.1

7.2 Electrical Discharge Machining (EDM)

The Electrical Discharge Machining process is one of the most accurate and low cost processes, when creating complex or simple shapes and geometries within parts and assemblies. EDM is also a very desirable manufacturing process when low counts and high accuracy is required, as well as has quick turn around time. When fabricating the gear and pawl, EDM was very useful in assuring that the angles were machined close to exact as it was designed, to avoid the gear and pawl not fitting together correctly. Another advantage in using the EDM process was that the material chosen for the gear and pawl is an extremely hard material, making this process extremely beneficial in cutting the 17-4 stainless steel.

EDM is sometimes called "spark machining" because it removes metal by producing a rapid series of repetitive electrical discharges. These electrical discharges are passed between an electrode and the piece of metal being machined. The small amount of material that is removed from the work piece is flushed away with a continuously flowing fluid (see the diagram below). The repetitive discharges create a set of successively deeper craters in the work piece until the final shape is produced.

EDM Process:

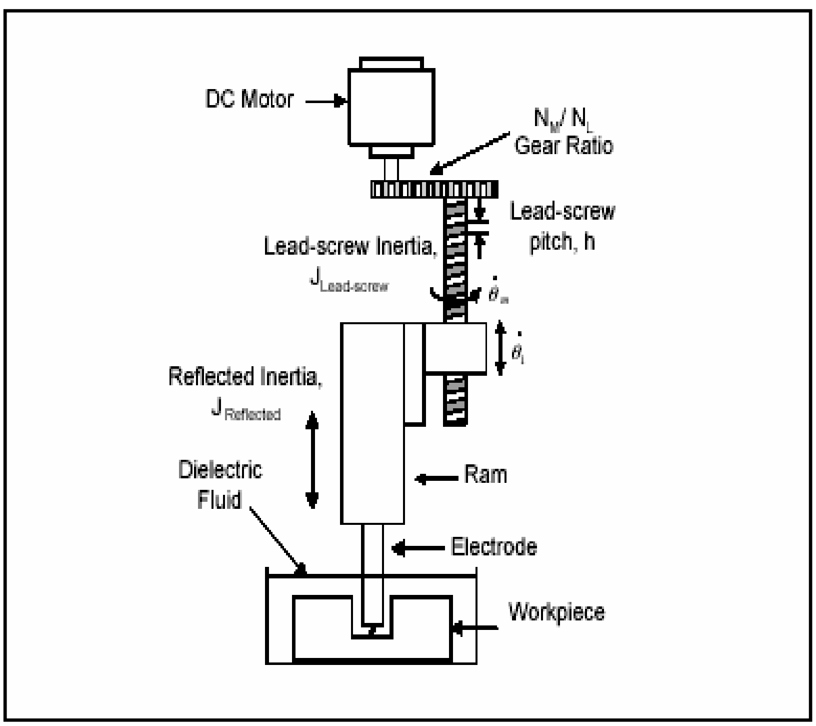


Figure 7.2.1

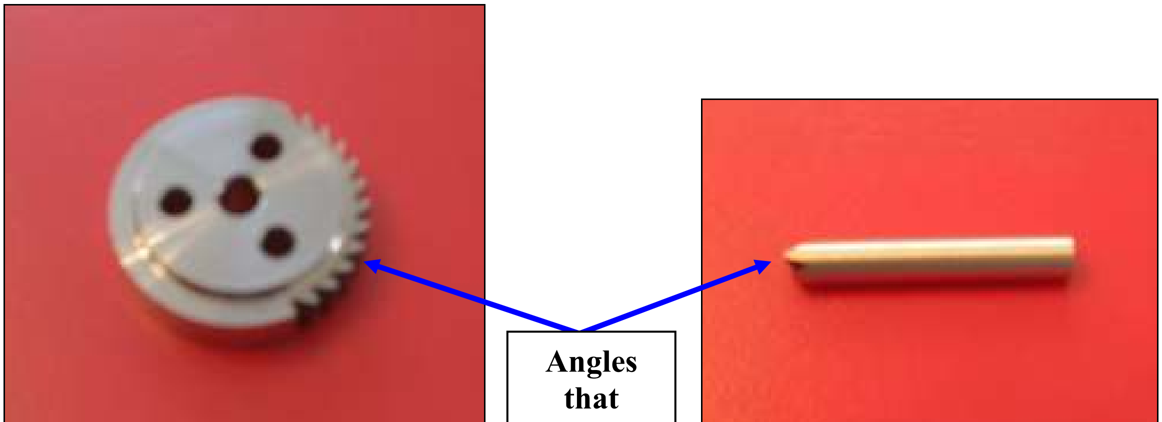
Illustration of EDM equipment:

Figure 7.2.2

EDM is commonly used for making prototype and production parts, which is exactly what was needed in the development of this project.

Machined using lathe

Figure 7.2.3



7.3 Lathe and Mill

The housing components, as well as the skeleton of the ratchet gear and pawl were machined using the traditional lathe and mill.

<u>Illustration of Lathe</u>:

Figure 7.3.1

Accuracy and clarity were vital in composing the drawings and tolerances for machining every component of the knee joint. All the parts were properly assigned tolerances on the respective drawings to allow for assembly of the knee joint. The group spent a total of 20 hours in the machine shop. The main parts were successfully fabricated and assembled.

8.0 TESTING

FIGURE 8.1

FIGURE 8.2

The testing process consisted of placing the knee joint device into the testing machine (above figures) in one specific locking position. This setup is testing for the strength of the actual gear teeth, because a main issue with existing products is tooth breakage. The machine is run for 1 million cycles and takes approximately 24 hours. It is tested to withstand a moment of 80 Nm on the test machine for 1 million cycles. It is also tested to withstand a moment of 12 Nm medial laterally for 1 million cycles.

Unfortunately, the prototype was unable to be tested due to the device ratcheting improperly. This problem is discussed in further detail in the problems encountered section.

9.0 PROBLEMS ENCOUNTERED

During the design phase, machining phase, assembly phase and testing phase, several problems were encountered. The very first problem encountered was formatting the team's drawings with Fillauer's current drawings. This caused several iterations of drawings that cost time, preventing the machining process to begin. Once the machining process began, the team realized it would be difficult to machine the gear and bearings. Eventually a process called Electrical Discharging Method (EDM) was used to machine the teeth on the gear hub. The bearing however was never machined. The small dimensions made in impractical. The short-term solution was to use a lubricant to prevent the metal to metal contact. After looking at the design of the bearing and the housings and grooves into which the bearings would have been placed, the most obvious solution was to change the dimensions of the bearings and grooves. Enlarging the bearings and grooves by 0.10 inches did not interfere with the current design of the housings either. Although these changes were not made to the prototype it will be one of the most important factors to discuss in future recommendations.

Once all the parts were fabricated, there was extra space within the gear hub and housings themselves. To alleviate this issue, plastic spacers of a smaller diameter than the gear hub, was placed into the device. The most significant problem came once the device was assembled. In the beginning, the device would not ratchet at all. After about 24 hours, the device was ratcheting properly and was sent out to begin testing. This success was attributed to some play within the device that worked itself out. However, prior to testing, the device began ratcheting both ways, thus not locking, a major specification for not only the project, but a prerequisite for the device to be tested. It was concluded that the angle and steepness of the gear teeth was the cause for the problem. The spring stiffness was also concluded to contribute to the problem. Inserting a stiffer spring may help alleviate the problem. Calculations were redone and a new angle was designed. A simulation using Working Model software confirmed that the gear would both ratchet and lock. To prevent this issue, a simulation should have been completed prior to fabrication.

10.0 CONCLUSION

The initial objective of the project was to design an incremental motion knee joint with certain specifications in the given amount of time. After researching and analyzing several incremental motion mechanisms, a pawl and ratchet mechanism was chosen using 17-4 Stainless Steel HT 1150°F. The completed design includes a pawl and ratchet clutch mechanism that contains 123 degrees flexion with increments of 11.25 degrees. The housing for the incremental knee joint was modeled after Fillauer's current free motion knee joint. Stress analysis was done for the ratchet teeth using engineering calculation and Finite Element Analysis software. The gear teeth properties were modeled as a cantilever beam in Mathcad. Both a single gear tooth and the gear hub was modeled in Algor using the finite element mesh analysis. Both analyses showed that the ratchet gear teeth would not fail under working loads. Once the calculations verified our preliminary design, a final design concept was completed.

The drawings and specifications of the final design were submitted to Fillauer and the supervising engineer over the project. Once fabrication and assembly of the prototype was complete, it was realized that the knee joint could not be tested. This was due to the angle and steepness of the gear teeth allowing the device to ratchet both ways. One solution was to change the spring constant, making it stiffer. The angles of the gear teeth were also slightly modified. An extra protrusion (tooth) was also designed to enable the ratchet to lock in each position, preventing the ratchet movement in the wrong direction. A simulation utilizing Working Model software was used to verify the design modifications of the gear and pawl, ensuring the mechanism would ratchet and lock properly.

11.0 REFERENCES

Erdman, Arthur G., George N. Sandor, and Sridhar Kota. Mechanism Design Analysis and Synthesis Volume I. New Jersey: Prentice-Hall, 2001.

Hibbeler, R. C. Statics and Mechanics of Materials. New Jersey: Prentice-Hall, 1993.

Norton, Robert L. Design of Machinery Third Edition. Boston: McGraw Hill, 2004.

Norton, Robert L. Machine Design An Integrated Approach Second Edition. New Jersey: Prentice Hall, 2000.

Sandor, George N., and Arthur G. Erdman. Advanced Mechanism Design: Analysis Synthesis Volume 2. New Jersey: Perntice-Hall, 1984.

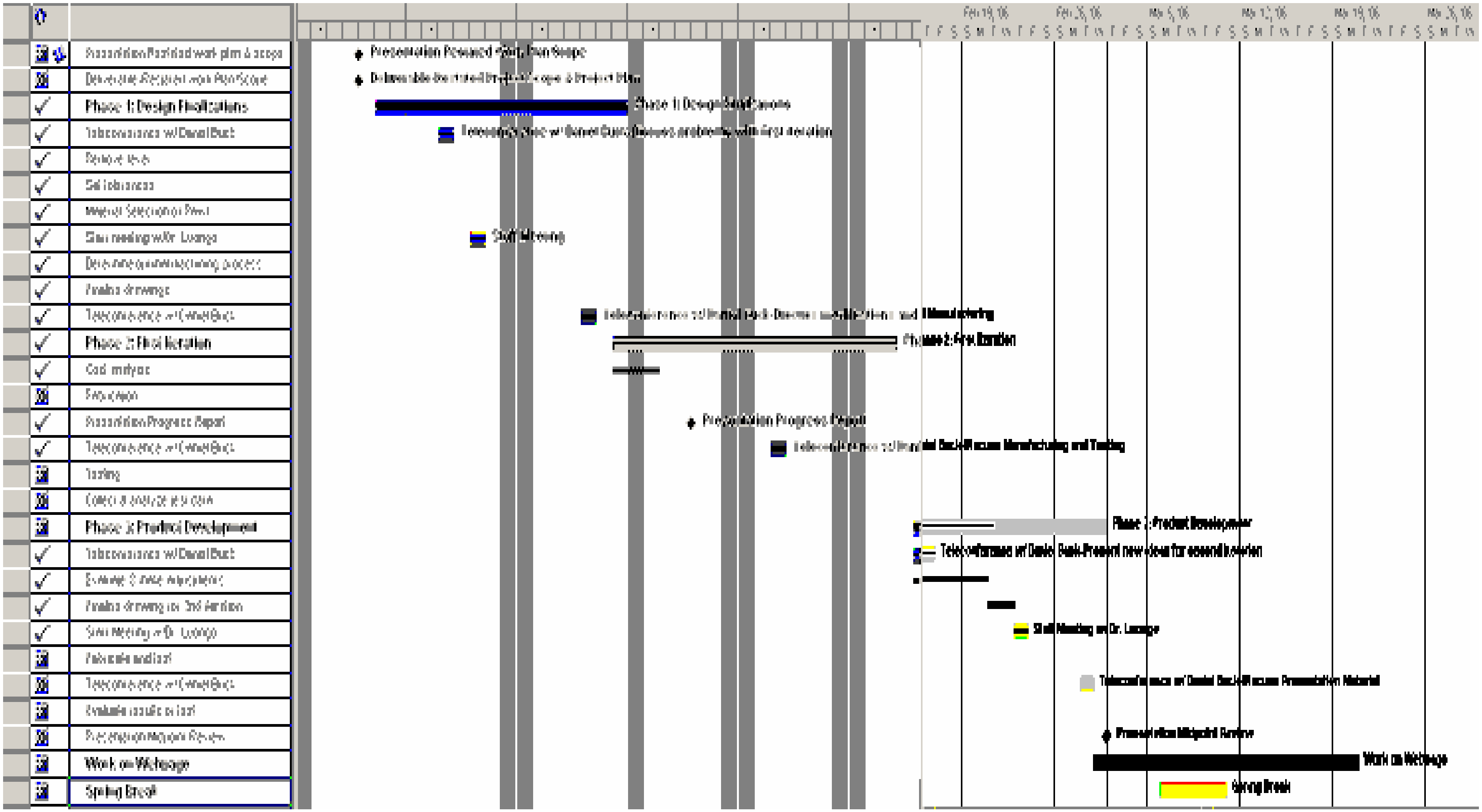
Fillauer Homepage, 2005. December 1, 2005. www.Fillauer.com

Becker Orthopedic Homepage, 2005. December 1, 2005. www.beckerorthopedic.com

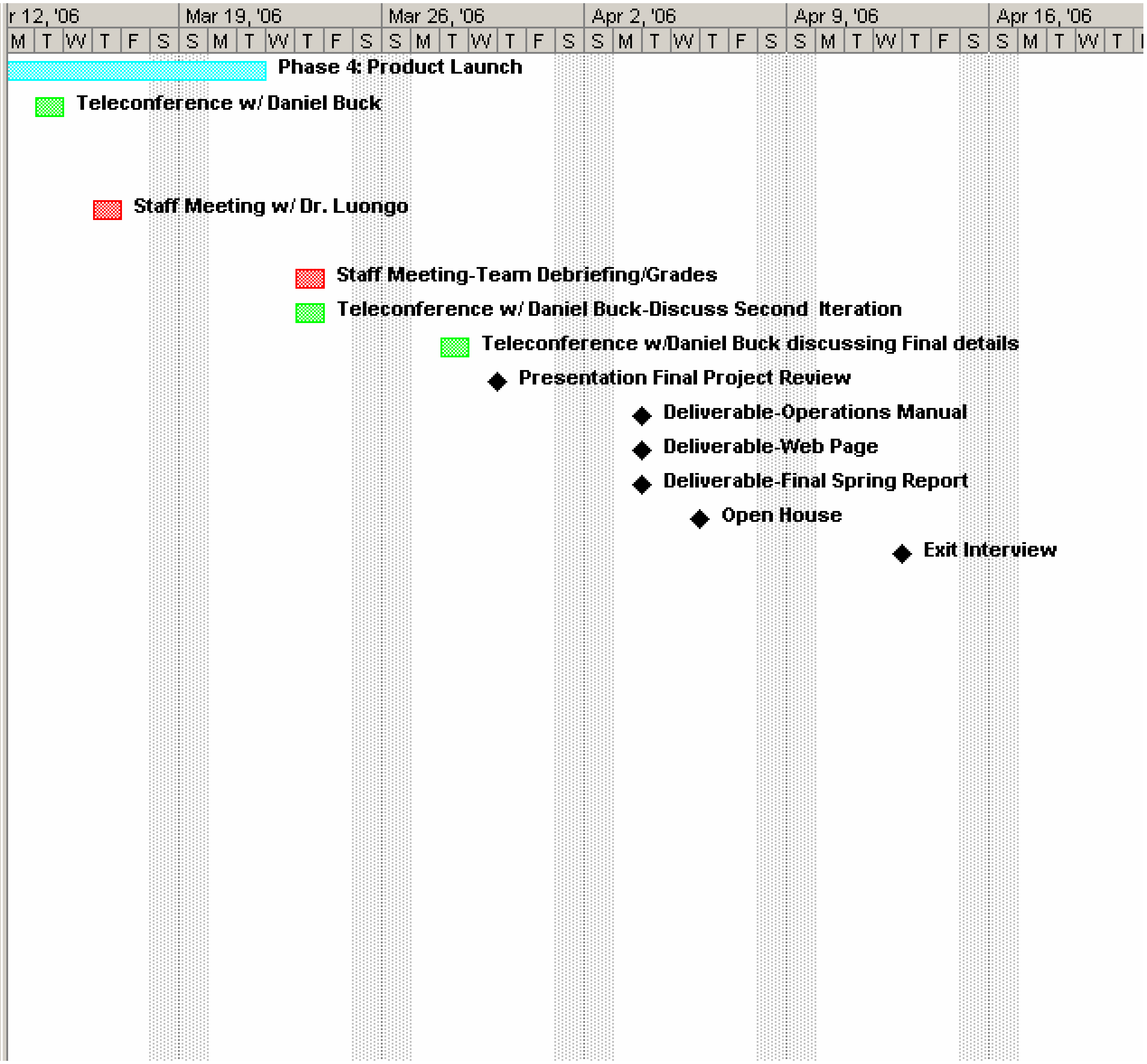
OTS Homepage. 2004. December 1, 2005. www.ots-corp.com

7.0 APPENDIX A:

<u>PROJECT SCHEDULE</u>


Phase 1: Design Finalizations
Staff Meeting
Phase 2: First Iteration
Presentation Progress Report
Phase 3: Product Development
Work on Webpage
Spring Break

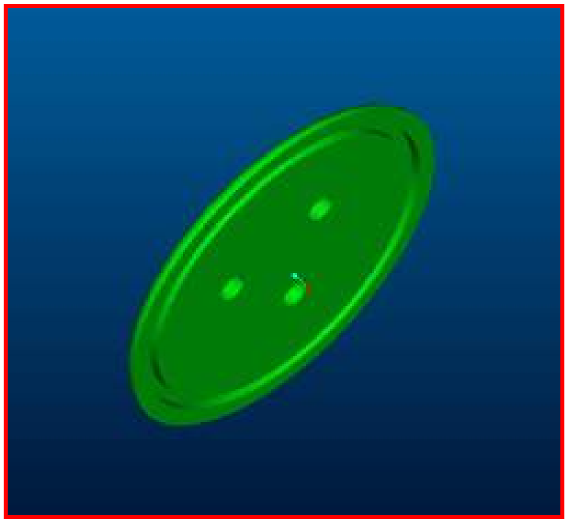
	Task Name
30	**Phase 4: Product Launch**
31	Teleconference w/ Daniel Buck
32	Develop product name and packaging
33	Assist in Marketing
34	Staff Meeting w/ Dr. Luongo
35	Begin patient trials
36	Staff Meeting Team Debriefing-Grade
37	Teleconference
38	Teleconference
39	Presentation Final Project Review
40	Operations Manual
41	Web Pages
42	Final Report
43	Open House
44	Exit Interview



8.0 APPENDIX B:

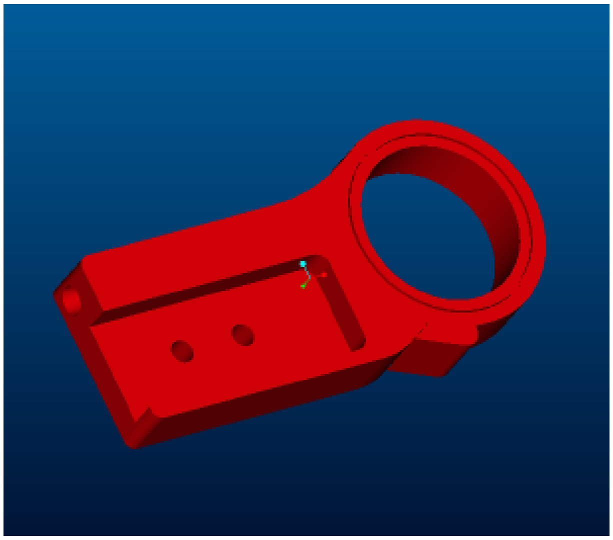
DESIGN CONCEPT PARTS AND ASSEMBLY

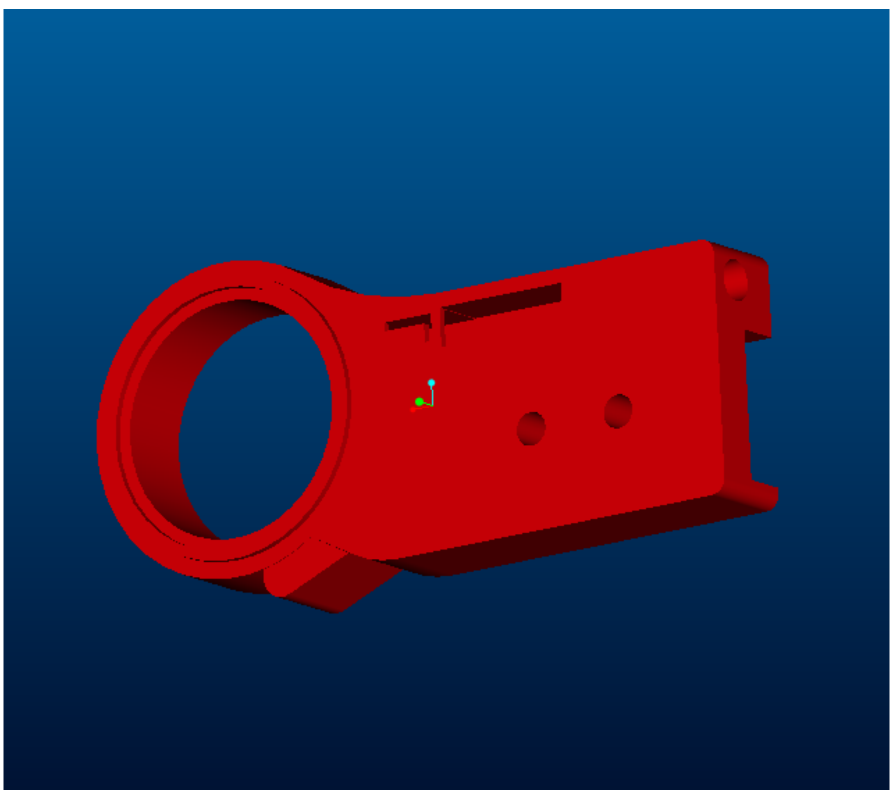
Part 1: Gear Hub



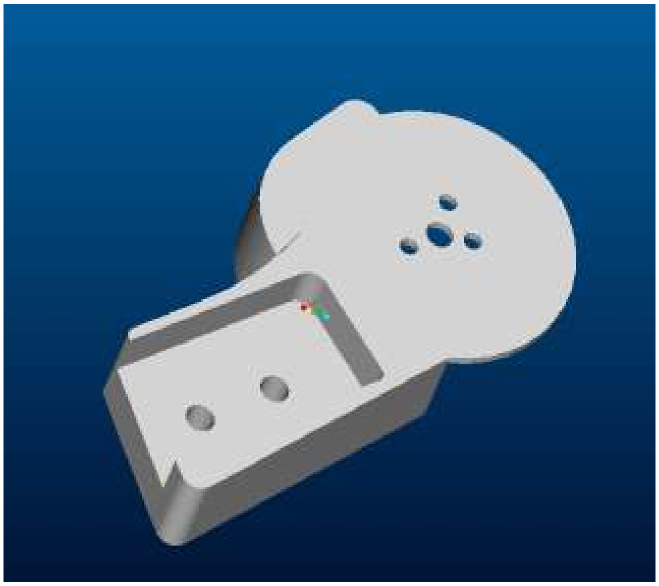
Part 2: Ratchet Gear

Part 3: Middle Housing



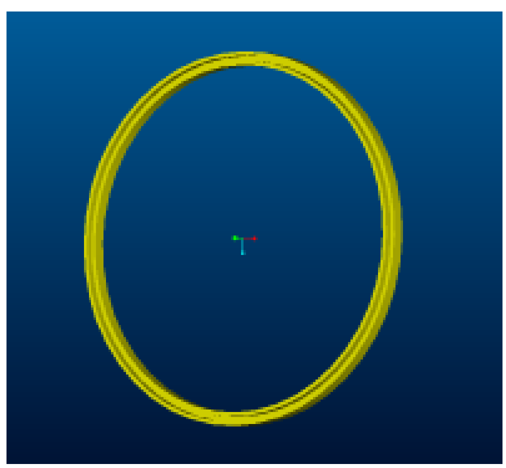


Part 4: Outer Housing

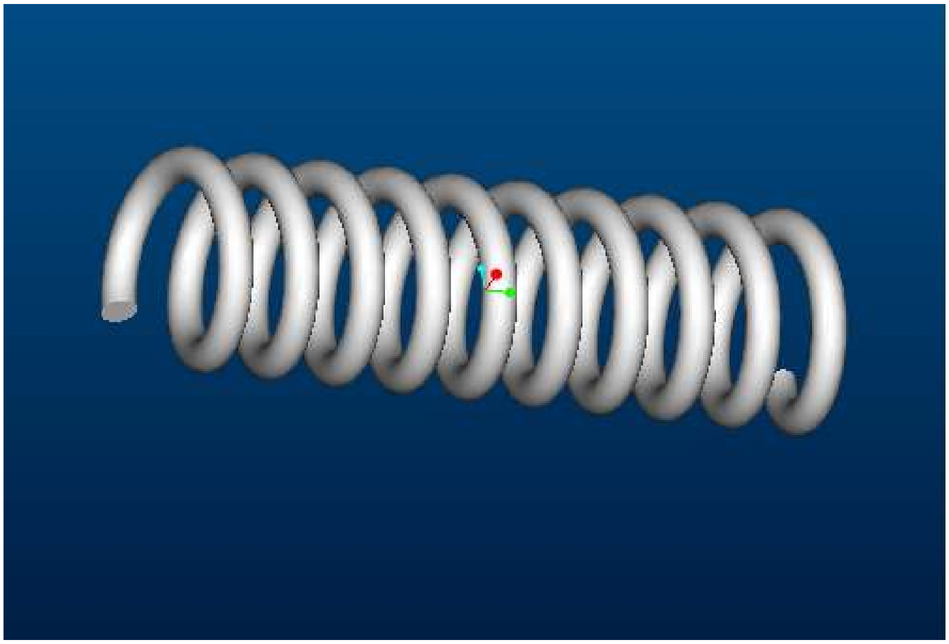


Part 5: Pawl

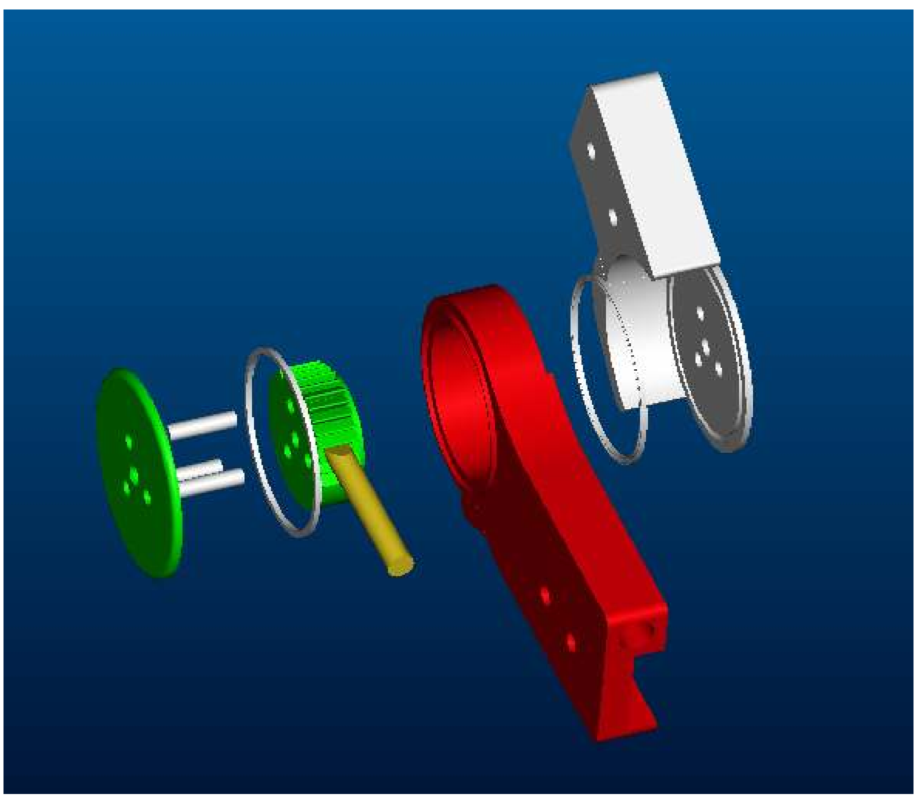
Part 6: Bushing 1



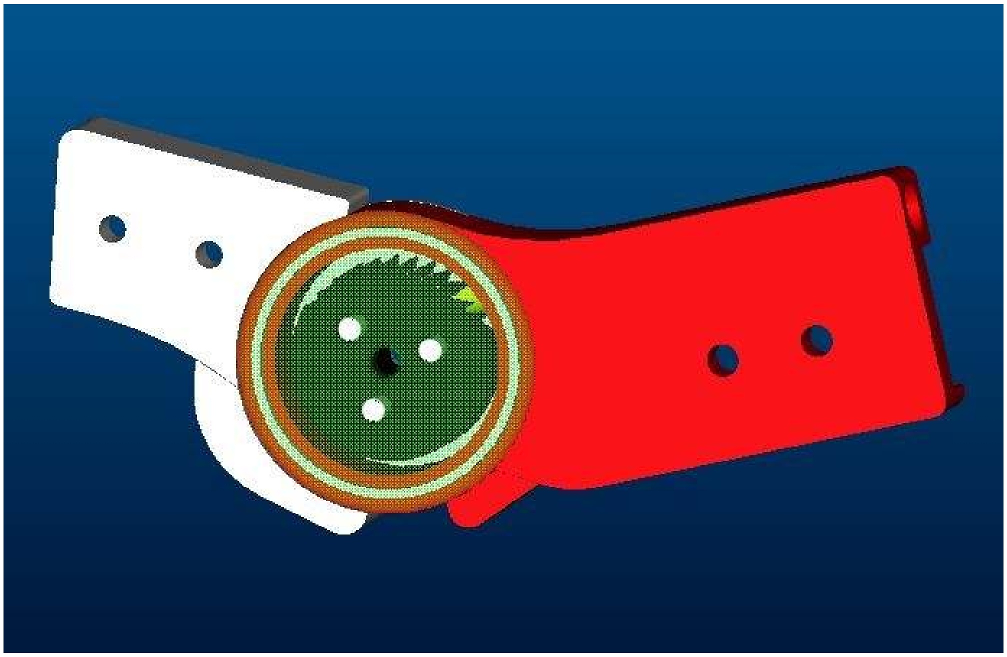
Part 7: Spring



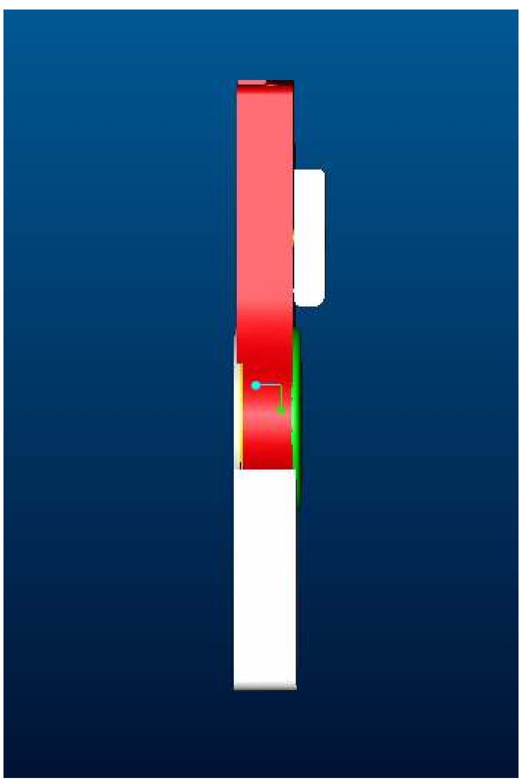
Assembly View 1



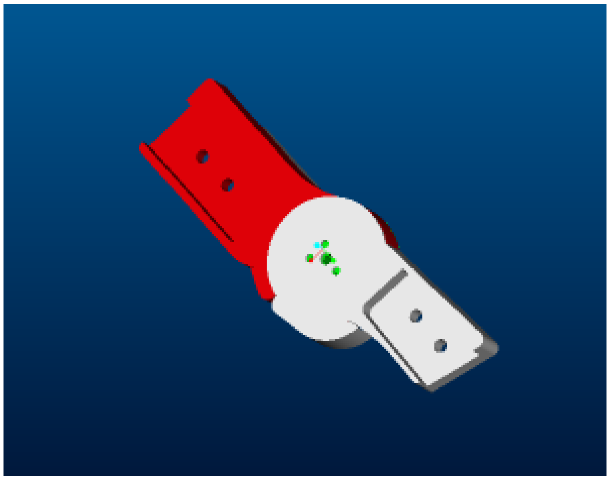
Assembly View 2



Assembly View 3



Assembly View 5



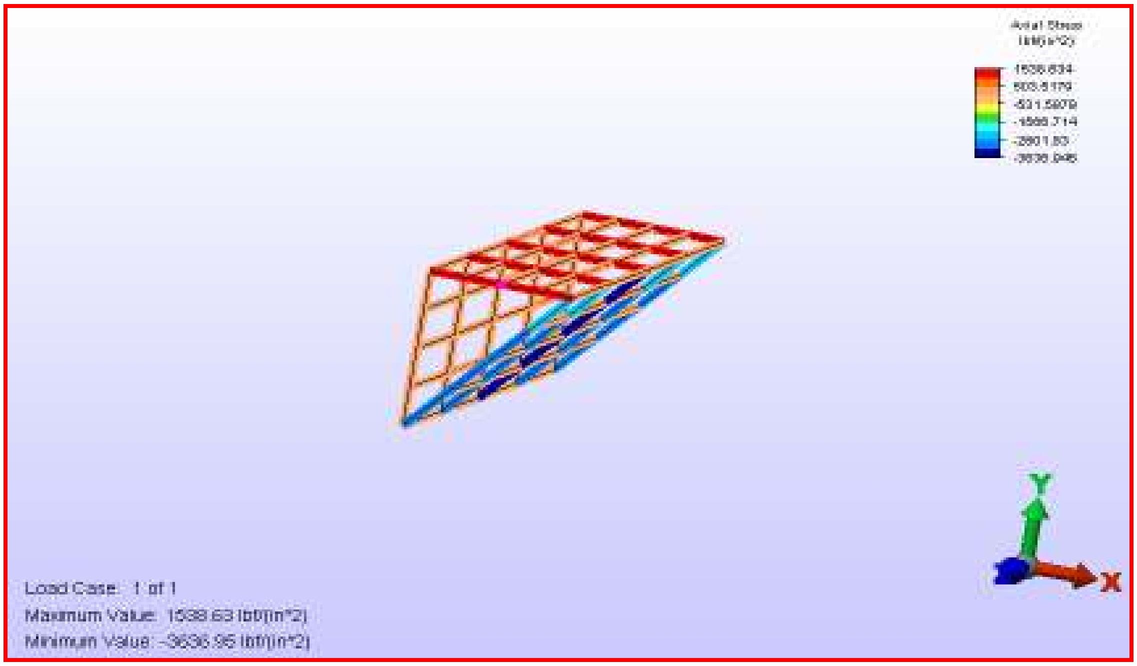
9.0 APPENDIX C:

DESIGN CONCEPT DRAWINGS

10.0 APPENDIX D:

ALGOR FINITE ELEMENT METHOD ANALYSIS

<u>**AXIAL STRESS**</u>



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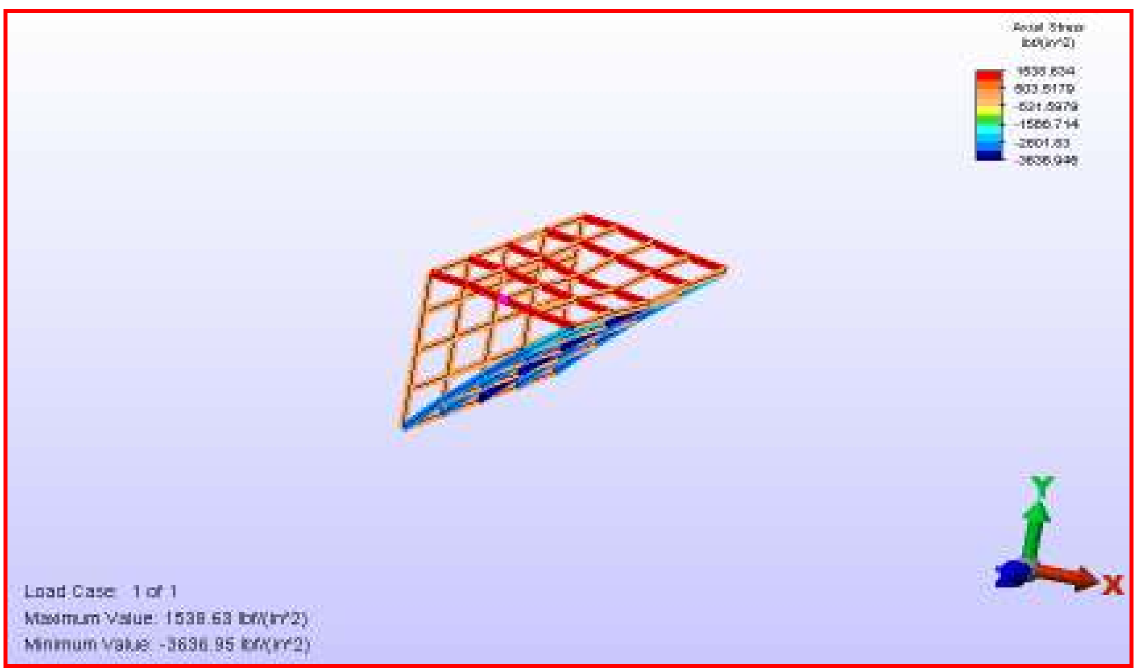
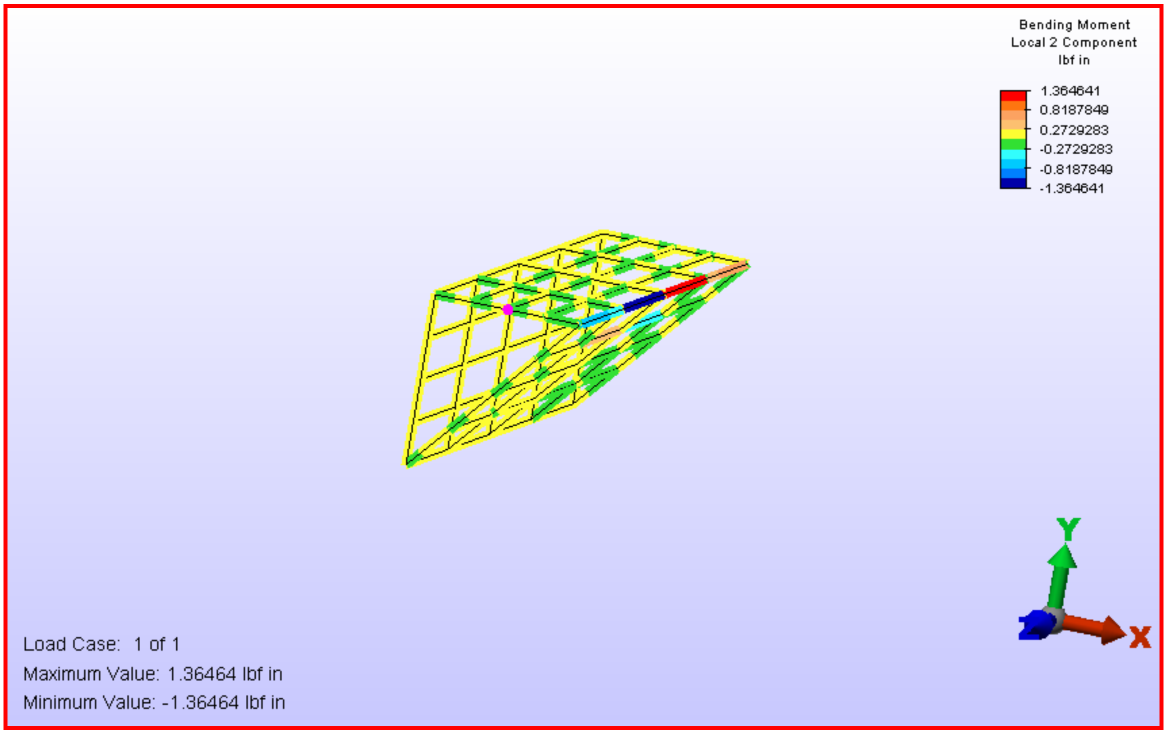
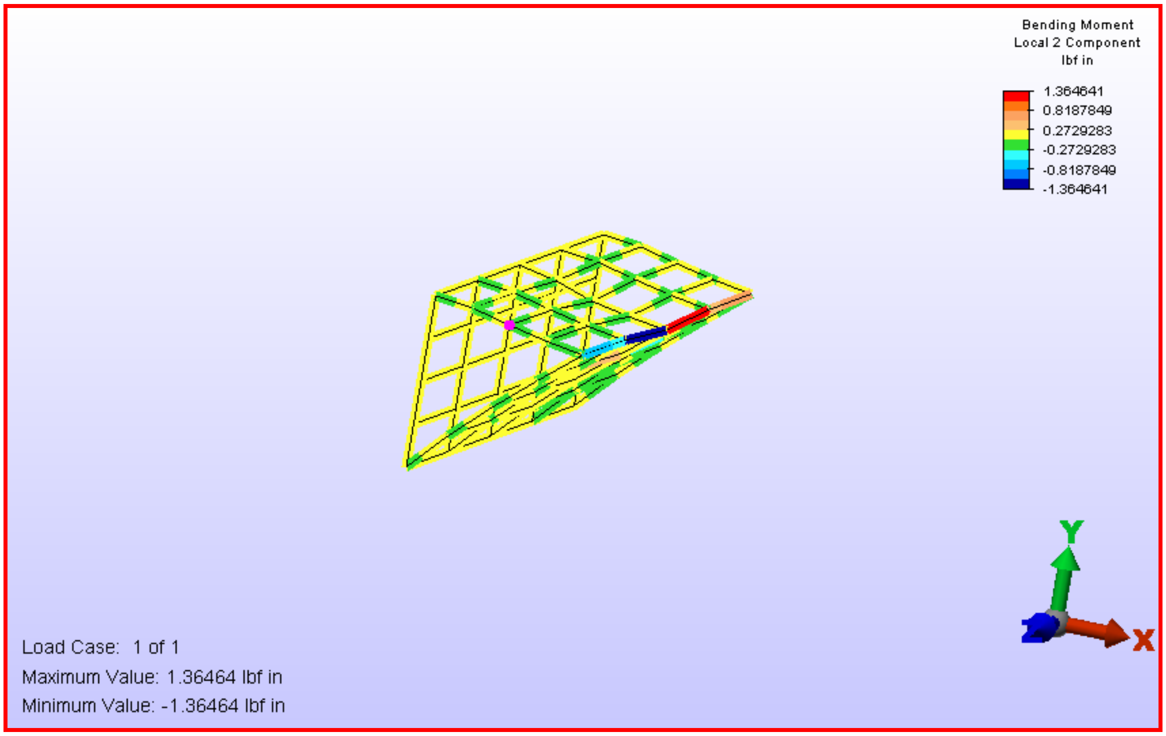


AFTER

BENDING MOMENT

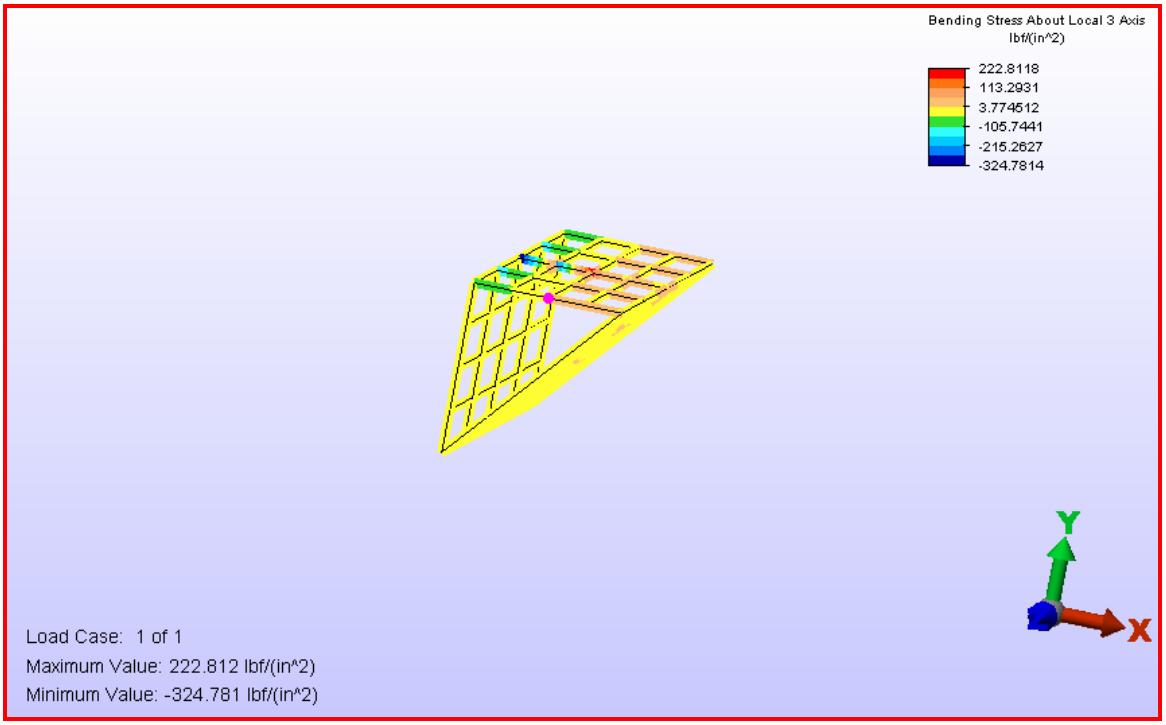


BEFORE

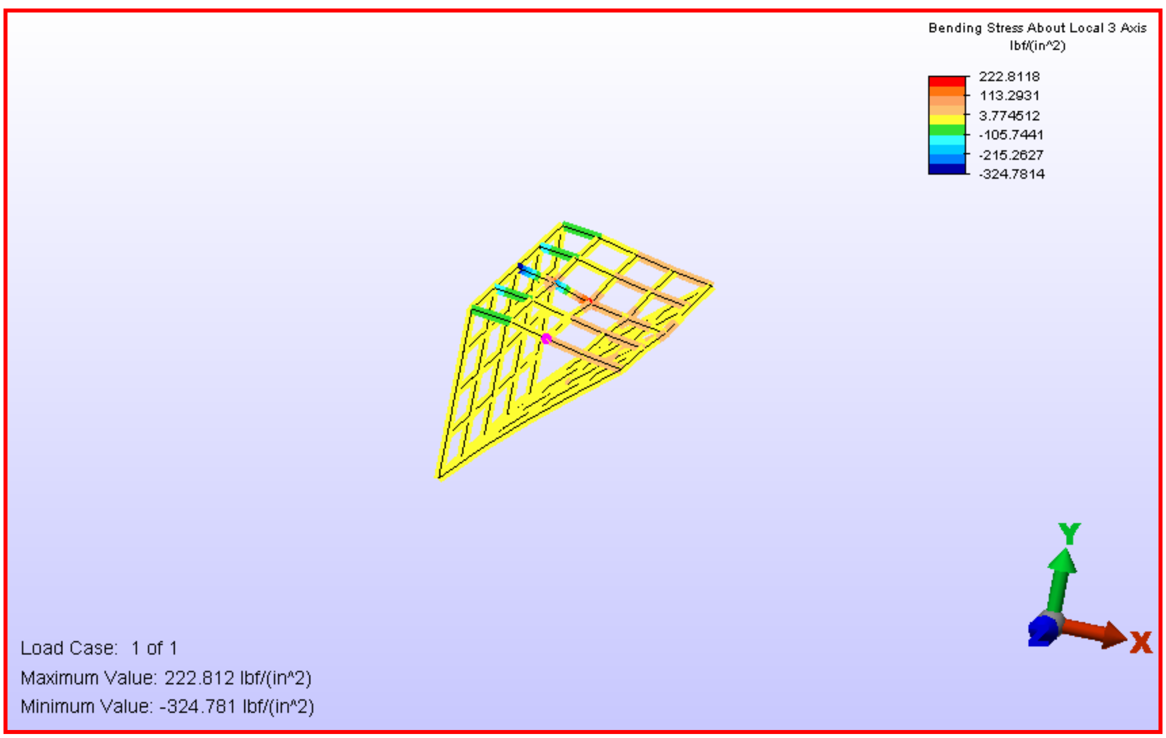


AFTER

BENDING STRESS

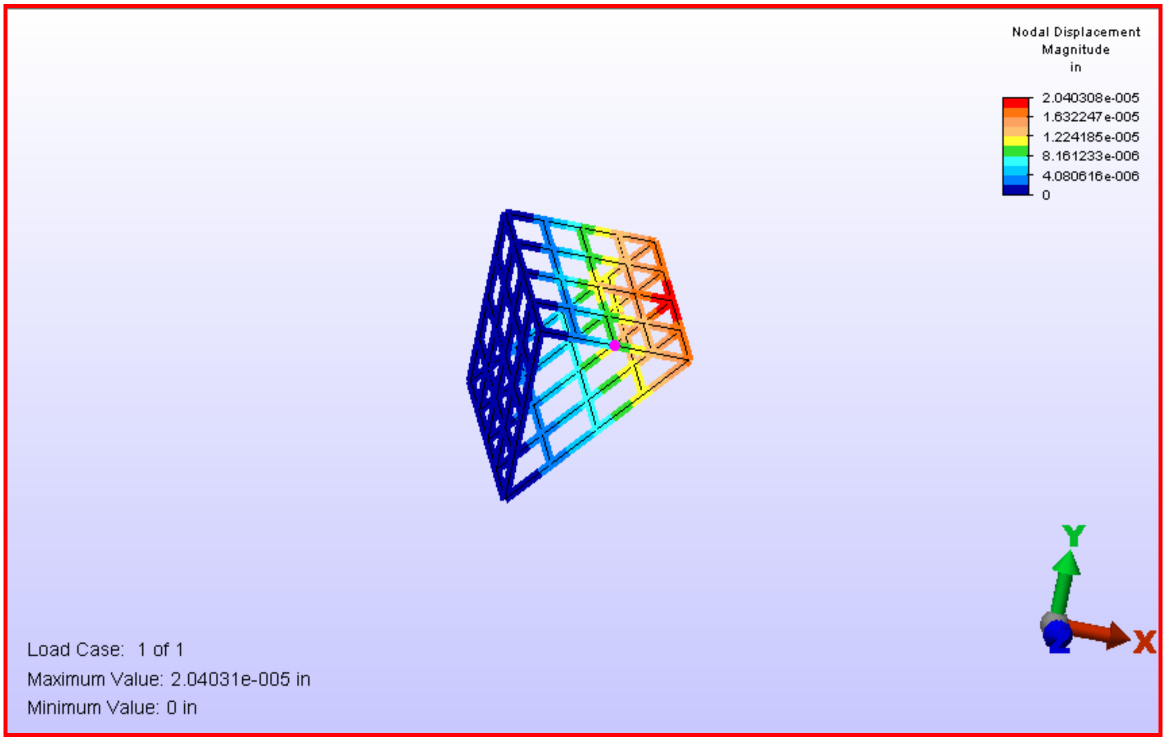


BEFORE

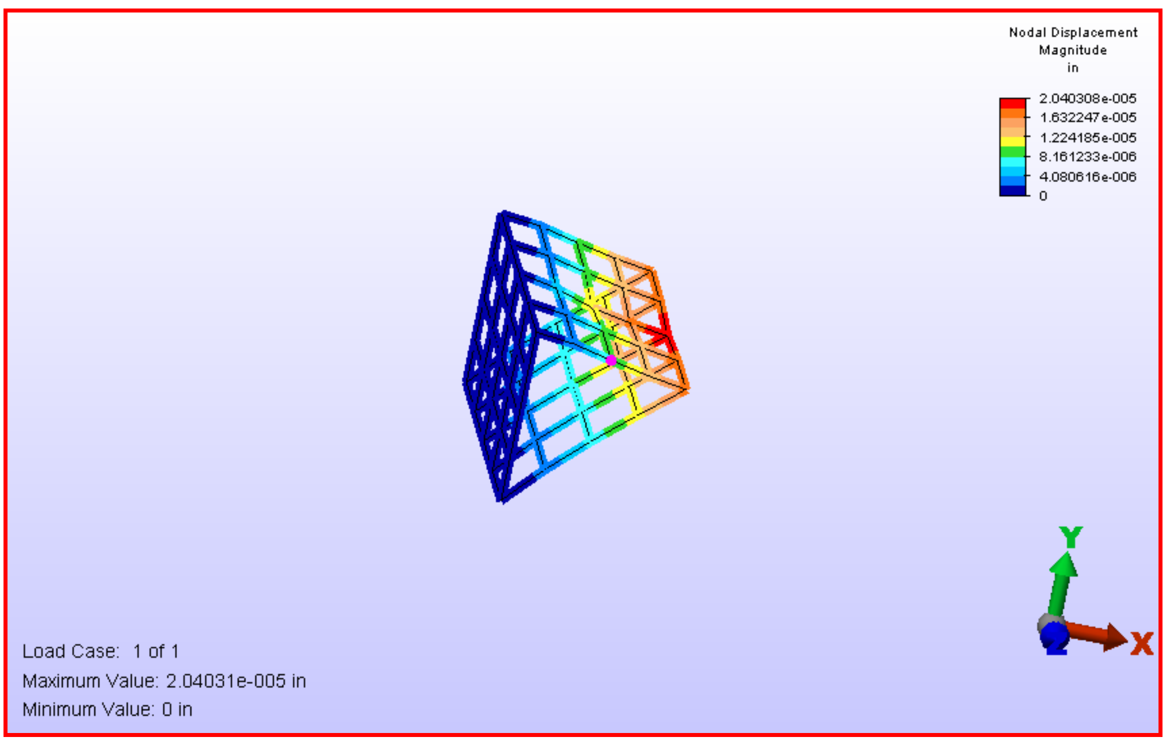


AFTER

DISPLACEMENT



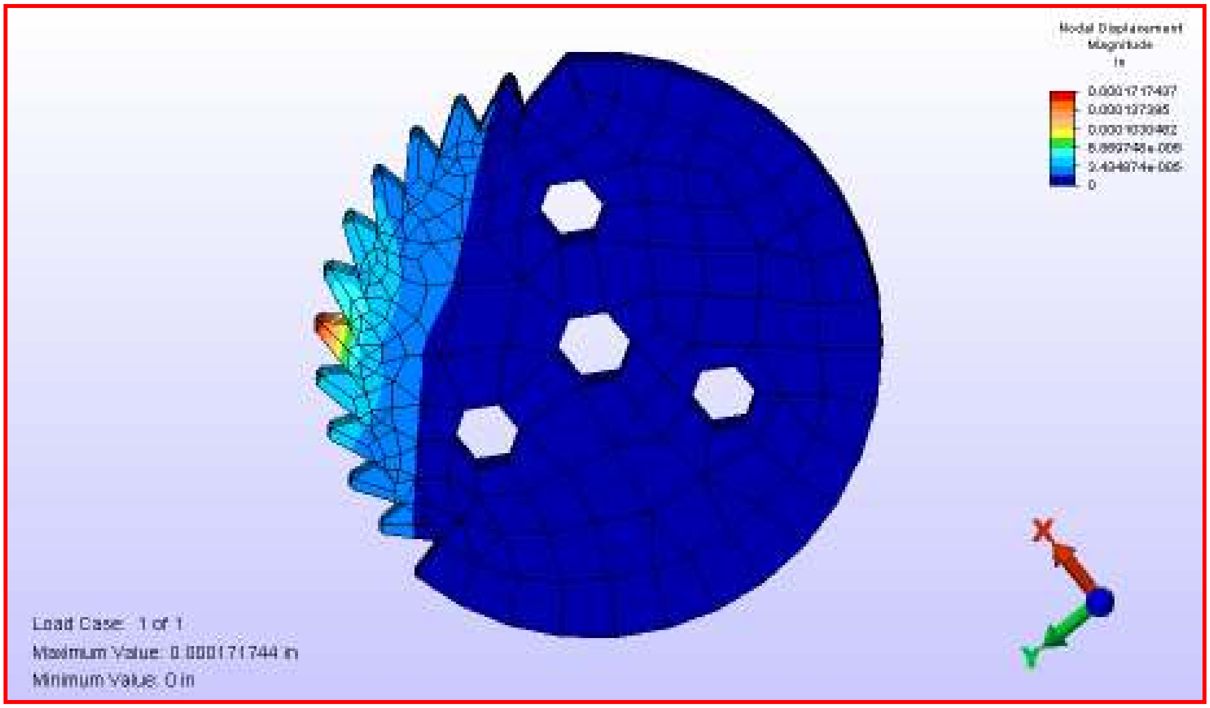
BEFORE



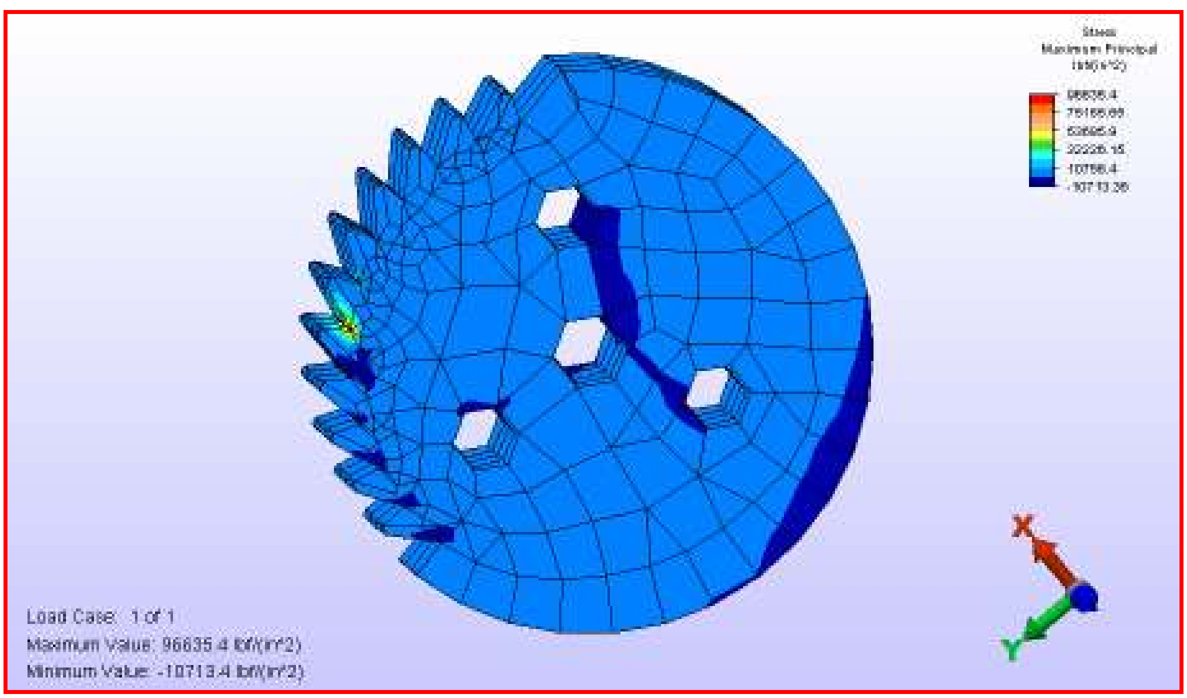
AFTER

ALGOR ANALYSIS OF ENTIRE GEAR

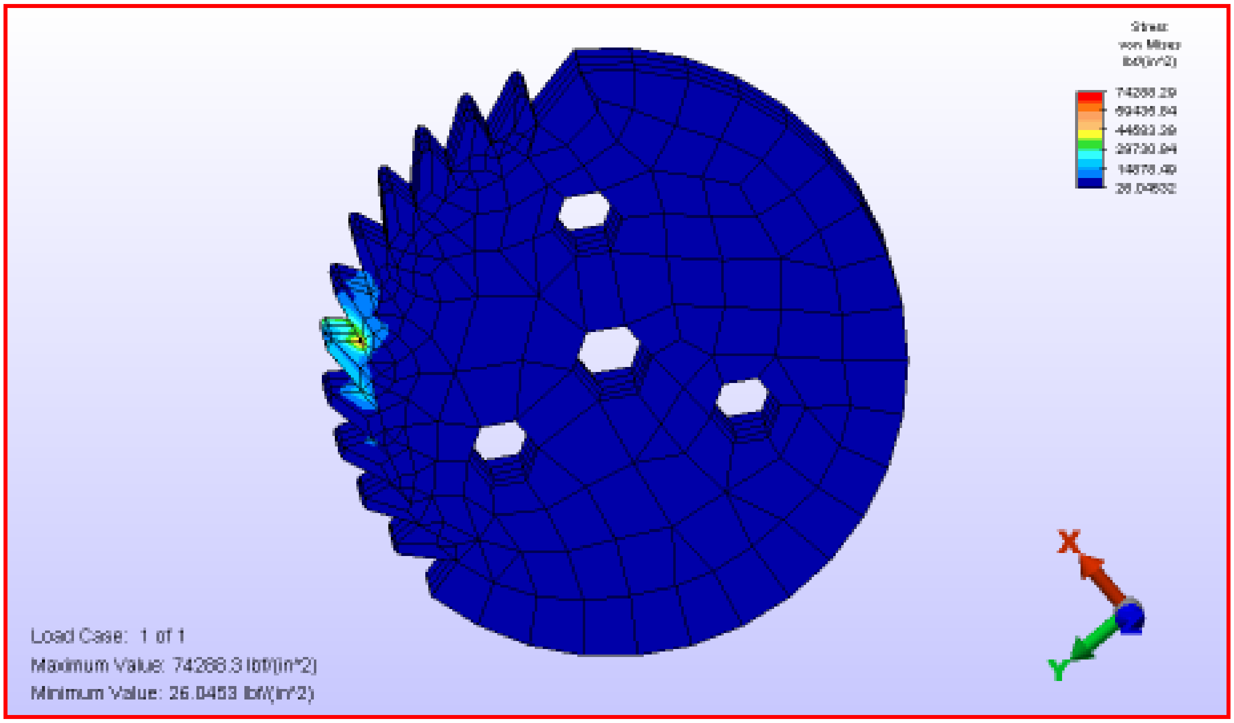
NODAL DISPLACEMENT



MAXIMUM PRINCIPLE STRESS



VON MISES STRESS



11.0 APPENDIX E:

MATHCAD STRESS ANALYSIS

Assuming a very thin cantileaver beam, with a height of 0.01 inches and a lenght of 0.07 inches.
The force is assumed as a point load acting at the center of the beam.

The material is 17-4 Stainless Steel HT 1150 degrees Faranheit.

$l := .07 \qquad a := .035 \qquad h := 0.01 \qquad tol := .000001 \qquad x := 0, .001 .. l$

Force in pounds: $F := 1416$ **Modulus of Elasticity:** $E := 27.5 \cdot 10^{6}$

Reaction Forces:

$R_1 := F$

$R_1 = 1.416 \times 10^{3}$

$M_1 := (R_1 \cdot l) - F \cdot (l - a)$

$M_1 = 49.56$

Moment of Inertia:

$I := \frac{1}{12} \cdot l \cdot h^{3}$

$I = 5.833 \times 10^{-9}$

$$step(x,a) := \begin{cases} 1 & \text{if } x \ge a \\ 0 & \text{otherwise} \end{cases}$$

$$ramp(x,a) := \begin{cases} (x - a) & \text{if } x \ge a \\ 0 & \text{otherwise} \end{cases}$$

$$para(x,a) := \begin{cases} (x - a)^{2} & \text{if } x \ge a \\ 0 & \text{otherwise} \end{cases}$$

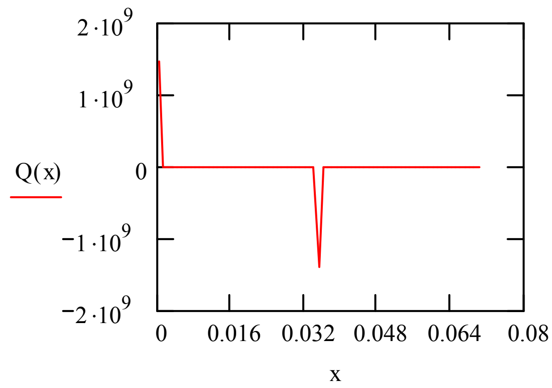
$$moment(x,a) := \begin{cases} \frac{1}{tol} & \text{if } |x - a| < tol \wedge x < a \\ \frac{-1}{tol} & \text{if } |x - a| < tol \wedge x \ge a \\ 0 & \text{otherwise} \end{cases}$$

$$pulse(x,a) := \begin{cases} \frac{1}{tol} & \text{if } |x - a| < tol \\ 0 & \text{otherwise} \end{cases}$$

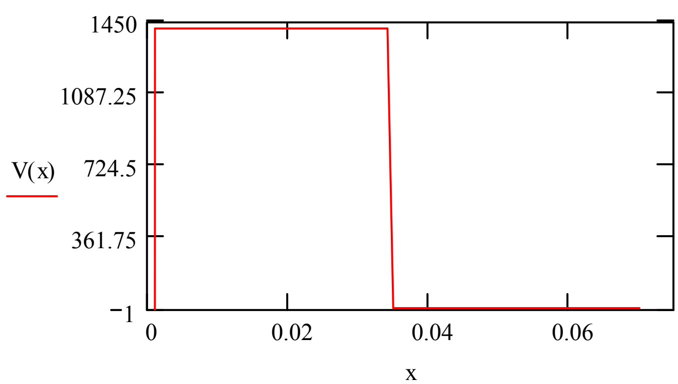
$$cubic(x,a) := \begin{cases} (x - a)^{3} & \text{if } x \ge a \\ 0 & \text{otherwise} \end{cases}$$

$$quad(x,a) := \begin{cases} (x - a)^{4} & \text{if } x \ge a \\ 0 & \text{otherwise} \end{cases}$$

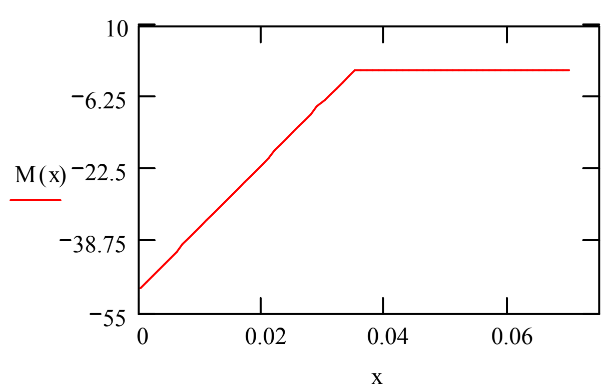
$Q(x) := R_1 \cdot pulse(x, 0) - F \cdot pulse(x, a) - M_1 \cdot moment(x, 0)$



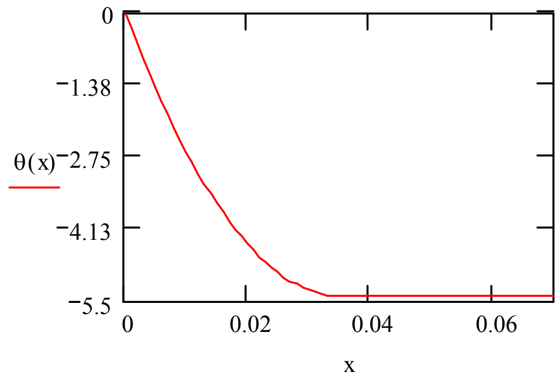
$V(x) := R_1 \cdot step(x, 0) - F \cdot step(x, a) - M_1 \cdot pulse(x, 0)$



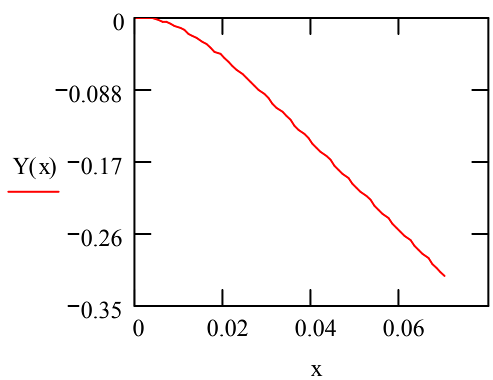
$M(x) := R_1 \cdot ramp(x, 0) - F \cdot ramp(x, a) - M_1 \cdot step(x, 0)$



$$\theta(x) := \frac{1}{E \cdot I} \cdot \left(\frac{R_1}{2} \cdot para(x,0) - \frac{F}{2} \cdot para(x,a) - M_1 \cdot ramp(x,0) \right)$$



$$Y(x) := \frac{1}{E \cdot I} \cdot \left[\left(\frac{R_1}{6} \cdot cubic(x,0) \right) - \left(\frac{F}{6} \cdot cubic(x,a) \right) - \frac{M_1}{2} \cdot para(x,0) \right]$$



$x := l$

Given

$x \geq 0 \qquad x \leq 0.07$

$V_{max} := \text{Maximize}(V, x)$

$V_{max} = 0.018 \qquad V(V_{max}) = 1.416\times 10^{3}$

Maximum shear stress

$V_{min} := \text{Minimize}(V, x)$

$V(V_{min}) = 0$

$M_{max} := \text{Maximize}(M, x)$

$M_{max} = 0.046 \qquad M(M_{max}) = 7.105\times 10^{-15}$ **Maximum Moment**

$M_{min} := \text{Minimize}(M, x)$

$M_{min} = 1.567\times 10^{-6} \qquad M(M_{min}) = -49.558$

$\theta_{max} := \theta(l)$

$\theta_{max} = -5.407$

Maximum slope

$$Y_{max} := \frac{F \cdot (a^2)}{6 \cdot E \cdot I} \cdot (a - 3l)$$

$Y_{max} = -0.315$ **Maximum deflection**

$M_1 := 7.105\times 10^{-15} \cdot lb \cdot in \qquad c := 0.005 \cdot in \qquad I := 5.833 \cdot 10^{-9} \cdot in^4$

$$\sigma_{max} := \frac{M_1 \cdot c}{I}$$

$\sigma_{max} = 6.09\times 10^{-9} \frac{lb}{in^2}$ **Maximum bending stress**

12.0 APPENDIX F:

PROJECT DELIVERABLES

Team Fillauer's Procedures

1. The Fillauer team, composed of four members, meets at least twice a week:

    - Organize activities and plans we have been tasked to perform and produce.
    - If a team member cannot show to a team meeting, the other team members need to be aware of his/her absence in advance.
    - If a member cannot make it to a team meeting, where a deliverable is to be completed, the rest of the team members will take initiative and responsibility in completing that particular assignment.
    - If possible, the team will accommodate (change meeting time) in the absence of a team member, in order to achieve 100% attendance, input, and cooperation of all team members.

2. Contacting the project sponsor (Daniel Buck):

    - Two team members (Giselle Rojas and Donna Wright) are designated to contact the project sponsor in the case of any modifications to the schedule via e-mail or phone.
    - The entire team is to be present during all teleconferences with the project sponsor, to ensure all questions/concerns are addressed and resolved during that particular teleconference.
    - The Fillauer team is to speak with the sponsor at least once every week to report any progress the team has undergone.
    - Teleconferences are all held in the Mechanical Engineering office.
    - Immediately following every teleconference, Donna Wright is responsible for signing the team up for the next teleconference on the sign-up sheet provided by the ME office.

3. The project schedule:

    - The scheduled tasks have been strategically laid out using Microsoft Project, in order to organize future activities, meeting, and steps that need to be followed in order to obtain the desired goals and meet all required deadlines.
    - Milestones have been put in place for all document deadlines as well as presentations. All documents are to be turned in to the class instructor overseeing the team procedures and performance.
    - All teleconferences, staff meetings, and team meetings have been documented and are to be followed to the best of the team's abilities.

4. Saving Data/Documents:

    - All team members are responsible for saving any documents pertaining to the project on their Engineering accounts under a folder labeled "Senior Design Documents".
    - All documents will be e-mailed to every team member, in order for all members to have access to all documents.
    - During all teleconferences, one team member (a different member for each meeting) will be responsible for recording any vital information given by sponsor, as well as documenting the main topic of that particular meeting.

5. Write-ups and Deliverables:

    - No one particular group member is designated to generate all write-ups.

- Write-ups will be disbursed among entire group.
- Write-ups and deliverables will be done during team meetings, and at that time the group will decide who will type up that particular document. However, the input of every team member is required at that time.
- Giselle Rojas is responsible for printing out all cover pages. Printing of all other documents will be dispersed among all group members.

6. Presentations:

- Will be prepared by the team, in its entirety, to average about 15 minutes in length.
- Every team member will contribute in the generation of the power point presentation.
- Every team member will also orally present a portion of the presentation.
- Presentations will be done during team meeting.
- Power Point Presentations will be completed at least two days in advance of due date, to allow team to have mock presentations and ensure all necessary information is included in the presentation.

The team works in an environment of mutual respect where each member can express his or her ideas freely, without any fear of being criticized or judged. The document that contains the expected behavior of team members is the code of conduct. Each team member is expected to abide by all rules stated in the code of conduct.

Project Scope

Problem Definition:

Fillauer, a leading manufacture of prosthetics and orthotics in the world, would like an incremental motion orthotic knee joint. This medical device helps patients with conditions such as Post Polio, Spinal Cord Injuries, Cerebral Palsy, and Multiple Sclerosis. This device is on the company's priority list, and therefore the goal is to have a device ready for patient trials by the end of the senior design project.

Background Info/Research:

1. Medical conditions that may cause a need for this type of device.
    a. Post Polio Syndrome
    b. Spinal cord injury
    c. Cerebral Palsy
    d. Multiple Sclerosis
    e. Quadriceps weakness caused by a variety of neurological conditions

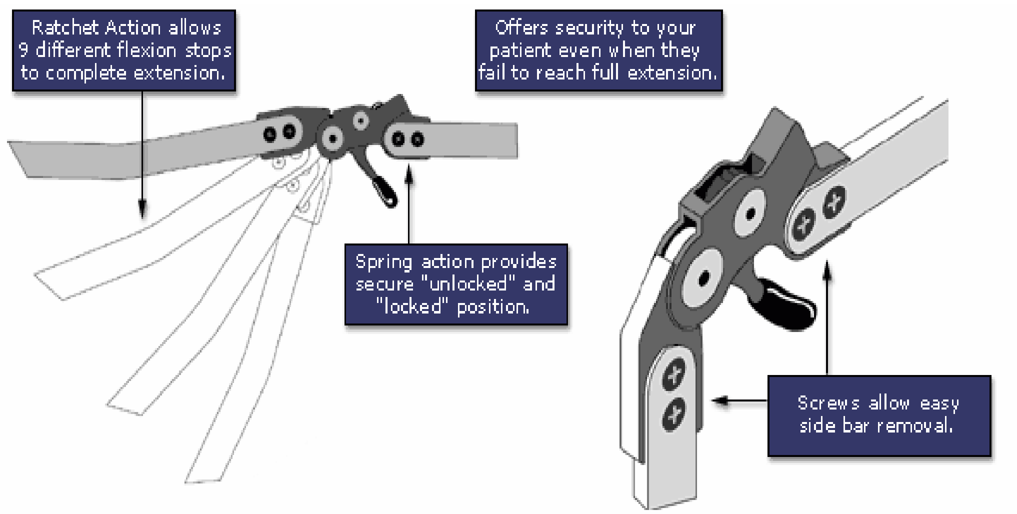
2. Competitor products & problems
    a. OTS (Step Lock)
        1. Teeth break
        2. Hard to unlock under load (may not be necessary)
        3. Price $100 (includes Aluminum upright bars)
        4. Increments every 10deg, has 9 locking positions.
        5. 135deg of flexion.
        6. 5 sizes available.
    b. Becker (Ratchet Lock Model 1014)
        1. Problems not known, only on market for a year
        2. Price $100 (includes Aluminum upright bars)

Project Outcome:

1. Expectations of designers.
    a. Once several concepts are explored Fillauer would like to discuss the most promising concepts and possibly prototype two designs.
    b. Ideally a second iteration could be fully developed to have a prototype for the students' final presentation.
    c. A joint that is cost effective under the expected volumes.
    d. By the end of the project would like to start patient trials (Fillauer will do this as well as produce the necessary quantities).
    e. Meet discussed deadlines so parts can be scheduled with R&D machinist.
    f. Work with marketing to assist in developing a name and package for new device (this will be done through the engineer assigned to this project).

2. Expectations of Fillauer
    a. Provide continuous feed back.
    b. Provide necessary materials and or machining at Fillauer.
    c. Provide competitor products.

Ratchet Knee Joint: Incremental motion



InterLock Knee Joint

Placement Illustration of Knee Joint

Becker Orthopedic 9000 Series Knee Joint

Needs Assessment

The need specified in this project is to **design, develop and test an incremental motion orthotic knee joint**. The incremental knee joint will function in a capacity to aid its users suffering terminal ailments with respect to standing, walking and other functions that are related with movements of the knees/legs. The existing knee joints on the market all have certain problems that our design will address:

a. A design of the joint that allows for locking positions ranging from users having their leg fully extended at 0° to -135° when fully bent backwards; IMPORTANT

b. May be set to a free motion joint; CRITICAL

c. Ensure that the joint will interface with all existing Fillauer "King-Pin Bars"; CRITICAL

d. Ensure that the chosen materials used in the design conform to all pricing guidelines which include a 40^{00} ceiling on the joint; IMPORTANT

e. Conform to ISO standards: ISO/TC 168/WG 3; CRITICAL

f. Stable enough so that it will handle the weights of its users when they are transitioning from the seated position to the standing position. TRIVIAL

Product Specifications

a. Should allow free motion joint settings.
b. Interchangeable with the L/XL KingPin Lock.
c. Can attach a bail rod or trigger release to mechanism.
d. Needs to accept all KingPin bars.
e. Needs to withstand a moment of 80 Nm on test machine for 1 million cycles.
f. Needs to withstand a moment of 12 Nm medial laterally for 1 million cycles.
g. Manufacturing price target $40 for just the joint.
h. Quantity per year 500 joints.
i. Range of motion from straight (Zero degrees) to minus 110degress; would like 130deg.
j. Maximum increments 15 degrees; would like 10degree increments
k. May have an infinite number of locking positions.
l. Conform to ISO standards: ISO/TC 168/WG 3
m. No weight limits identified, however weight will be taken into consideration when designing knee joint.
n. Steel/Aluminum material

12.0 APPENDIX G:

<u>OPERATIONS MANUAL</u>