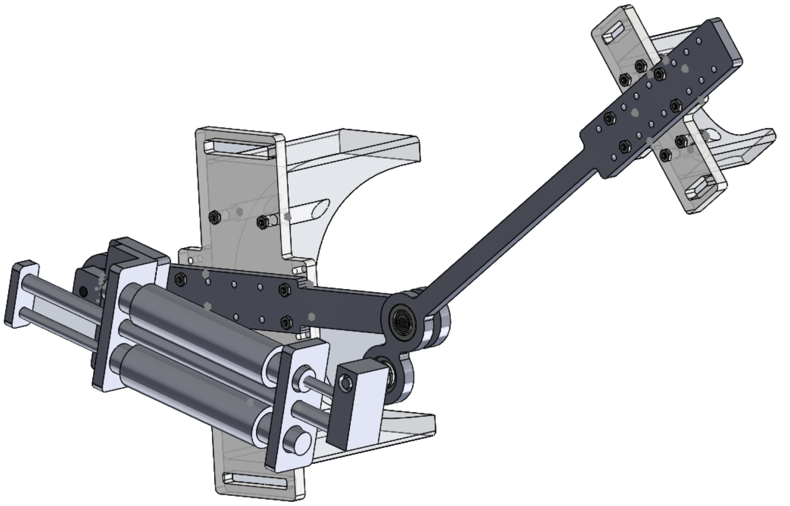
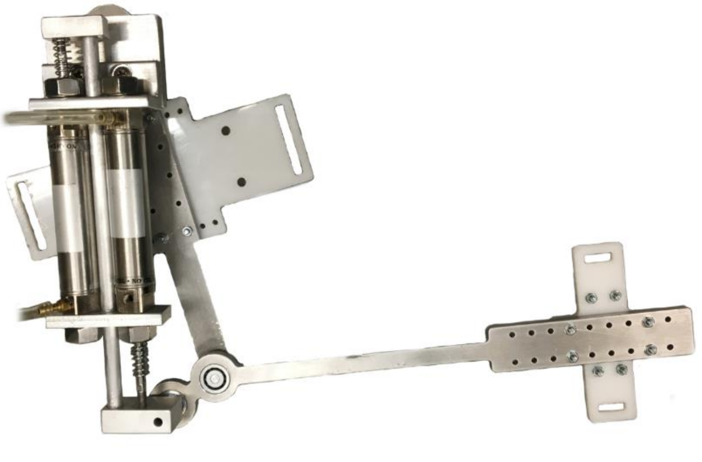
Final Report





Team 24: “Robo-Bros”.
Yechan Kim, JangWon Ko, Ronnie Trower, Zhentao Xu

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EXECUTIVE SUMMARY

Our team has been tasked to design and fabricate a wearable robotic device to be used for upper limb rehabilitation by stroke survivors who are struggling with paralysis in their arm. Initially, our team focused on a soft material robotic design that would be worn by the user, and specifically, function as an assistive device to move the user's arm from the fully flexed position to the fully extended position. However, after a change in priorities from our sponsors, we had to revamp our mock-up design utilizing "soft" (balloon) actuators from DR2 to a backdrivable actuator design composed of pneumatic cylinders. Additionally, only single-acting actuators could be used to achieve both motions (extension and flexion) of the arm. Our team conceptualized numerous iterations of potential prototypes. After many alternations in our design due to selections of different materials to use, number of actuators needed, decisions on location of these actuators, and optimization of the wearability and maintaining structural integrity of the device, we have fully manufactured a functional prototype. The design is composed of two pneumatic cylinders fixed on the outside of the arm, a two bar linkage which transfers the power generated from actuators, and silicone moldings which will cup around the biceps and wrists to ensure comfortability and stability. After fully assembly, our team validated many of the given target values from the beginning of the semester. Namely, our prototype is capable of producing ample forces needed to actuate the arm, it meets all the weight/volume/price requirements, and has a quick operation time. Having completed the first prototype, if continued there are many areas to improve this design. We could reduce weight, decrease friction in the design, and re-engineer the rigid components to have a more flexible and optimally functioning device.

PROBLEM DESCRIPTION AND BACKGROUND

Approximately 800,000 people suffer from a stroke each year, and more than 140,000 people die as a result [1]. The most common type of stroke is an ischemic stroke, which accounts for 80 percent of occurrences, and it commonly leads to a disability of a part of the body, called paralysis, due to unstable connection between the brain and muscular system. Statistically, 9 out of 10 patients who survive from strokes experience paralysis [2]. If the patient experiences paralysis, physical therapy is needed for recovery and these rehabilitative measures can require long and intensive effort to relearn and regain their ability of physical movement and coordination.

Studies confirm that robotic assistive trainings can be more effective than conventional therapy. One study [4] showed that after 6 months, patients with the robotic devices had an increase in kinematic movement of 5% over the conventional therapeutic group and a 30% bigger gain of strength. Another benefit is the larger motivation with the robotic devices that the patients using robotic devices had higher attention and motivation levels, expediting motor control recovery within the same amount. Conclusively, compared with conventional therapy techniques, robot-assisted rehabilitation processes have advantages of not only in biomechanical measures but also in terms of clinical measures.

Exoskeleton technology has become an emerging field of engineering to not only augment human capabilities, but in rehabilitative settings as well. Our team was tasked to design a wearable and therapeutic robotic device that can assist the patient's arm movement from a fully flexed position to the fully extended position and vice versa.

Background

Our team is tasked with creating a wearable, therapeutic robotic device. Though studies are rather inconclusive as to confirming whether or not robotic assistive devices are more beneficial than conventional therapy, results still remain promising in this growing field of research. It has been seen that in UE rehabilitations, robotic devices hold a greater chance of improving recovery, than conventional methods [4-6]. One study [4] showed that after 6 months, patients with the robotic devices had an increase in kinematic movement of 5% over the control conventional therapeutic group. In addition, the robotic therapeutic group had a 30% bigger gain of strength.

Another added benefit that has been tested is motivation with the robotic devices [5]. This study showed that patients using therapeutic robotic devices had higher attention and motivation levels. This increased encouragement allowed for longer exercise periods on a regular basis, and thus led to increase motor control recovery within the same amount of time as another control group without robotic devices.

Conclusively, compared with conventional therapy technique, robot-assisted rehabilitation process seem to hold advantages of not only in terms of biomechanical measures, as in relearning the physical movement, but also in terms of clinical measures, such as patients' motivation and encouragement levels. Thus, has emerged the field of exoskeleton technology to not only augment human capabilities, but in rehabilitative settings as well.

Benchmarks

Due to the advantages of robot-assisted rehabilitation process, many research teams around the world have been working on developing better robotics rehabilitation devices for those who are suffering from paralysis after stroke. There are many possible solutions: one solution is to use electrical motor to assist the motion of human arm, and another solution is to use the expanding property of "balloon" to enforce the movement of arm.

1. Titan Arm:

One example of an UE exoskeleton device used in the fields of rehabilitation and therapeutic is, Titan Arm, which was designed by students at the University of Pennsylvania [7]. It is a 20 lbs wearable device powered by electrical motor, and it consists of two parts: 1) back-pack part and 2) rigid arm structure. The back-pack part, which includes motor, battery, and gears, is packed in a backpack. Two cables are used to connect the motor and rigid arm structure in order to transfer power from motor to arm structure and eventually to the patient's limb. The motion of the arm structure of Titan Arm is controlled by using joystick which patients can control with their unimpaired arm to control the impaired arm.

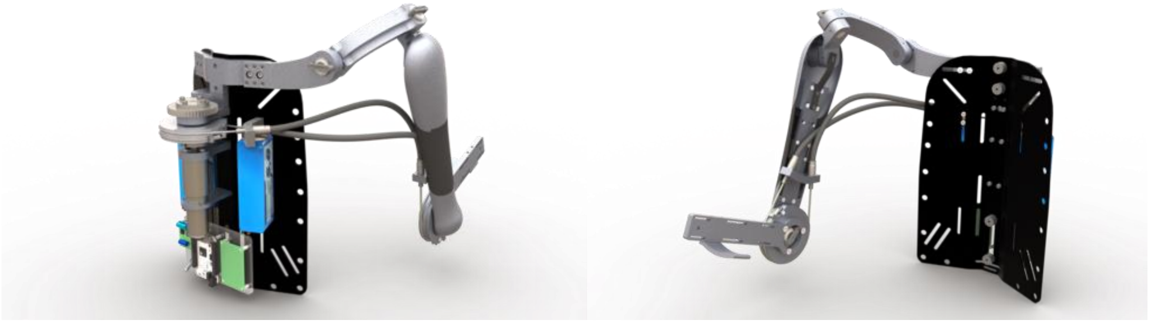


Figure 1: Titan Arm [7]

The possible advantages that can be found from this device are easiness of control, broad capability of work, and appearance. On the other hand, there are downside aspects that need to be improved. For example, the weight of this devices is approximately 20 lbs, which might be heavy for the stroke patients, most of whom are ages over 65 [8]. Considering the stroke patients' average age and their physical conditions, it might not be appropriate for them to bear such heavy load of 20 lbs for a long time. In addition, the price of this devices can be improved. The manufacturing cost of the Titan Arm is around $2,000. This price might not be considered expensive to most of the patients who need the device to have a "normal" life. Nevertheless, it would be better if the price can be reduced without affecting the functionality and taking advantages of other actuating mechanisms.

2. Soft robotics rehabilitation devices:

Soft robotics is a new field of robotics engineering. The main concept is to replace the conventional rigid components of the robot to soft and flexible material in order to take advantages of movement in very limited spaces, which allows easy change in the gait [9]. Due to this possible beneficial aspects, soft robotics rehabilitation technology receive attention from people around the world and become emerging field of engineering.

An example patent that uses the technology of soft robotics, is Wearable U-shaped Limb Power-assisted Airbag as seen in Fig. 2. This device consists of an airbag, which works as an actuator. There are three straps for installation on the body and a nozzle to inflate air [10]. Before inflated, the shape of the airbag is flexible, providing no force to user's elbow. However, when inflated, the airbag will have a large increase in its volume and provide force to the elbow, pushing the elbow inward along the horizontal plane. Therefore, the arm will be fully extended.

Compared to the Titan Arm, a noticeable advantage of this device is its lightweight. Due to its simple structure and use of lightweight material, it is far more portable and easy to use on a daily basis. Also, because of its relatively simple structure, the price must be significantly lower compared to other electrical devices. On the other hand, the possible disadvantage is its limitation of backdrivability. In other words, the applications of this device on the human body is limited, since the inflation of the balloon can only provide push force to generate extensive motion but not the pulling force to assist flexing motion.

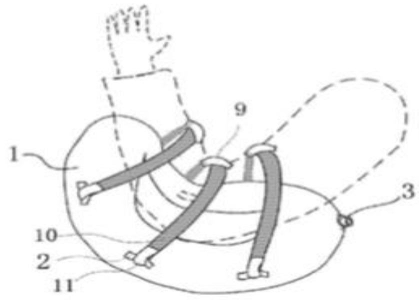


Figure 2: Wearable U-shaped Limb Power-assisted Airbag [9]

3. Other exoskeleton rehabilitation devices:

Apart from motor driven and soft robotics, we also found other exoskeleton rehabilitation devices aimed in assisting the movement of limbs [11-14], such as Flexible exoskeleton elbow joint based on pneumatic muscles [11], Device for assisting the motion of a limb [12], Wearable device to assist with the movement of limbs [13, 14].

USER REQUIREMENTS & ENGINEERING SPECS

Beyond our product design to simply function well, our final design needs to meet goals that are set and desired by the end-users, our sponsor, and our team. Our group has not yet been in touch with a possible end-user of such a device that we aim to create. However, we and our sponsor have created a prioritized list of wants for the user as well as the engineering specifications that we will need to abide by as seen in Fig. A (pg.23), which shows our quality function deployment of our product.

User Requirements

In designing our device for the end-users, our team must understand that there are more desires from the device than simply functionality. The most important criterion is a wearable device that is safe. In case our design uses a form of a mechatronics system, our electronics must be all housed. It would be uncomfortable for the end user if there were loose wires or incorrect circuiting that could cause failure and combustion of parts. Next, the ergonomics of our device is all-important. To have comfortability for the user, while maintaining stability on the arm is highly desirable [3]. If any significant slipping of the device occurs along the arm, then proper extension and functionality will be suffered for the user. Another factor that must always be considered for most of our parameters, is the demographic of our end-users. Those that have had a stroke are typically advanced in age, between 55-85 years old [1]. This increases the importance that our team must place on the factors such as weight, ease of use of the device, and portability. Devices like the Titan Arm are close to 20 lbs [7], and this kind of weight is far too much for the aim of our device. Furthermore, our device’s technology should not be too complicated for everyday use by the average senior citizen. Thus, our team will need to strive for an easy user-to-technology interface to help aid in the operation of the product.

User Wants:

Our team wishes to achieve the maximum number of goals set by our sponsor, but prioritization of these goals is also important when creating our design. Other aspects that our sponsor and we believe would be good to achieve, but not necessarily “must-haves” for our design, include affordability, noise levels, and weight/volume. Our product would be supplied in the medical field, thus, its final price not determined by us. We can consider the price of the raw materials that we will be using, but the final price tag will be inestimable. Another parameter to keep in mind is the noise levels, because we know that this device will be used in a home, daily. However our team’s greater priorities lie with the functionality of the device, as opposed to the noise levels generated from inflation of device or working motor mechanisms. Furthermore about functionality, our team is tasked with creating a one-way extension path for the arm as seen in Fig. 3 since the arm of a stroke patient automatically contracts when the arm is raised. It would be desired to have backdrivability, so that the forearm could easily be mechanically retracted back with our device. However, this requirement may be too advanced of a design to create within such a short time span for prototyping and manufacturing [3].

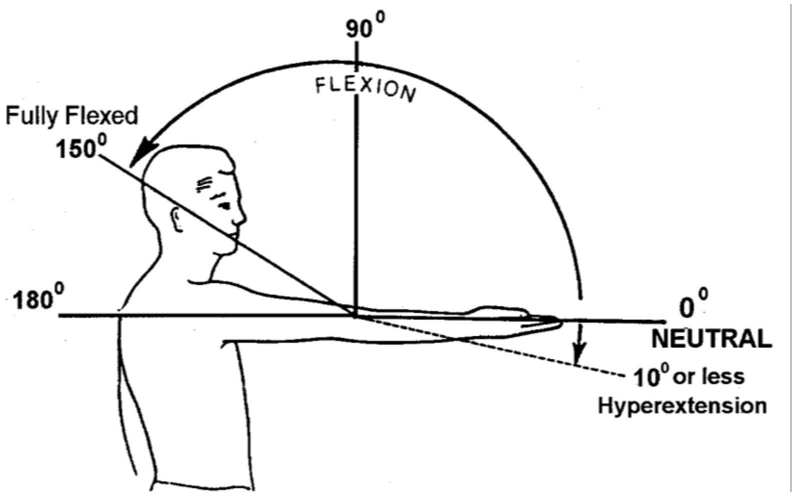


Figure 3: Extension Motion of Arm [15]

Engineering Specifications

Life Cycle:
Our sponsor suggested that the device should be able to operate "at least three years." The wearable device will be used on a daily basis for rehabilitative purposes. Due to its high volume of the number of times one may need to outreach his or her arm, our team estimated that a high number of cycles should be achieved in addition to practicing this movement to regain motor control. Estimating that stroke patients were to extend their arms about 250 times a day at most, it was decided that the life cycle must be bigger than 300,000 cycles. Although it came out to be 273,750 cycles, if a patient were to utilize the device 250 cycles a day for three years, we rounded up to 300,000 cycles considering some safety factors.

Operation Time:
When we were considering about operation time for one cycle, our group and the sponsor came up to an agreement that overwhelming fast response of the device might be dangerous for the end users. This rapidness of operation may harm the objects around the users and users themselves unexpectedly. For example, the quick movement of the device may not give a user enough time to move away from an object when the user were to extend his or her arm to reach it without considering the right range. This smash against the object would damage the already impaired arm. Since we do not want such situation, we did not want the operation time to be too short. Therefore, our sponsors and we concluded that about three seconds should be right fit for a cycle. This will be enough time to reach to the right target safely.

Volume:
Our product will be used in daily basis, and it will be placed near the user even if it is not in use. Thus, the volume of the device is important. We do not want our device to be big enough to become a burden to carry around by user. Our sponsor told us that the device should fit into a shoebox in order to prevent such situation. The United States Postal Service (USPS) lists

shoebox with size of 7-1/2” x 5-1/8” x 14-3/8” [17]. Therefore, our device shall fit into the particular shoebox.

Roughness:

One of the user requirements that was suggested by our sponsor was being comfortable. We found that the human comfort is directly related to temperature and humidity of the skin [18]. Generally, the optimum condition is the combination that allows moisture to evaporate from the body at a rate at which maintains ideal body temperature. It suggested that silicon might be the best material to wear on skin without discomfort. According to the article “Materials matter in wearable medical devices” by Norbert Sparrow, fiber-reinforced liquid silicone rubber (LSR) is the prime candidate for wearable devices [19]. Through profound research regarding LSR, we decided our device to have a roughness around 50 Shore A silicone durometer measure, which is equivalent to the roughness of pencil eraser. The Shore A scale measures the hardness of flexible mold rubbers that range in hardness from very soft and flexible, to medium and somewhat flexible, to hard with almost no flexibility at all [20].

Moment Generated:

It is common for people to have suffered from ischemic strokes to experience paralysis of a limb. To rehabilitate the extension of an arm about the elbow, our device will be subjected to a moment of inertia. Furthermore, to aid as many people as we can, we have calculated our needed forces for up to the 70th percentile “largest” American. Utilizing BMI index as an indirect method for determining the weight of the arm [26,27], we accounted for an approximate weight of 230lb and 6’ 1”. Furthermore, our device will only be translating the forearm and hand of the end-user. This weight accounts for 2-2.5% of total body weight [25]. Combining these fractional lengths and weights, a good estimate of where the center of mass is on our largest demographic of end-user puts us at a length of 0.38-0.43ft. Thus, requiring a minimum of 2.5 ft. lb. of moment. This moment should be sufficient to assist full extension and flexion of an arm that produces little to or no resistance to the device.

Material Strength:

The majority of our design process will be prototyping and experimenting with an array of materials. At this stage we do not know what kind of material our wearable device will take. If our team decides on a more rigid structure by using motors and mechatronics, there will be some event we take the design route of soft robotics, we will experience with variety of materials such as a silicon and plastic polymers. Other products we have researched, and what other members of our own team have researched already, have discovered that these types of materials work optimal [3,19]. Likewise, form of padding that makes contact with the skin between the user and the metal (most likely aluminum) frames. Although our planned design materials are unknown, we must ensure that the design will be able to complete many cycles while comfortably holding its physical integrity.

Power Consumption:

Similarly to material strengths, our team has yet confirmed whether or not we will be using some electronics besides using pneumatics. To achieve the arm extension motion, we have options for how the device will transfer energy. It could be in the form of mechanical (body-powered) energy – fluid – back to mechanical energy. This instance would be if the healthy arm was powering an inflation device that would then extend the impaired arm. As with the Titan Arm, they used LiPo (lithium polymer ion) batteries. These batteries are rechargeable and can last up to 8 hours [7], which would sufficient as well for our device, but we are not to the stage to estimate the conversions of such energies.

CONCEPT GENERATION

After our team created a functional decomposition for our robotic device, our team members set out individually to brainstorm concepts that both performed the desirable functionality and met our engineering specifications. The use of the functional decomposition as a guideline and utilizing the SCAMPER and TRIZ methods to aid in our further exploration of possible concepts, provided the means for our team to create approximately 21 unique concepts. An important aspect of our project is to decide on and create an actuator that performs the functionality of extending the user's arm, while simultaneously being a wearable device that is comfortable for the user. Finding a perfect balance of just these two parameters was indeed a challenge and ultimately required our team to explore numerous options for the form of the actuator should take and how to orient these devices. Our team divided up our designs based on the type of actuator which was utilized for that concept and these categories can be read below.

Category 1: "Balloon" Actuator

Figure 4: Soft Robotics Actuator

The balloon actuators behave, in essence, the same as your everyday party balloon. However, in most of these designs the use of straps around the arm and balloon, or orientation of the balloons in a sleeve, produce a moment around the elbow. By using an external power source (potentially an air compressor) and linking a hose connecting the pump to the inside of the balloons, the fluid is used to inflate the balloons, thus transferring mechanical energy to any surrounding objects of the balloon. The different form of concepts in this category vary with the orientation of the actuators, number of actuators, and the rigging system used to mount the actuators on the arm.

One design among the balloon category is shown in Fig. 4. In this design, an air bag (which takes the shape of a rectangle when fully inflated) is mounted via straps onto the inner surface of the elbow. A nozzle on the airbag is connected to an air pump. When inflated, the now-V-shaped air bag will take its rectangular form, thus forcing the arm to extend.

This category has its own unique and outstanding advantages. Firstly, the lightweightness of air in a virtually weightless actuator provides both comfort to the user, while remaining intuitive for use. Also, because of how compact these designs can be, this kind of actuator is quite portable and wearable. One disadvantage however, when compared to electrical motors, is that soft robotics have greater difficulty with generating large forces or moments, which might limit the application of these devices. Also, due to the complexity with fluid mechanics and the novelty of soft robotics field, there will be difficulties calculating the forces necessary to generate the required moments and obtaining a material that can remain structurally sound in these unique geometries.

Category 2: Piston-cylinder

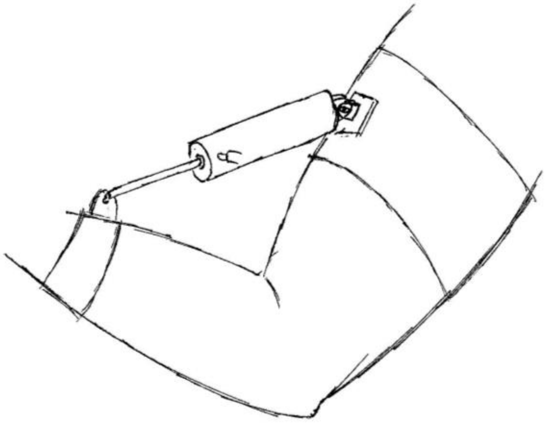


Figure 5: Pneumatic Actuator

The piston-cylinder category uses the property of pistons to assist the motion of arm. When air is inflated into the cylinder, the piston can transfer the linear motion generated by air pressure. We can take the advantage of this energy conversion process, assisted with other mechanical structure to make the actuator. Even within the piston-cylinder category there are variances in the type of pistons that would be utilized. There are possibilities to take the route of hydraulics or pneumatics.

One design among the piston-cylinder category is shown in Fig. 5. In this design, a piston has its two ends connected to the forearm and upper arm. As the air pressure inside the cylinder increases, the piston will move outward, and the arm will therefore be extended. This is the basica design of the piston-cylinder concepts.

The primary advantage of piston and cylinder is that it can sufficiently transfer force to generate a moment on the arm as long as the pressure is large enough.
On other hand, the piston and cylinder poses a greater weight to the device. Since the cylinder and piston are made out of rigid materials, such as metal, plastic, and glass, the weight is generally higher than other soft materials, such as silicone, fiber, and foams. Thus, due to its material used, the high weight makes this design not suitable for rehabilitation purposes. Another disadvantage is that, since piston-cylinder are made of hard material, it is possible for the end users to feel uncomfortable when it contact with their skin. In addition, due to the inflexibility of the cylinder and piston actuators, they may limit the motion of the arm and degrees of freedom for the end-user.

Category 3: String-servo motor actuators

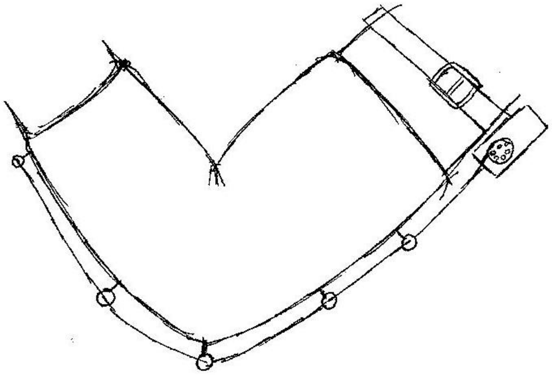


Figure 6: Stringed Actuator

The string-servomotor category uses servomotors and strings to convert and transfer energy. In this category, we use strings or wires to transfer power because of the flexibility they possess. The tension in the strings will pull the arm to the extended position after being wounded up into the servomotor housing unit. To some extent, the use of strings, like fibers in muscles, exhibit biomimicry and are a form of soft robotics.

One design among this category is shown in Fig. 6. In this design, a sleeve with aligned rings fixed on the surface can be worn on the user's elbow. One end of the string is connected to the sleeve on the arm and the other end is connected onto the servomotor. Activating the servomotor, will reel in the string(s), thus generating a moment about the elbow and causing the arm to fully extend.

The advantage of the string-servomotor actuator category is that it not only produces a large force from the servo motor, but it's also flexible and a lightweight device.

However, the feasibility to wear this device under clothing or the amount of caution the user must take to ensure no entanglement of the string to their surrounding environment poses a serious problem. Furthermore, having an exposed string network as this would greatly reduce the life cycle of the therapeutic robotic device.

Category 4: Electro Stimulation

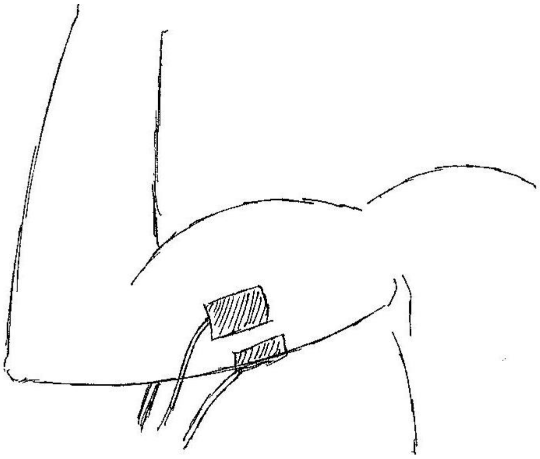


Figure 7: Electo-Stimulating Actuator

The last device concept category is the utilization of electrodes. In rehabilitative muscle re-education settings, the use of electro stimulation on the muscles emulates the same process how the central nervous system sends electrical signals to the tendons and muscles to activate movement. The electro stimulation of the correct muscles can enable the user the ability to have motor control of their appendage. As is shown in Fig. 7, some electrodes are placed on the arm. Placement of the electrodes on the bicep brachii will cause flexion, while electro stimulation on the tricep brachii will enable extension of the arm.

The biggest advantage of electro stimulation is the capability for the user to have backdrivability of their arm (meaning the user can both extend and flex). However, despite the great functionality of the device, there remains too many disadvantages to pursue these concepts. First, the constant electrocution of the end-user is undesirable. Also, the setup of not only the power source, but alignment of the electrodes on the proper sections of the arm, would pose a serious challenge to the end-user. Though these designs remain somewhat plausible the field of electrophysiology is rather new and the safety measures for the end-user may be easily-overlooked by our team. After our team spoke with the University of Minnesota professor, Dr. Durfee, who specializes in rehabilitation engineering and electrostimulation of muscles in humans, we concluded that this category should not be a continued venture for our group. Citing the said difficulties.

Functional Decomposition

Our team generated concepts with the help of our functional decomposition diagram **(**Fig. 8**).** We estimated we would use compressed air as the power source of our device. The compressed air, which can be either generated by body power or by an external air pump, is delivered to the actuator via an air tube. The actuator will transform the mechanical energy, provided by the healthy arm or pump, to fluid energy (air pressure). Then this fluid will “inflate” the actuator, transforming this energy to mechanical energy which will be the force that generates the moment about the elbow or on the arm to cause extension of the arm. All concepts can be found in Appendix C (pg. 54).

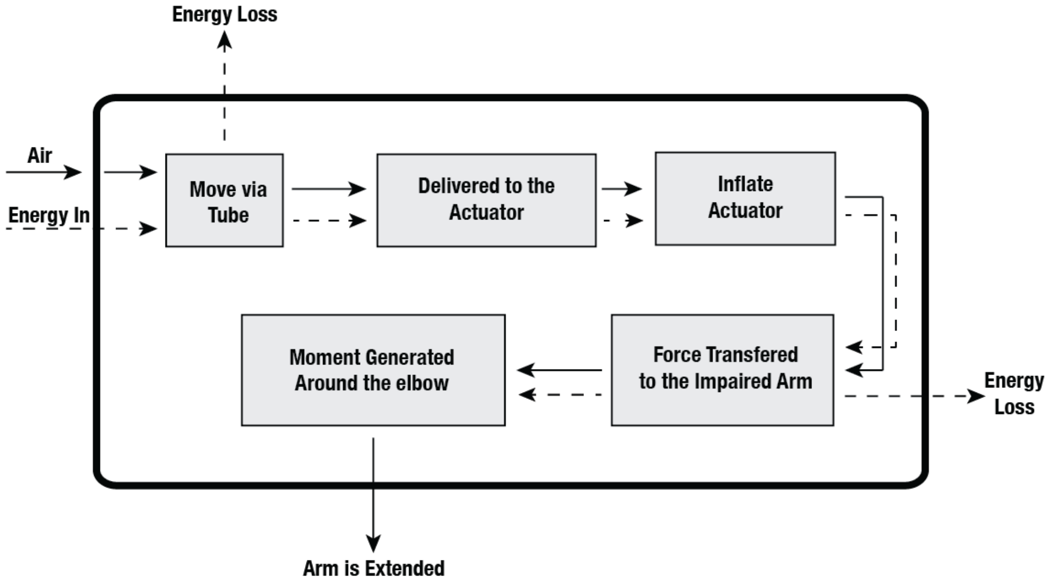


Figure 8: Functional Decomposition of Device

CONCEPT SELECTION

After our individual endeavors with brainstorming for functional concepts that our project team could create, our team sifted through all of our designs to conclude on a final concept to pursue. Through presentations, a modified Pugh chart (a scoring system which has been implemented in previous UM design courses), and a talk with our sponsor and an out-of-state-professor, we were able to create a design fitting for our engineering specifications and other criteria.

Presenting Designs

After everyone had individually produced 10+ number of concepts for a wearable robotic device, our team grouped up to discuss our proposals. We were able to produce a diverse range of ideas, though not every concept explicitly followed our team's functional decomposition breakdown. To narrow down our number of concepts, every team member presented each of their concepts to the rest of the group members. In these presentations one would discuss the function, possible materials used in manufacturing, and provide their estimation on how plausible that concept would be to create. Through this group presentation, it was quite clear which concepts were well-conceived and which would just not be feasible to produce.

Selection Matrix

With eight various concepts that were ready for further review, our team created a selection matrix to aid in extracting bias in our selection process. Slightly modifying a Pugh chart that we had implemented in ME 250 (another design course) we were able to analyze the concepts. As seen in Appendix D (pg. 39) in the leftmost column, we began with parameters which were copied from our QFD. Because we had extensively worked with our sponsor and within our own team to provide design metrics to our eventual device, we agreed these parameters were suitable to judge our created concepts. Next we had to give weights to these parameters, ranging from 1 (the least important) to 5 (most important). These weights would act as multipliers in our final evaluation of the generated concepts. Our team then selected a design, from our big pool of concepts that we thought was not only most feasible, but also most likely to be used through the remainder of the course, as our "standard design". Each parameter value for this standard design was designated a zero. Thereafter, every new concept was judged in comparison to the standard design. The given value for each parameter for the new concept ranged from -5 (far worse) to 5 (far better than the standard design). Thus, after going through all the parameters and using the multipliers based on the weight of the parameter, our team was able to rank our designs in an objective method. A negative sum value would indicate a concept which was inferior to the standard design, and a positive sum value would indicate a superior concept. As it turned out, two other concepts proved to have positive values. However there was a clear winner after our evaluations, which we ended up using as our mock-up (see Fig. 13).

Top Concepts

Top Concept 1: Vertical Air Actuator

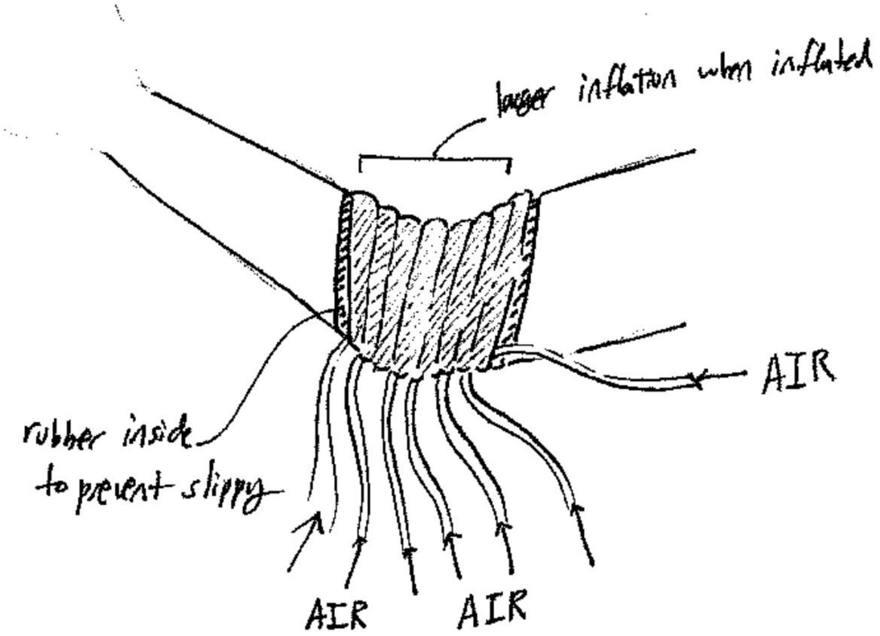


Figure 9: Inflatable Design

The primary advantage of this concept is its uncomplicated and straightforward usability. Since it is only constructed with groups of air chambers connected together with air tubes, the end user will not have hard time on learning how it operates. Moreover, because it is thoroughly made out of soft materials, such as silicone, it is light and portable which a patient can directly use in daily basis. In addition, due to its geometrical property, ring shape air chambers, the energy loss is expected to be less than other concepts that use air chamber or balloon as an actuator. Thus it will generate higher force and moment to patient's arm. On other hands, there are some of disadvantages that must be considered. First, since the device is consisting of multiple air chambers connected side by side, the method of hold those in correct place must be solved. In short, it is hard to manufacture because numbers of air chamber are needed for each device. Moreover, in order to expand the air chambers in axial direction, there must be high air pressure needed or we need to connect an air tube to each air chamber. In either way, the end user should carry heavy air pressure pump or the device will get too messy with many air tube attached.

Top Concept 2: Airbag

Figure 10: Airbag Design

The airbag design have some unique and excellent advantages. Firstly, the lightweightness of air bag category actuator more comfortable and therefore more user friendly. Since the average age for those who have stroke is about 60, the lightweightness will make this design more suitable for its user.

Another advantage is the flexibility of thin plastic airbag. Airbag actuator is basic a balloon, so the thin, soft and comfortable surface make people more willing to wear comparing to rigid structure like motors and gears.

The portability of airbag design also make it a distinguished design. Since when deflated, it will be just like a little empty bag, potentially can be put into any space.

The disadvantage of airbag actuator is that, comparing to electrical motors, soft robotics has some weakness in generating large force or moment, which might limit the application of them. Also, due to the complexity fluid mechanics and the novelty of soft robotics field, we might be lack of systematically theoretical analysis during designing and innovation.

Top Concept 3: Servomotor-String

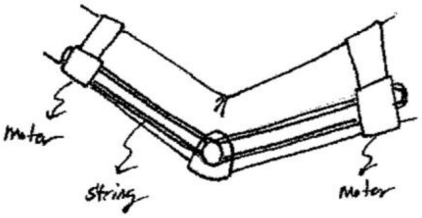


Figure 11: Servomotor-String Design

Using motors and strings is a tried and tested form of muscle re-education in rehabilitative settings already [23, 24]. Typically, in regard to the upper extremity, they are implemented on the hands. In this design, there are multiple lines of strings or wires that line the arm, from about mid-forearm to mid-upper arm. On the forearm there is one strap that holds two identical system of strings (one on each side of the arm), that the user will be wearing. While under the upper arm and elbow, a motor and some form of winching system will be reeling in the strings. The tension in the strings serves as the driving force that moves the arm to the extended position.

The advantages of this design are that it's strong, flexible, and relatively portable and lightweight. The forces necessary to create a moment about the elbow would be easy to achieve in theory, but taking in account the geometry around the elbow, it would be quite difficult to be efficient around this joint. The implementation of some hard plate under the elbow to block against scraping and scratching of the rope on the body would be necessary. Also, the high forces that are pulling down on the forearm would pose extreme difficulty in creating a fabric that would hold up against these sort of forces, and beyond that, not slip on the arm. Though similar concepts as this are being researched and hold some promise in the field of therapeutic robotics, the cost of such a design would be too high for the aim of our project team.

Chosen Concept

Elastic Actuators on Inner and Outer Elbow

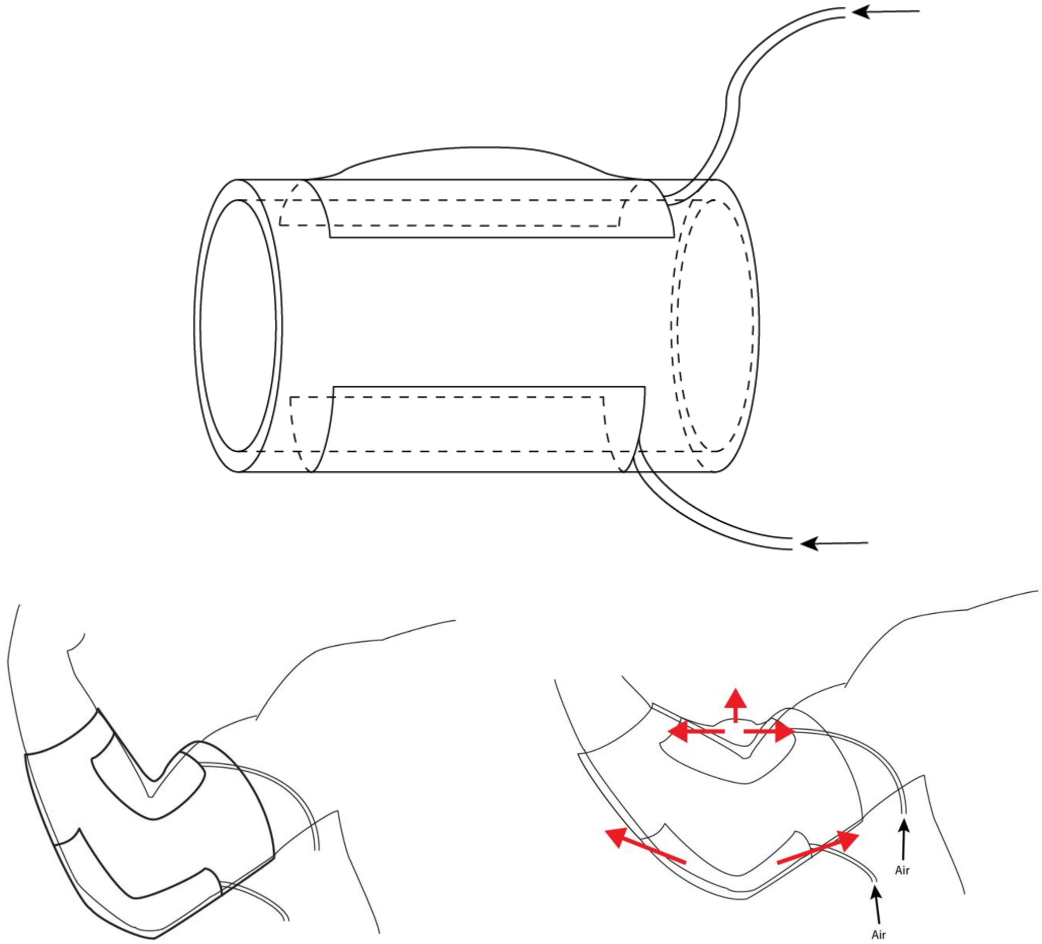


Figure 12: First Mock-up Concept

Our chosen concept is shown in Fig. 12. As air flows into the actuators that are positioned on the inner and outer elbow through the air tube, the elastic actuators will be inflated. This inflation will support the extending motion of the arm.

The customers that would use this device suggested several aspects that need to be implemented on our design. The aspects include wearability, comfortability, light weight, safety, ease of use, low noise, portability, no slipping, affordability, and backdrivability. Our chosen concept has many advantages over other concepts since it has met most of the aspects that was asked by the users. First of all, this device is wearable since it is a sleeve form. Being made out of fabrics, elastic actuators, and air tubes, it is light and comfortable when worn. Furthermore, it will be run by pneumatics. Small amount of air pressure will be applied to activate the device. Therefore, it is easy, safe, and quiet to use. This design also does not contain complex setup that may affect negatively on the portability of the device.

Nevertheless, we also found out some disadvantages of the design. Firstly, it is less efficient than using other kinds of actuators. For example, a piston moves linearly. The linear motion is converted to force only along the same axis. However, elastic actuator expands radially when inflated. Some forces that are wasted during the expansion process. This results in lower efficiency, which is an important fact for all kinds of devices. Since not all the forces that are created by the expansion of the elastic actuator are used to support the extending motion of the arm, it is harder to generate force compared to devices that use pistons or motors. There were also some aspects that were not able to be satisfied yet. Since we still are looking for best materials to use for our prototype. It is not possible to predict the affordability of this device. Moreover, backdrivability is an aspect that needs to be studied more. When the arm is bent in, the actuators are not fully deflated. Some air still remains in the actuators, failing to back drive the "driver."

KEY DESIGN DRIVERS AND CHALLENGES

The key design driver for our device is the elastic actuators that are placed on the inner and outer elbow. As the actuator that is on the inner elbow is inflated, it will cause the bent arm to begin to extend. Simultaneously, as the actuator that is on the outer elbow is inflated, the generated force will push the outer elbow inward, supporting the arm to extend. Our final concept design initially had one actuator on the inner elbow. When we were building and testing the mockup design, however, we hypothesized that placing more actuators on the inner elbow may result in faster extending motion of the arm. The actuators will be pushing each other when inflated together, stimulating the extension of the arm. Nevertheless, it would be challenging to find the right elastic actuators for this improvement. We might have to create our own geometry of our balloon by molding silicone.

The orientations of the actuators are also challenging aspect to consider. As we were testing the device, we realized that the inner elbow and outer elbow are not positioned 180 degrees to each other. The two parts are apart from each other less than 180 degrees. Thus we need to perform more research on the ergonomics of the motion around the elbow. Moreover, we need to look for new material for our sleeve. The mockup design was made out of soccer socks. Since they are used for legs, we thought that they would fit well on arms, which are thinner than the legs. However, it was very tight and not comfortable to wear. We have to look for other kinds of materials for our sleeve that fits well on most of the arms.

Another challenging aspect of our device design is designing it to be backdrivable. Backdrivablity, is the ability to drive the mechanism inversely. For example, if we were to inflate the device using a bike pump to extend an arm, we should be able to move up the bike pump handle to its initial position when we bend the arm, or deflate the device. The air in the actuators should be able to go back to the bike pump as before. This is very challenging because of the characteristics of elastic materials. As the arm bends back, the elastic material may be deformed and keep some air inside. This may affect the backdrivability of the device. And also, the size of the tube that transfers the air into and out of the actuators needs to be modified. The tube that we used for our mockup design was so thin that it was hard to inflate and deflate the actuators without pump. Because the tube is thin, air takes some time to travel in and out of the actuators. Therefore, the desired tube size must be decided after careful calculation.

Lastly, we need to find how to measure the force generated by the device to check if it produces enough force to extend an arm. It is also important to consider the operation time, which may depend on material selection. For example, thick and stiff elastic material will be very hard to inflate. All these challenges, however, are not the only challenges that we will face. There will be unsuspected challenges coming towards us as we progress on building our prototype.

CHOSEN DESIGN MOCKUP

Figure 13: Second Mock-up Design

The prototype we manufactured is proposed for both display of rough shape of our chosen design and slight physical testing. In structure wise, the prototype consists of 6 major components. First, we have used elastic portions of a soccer sock for the main body of a device which a patient wear on his arm. Two expandable pockets, which function as the chambers of balloons, were sewed on the top and bottom of the main body by using sewing machine. On each of pockets, we inserted a balloon with different geometrical properties, and air tubes were connected to each of the air balloons. When a patient installs the device on his arm, the air is transferred through the air tube so that the balloons can be inflated. As the air pressure inside the balloons get higher, the volumes of balloons will increase and provide the pushing force on the wall of pockets, generating moment on the patient's arm. Consequently, the force generated during the expansion of the balloons will assist the movement of patient's arm to the full extension position.

For the demonstration to design review attendees, we have completely assembled them so that the attendees can have better understanding on how our device function, and possibly provide practical advices. All constructions were completed at the HaptiX lab. Fig. 13 shows a picture of our mockup prototype and drawings that explain the structure and mechanism of the mockup. Through the progress of constructing mock-up prototype, our team members were able to have hands on experience on the project and eventually learned and realized current status of chosen design in terms of engineering parameters that we used for our design selection matrix and QFD. In addition, we learned the necessity of repetitive and continuous of testing and engineering approaches in order to find fulfill our sponsors' expectations.

Changes

Our new concept design varies dramatically from our originally mock-up which we proposed in DR2. The most notable change in our design is that the alteration of our actuator. Originally, we decided to use some balloon system. The number of balloon actuators was in question to implement on either side of the user's arm, but in such a system, the possibility of being backdrivable was non-existent. Thus, our team decided to incorporate the use of pneumatics and use an air cylinder as our actuator. Additionally, our team has transitioned from a completely "soft" robotic design of using a sleeve and expandable pockets composed of some fabric (most likely a ratio of polyester and spandex) to a rather rigid-body design. This concept has two sets of linkages (one side resting below the upper arm and one side resting below the lower part of the arm) that maintain their rigidity through the connection of spacers. This concept would become more "soft" with the implementation of other materials such as a durable and flexible plastic for the linkages, and possibly lining the upper sides of the linkages (which come in direct contact with the user's arm) with silicon. Though we use this rigid structure to transfer the forces from the pneumatic cylinder to the user's arm, we intend to incorporate a sleeved or ratcheted design system through the linkages to aid in comfort and stability of the device on the user's arm.

CONCEPT DESCRIPTION

Since DR2, our team set out to refine our original mock-up design, which was created after an extensive concept generation process. Originally, we had used a sleeved system fixed with balloons that worked as our actuators to control the movement of the user's arm specifically from the flexed to fully extended position. After speaking with our sponsor, our project's end goal for a product had altered to include the feature of backdrivability. Now tasked with key design parameters of being a backdrivable system yet a wearable, "soft" robotic device, our team revisited the concept generation stage and developed a mock-up design and concept.

Model Description

Similarly to our mock-up design in DR2, our new concept is not overwhelming in the number of different materials needed, nor a complex system. The main parts that comprise our new wearable device include two sets of two-bar linkages, spacers, an actuator, and a sleeved system. For the linkages, our team may use acrylic, but perhaps a better option would be a form of Delri plastic. The benefits of Delrin are that it can be very easily manufactured via laser. It is a durable yet low density material that could be implemented in a number of ways on the prototype. Using Delrin as opposed to acrylic or aluminum, would decrease our structures weight and increase flexibility, which would be good for the user who uses this device at home on a daily basis. For spacers, our team will currently use stock, tubed aluminum. A hard rubber may be preferred, but a solid slab of rubber may marginally be more lightweight, but definitely more expensive to our team. Aluminum has the physical integrity to hold the pair of linkages apart from each other. For our actuator, our team has implemented an E16 Double Acting Airpel Anti-Stiction Air Cylinder. The range of this cylinder ranges from full vacuum to 100psi. Additionally, with a 0.627in bore size, we can achieve approximately 3ft-lb of torque on our design. Finally, our team is still in the prototyping stage for our fitting system. Utilizing a heavier rigid-body system as opposed to the sleeve design in DR2, in addition to using a piston-cylinder rather than balloons, our design will be much heavier in weight. This additional weight will pose greater problems for us in combating the rotation of the device around the arm, and slipping of the device up and down the user's arm. A proposed sleeved-system will be some combination of fabric, of spandex and polyester composition, and ratcheting system similar to that seen in most ski boots. This ratcheting system would act to secure the device onto the arm and help the device to be more universal amongst users.

ENGINEERING ANALYSIS

As our concept was decided, we have performed detail engineering analyses regarding our design drivers. We have made our engineering analyses by using our engineering knowledge including solid mechanics, fluid dynamics, structure dynamics and material strength. Moreover, we used computer programs including Matlab, ADAMS, etc. These engineering approaches, such as mathematical analyses and engineering principles, guided and helped us to approach a design with higher performance.

Wearability – Mockup Construction

The mock-up for our latest design was made of simple materials that we scavenged from the HaptiX lab. To create the linkages we used appropriate, yet thin sheets of Styrofoam, and glued a thick paper on the outsides to prevent easy tearing of the Styrofoam. For one of the spacers we used a thin wooden rod, and for the others we took more Styrofoam and duct-taped the outer surface to make them more structurally sound as well as giving the appearance of the aluminum we may use. With a knife we carved out the slots for the air cylinder to rest into the appropriate spacers, as seen in Fig. 14.

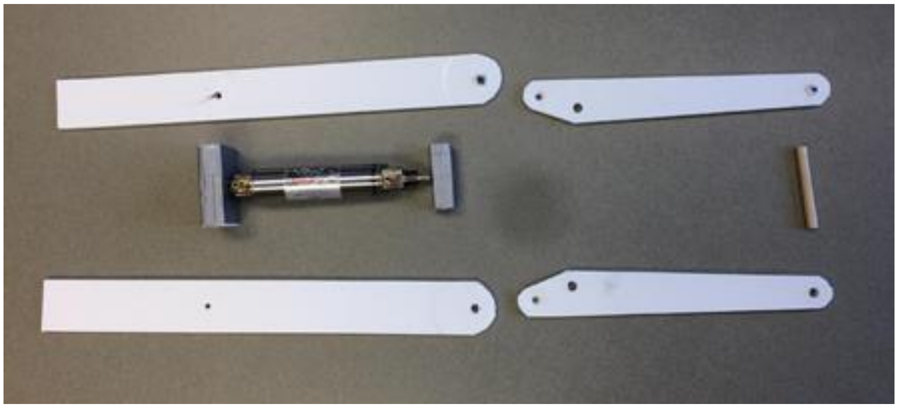


Figure 14: Materials in Second Mock-up

With all the pieces formed and ready to assemble, we aligned the linkages in accordance to our CAD model and poked holes through where the bolts would go, with a pencil. We then secured all the linkages together with the spacers and bolts, and tightened everything together with nuts. This can be seen in Fig. 15 and 16 (pg.26). With our mock-up fully assembled, our team began to test how to best fix our model design on the human arm.

From our model, we knew it could not be immediately worn, but creating a physical mock-up was the best way to see what modifications could be added to this “bare-boned” structure. Simulating the motion of the flexion and extension, with the device guiding below our arm, we noticed our device would easily slip up and down the arm. Additionally, with this much heavier design, there is a high risk of rotational slipping as well, which would cause a moment to generate in an inappropriate fashion. We believe a sleeved-system could best combat this, and if not, a follow-up with our sponsor has been scheduled to confirm whether our proposed modifications would be even feasible. Our team also recognized that there would be positions of the device, that if reached, the air cylinder would not have enough force/ moment arm to backdrive the system. For example, if the device reached a straight-180^{o}-line, all the force the air cylinder generates will be acting on a zero length moment arm, which would not allow for any form of rotation about the elbow. Thus, our team will need to equip hard stops at the joint next to the elbow, on the device, to ensure that the device does not reach these unretractable positions.

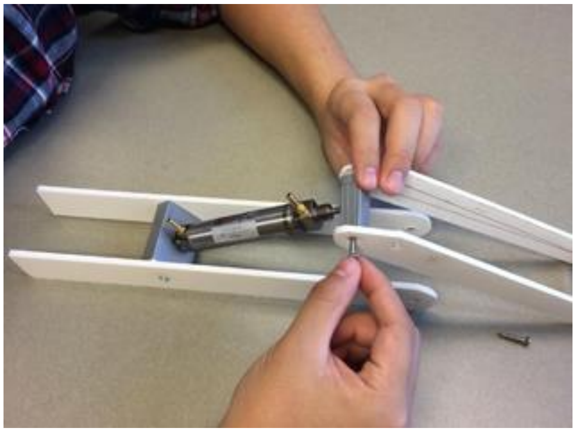


Figure 15: Assembly of Second Mock-up

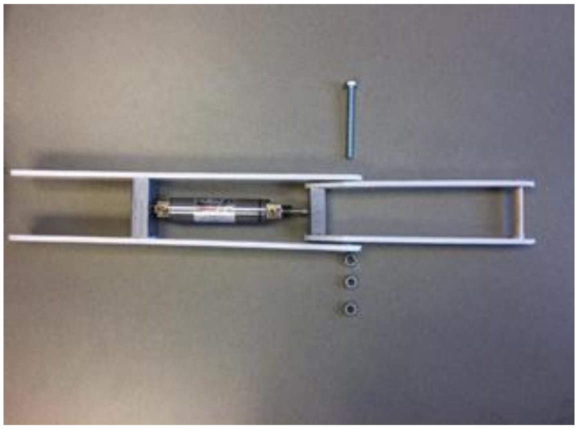


Figure 16: Assembly of Second Mock-up

Backdrivability – Empirical Testing

Our sponsors do not want the device to run by external power source. Instead, they desire to use body power to drive the device. For example, the stroke patients can wear the devices that are connected with air tubes on each arm and bend their healthy arms to extend the impaired arms. They can also extend their healthy arms to flex the impaired arms. In order to check this backdrivability, we conducted an empirical test. The experimental step is listed below with Fig. 17.

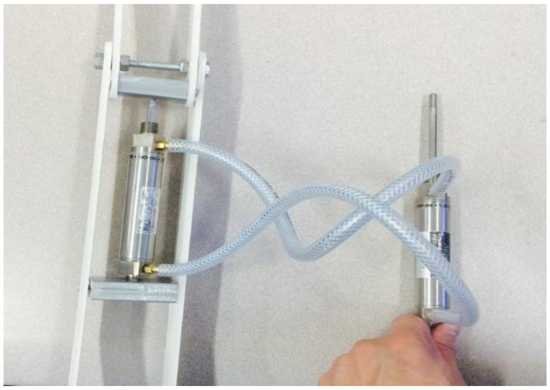


Figure 17: Backdrivability Testing of Design

1) Besides the mockup design, we prepared another identical piston (Piston 2 in Fig. 17) that can be used for the other device.
2) With an air tube, we connected upper nozzles from both pistons. We made sure that one cylinder is compressed into the piston while the other cylinder is extended out of the other piston.
3) The lower nozzles are also connected with another air tube.
4) To test the backdrivability, we pulled and pushed the cylinder.

When we pulled the cylinder from the Piston 2, the cylinder from the Piston 1 was contracted, providing extending motion of the device (Fig. 18). On the other hand, when we pushed in the cylinder from Piston 2, the other cylinder was extended, generating the bending motion of the device (Fig 19). Through this empirical analysis, we were able to conclude that the device is backdrivable. If we were to make two identical devices and place each device on both arms, the stroke patients will be able to use their health arms to generate power for the devices on their impaired arms.

Figure 18: Extended Position of Device

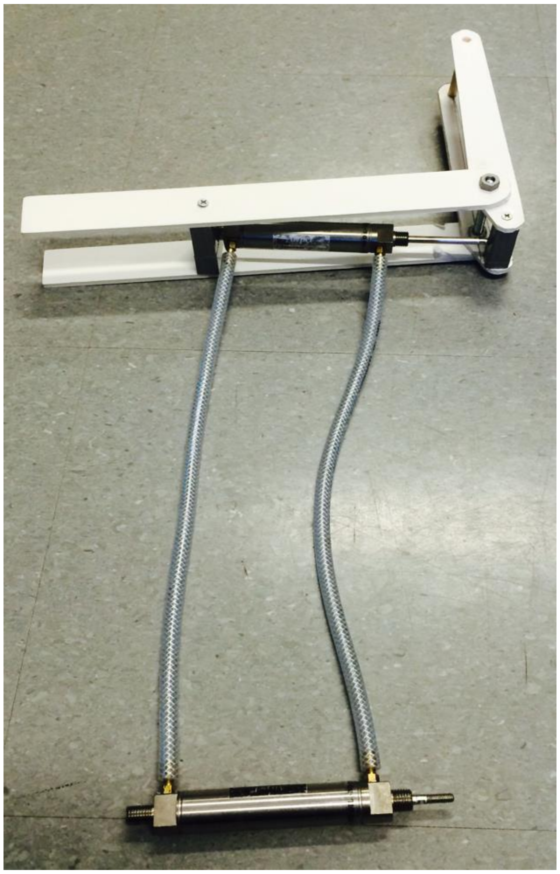


Figure 19: Flexed Position of Device

Moment Generation – Theoretical Modeling

Governing Equation for Determining Dimensions

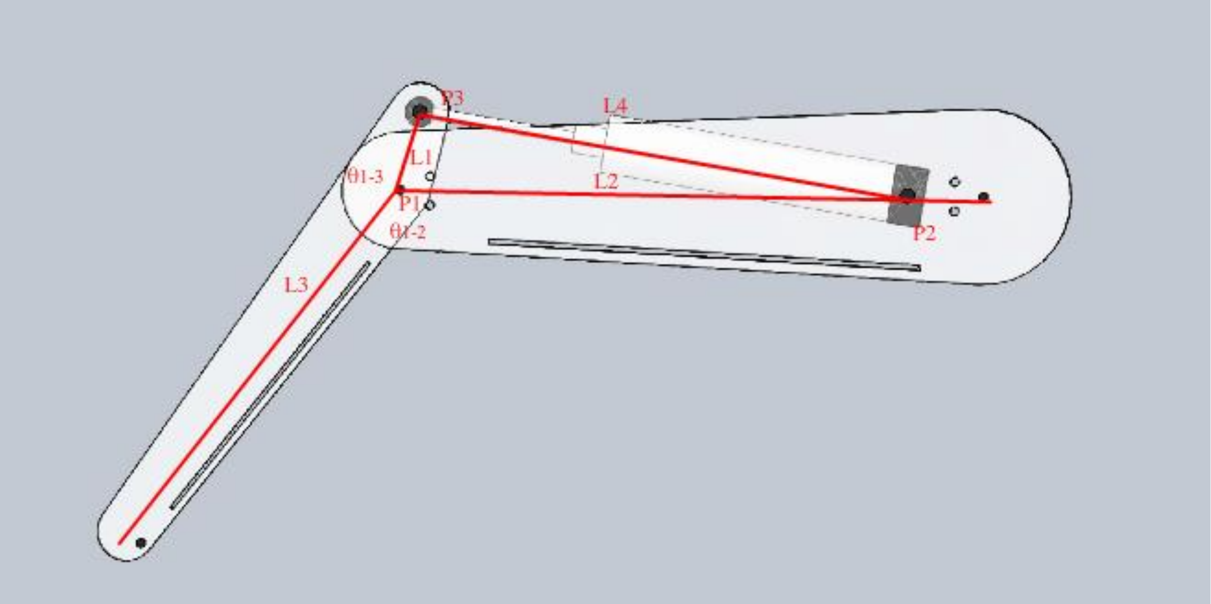


Figure 20: Force Analysis of Mock-up Design

The structure of our actuator is a two bar linkage that can rotate around a joint denoted by P1 in Fig. 20. The size of these two bars are governed by length and angles, which are denoted by $L1$, $L2$, $L3, L4$, θ_{1-2}, and θ_{1-3}.

$$\theta_{1-2} \in [\theta_{1-2-min}, \pi] \quad \text{(Eq.1)}$$

$$L_4 = \sqrt{L_1^2 + L_2^2 - 2L_1L_2\cos(2\pi - \theta_{1-2} - \theta_{1-3})} \quad \text{(Eq.2)}$$

$$\theta_{1-2} = \pi - \frac{1}{2}\theta_{1-2-min} \quad \text{(Eq.3)}$$

Variables:

- P_1 : Joints between two pieces of actuator arm
- P_2 : Joints between actuator's forearm and piston
- P_3 : Joints between actuator's arm and piston

- L_1: Length of line segment between P_2 and P_1, [mm]
- L_2: Length of line segment between P_3 and P_1,[mm]
- L_3**:** Length of actuator's forearm, determined by human forearm's size,[mm]
- L_4 : Length of piston and cylinder, determined by piston's geometry, [mm]

- θ_{1-2} : angle between actuator's forearm and arm (Line L_2 and L_3),[∘]

- $\underline{\theta_{1-2-min}}$:The minimum angle between human’s arm and forearm,[∘]
- θ_{1-3} : angle between lines L_1 and L_3,[∘]

Take a note that the values from the variables with underline can be determined by directly measuring corresponding length of human arm.

Result:

$$\theta_{1-3} = 155^\circ$$
$$\theta_{1-2} \in [50^\circ, 180^\circ]$$
$$L_1 = 27.65[\mathrm{mm}]$$
$$L_2 = 174.6[\mathrm{mm}]$$
$$L_3 = 150[\mathrm{mm}]$$

Governing Equation for Moment Generation

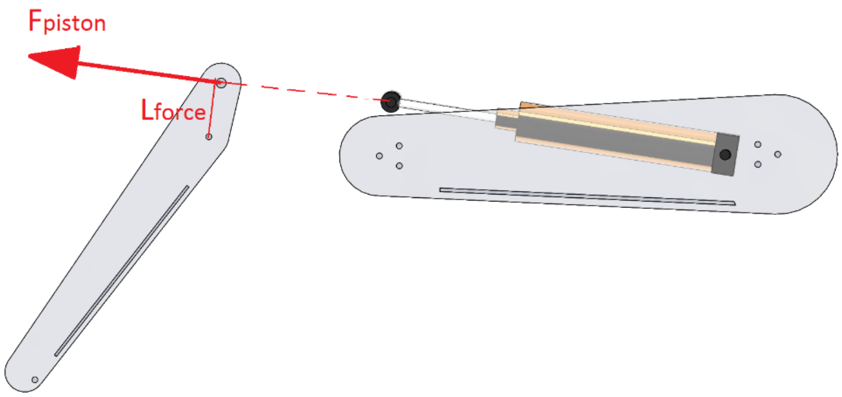


Figure 21: Force Analysis of Second Mock-up Design

We analyzed the moment of our actuator can generate based on the force diagram Fig. 21. High pressured fluid pushes the cylinder and provide the piston with a moment to rotate the forearm linkages of the actuator. Since there is distance between rotating pivot and the force of piston, moment is therefore generated, which can assist rotation of the forearm. In order to determine the relation between moment generated and angle between two arms, we calculated the analytical expression of moment M_{piston} and plotted it against the angle θ_{1-2} (Fig. 22, pg.31). Variables are detailed described below.

The governing equations are shown below. Dimension of the ball in cylinder determine the inner area, which in turn determines the force by multiplying with air pressure (Eq.5). Length between rotating axis and force line is determined by using cosine theorem (Eq.6) with the triangle P1P2P3 in Fig. 20. Since the length is a function of angle θ_{1-2} between the two arms, the moment, which is calculated by Eq.4, is also a function of angle. This relation is illustrated by Fig. 22.

$$M_{piston} = F_{piston}L_{force} \quad \text{(Eq.4)}$$

$$F_{piston} = \frac{P_{piston}\pi D_{piston}^2}{4} \quad \text{(Eq.5)}$$

$$L_{force} = \frac{L_1L_2\sin(2\pi-\theta_{1-2}-\theta_{1-3})}{\sqrt{L_1^2+L_2^2-2L_1L_2\cos(2\pi-\theta_{1-2}-\theta_{1-3})}} \quad \text{(Eq.6)}$$

Result:

$$M_{piston}(\theta_{1-2}) = \frac{P_{piston}\pi D_{piston}^2 L_1L_2\sin(2\pi-\theta_{1-2}-\theta_{1-3})}{4\sqrt{L_1^2+L_2^2-2L_1L_2\cos(2\pi-\theta_{1-2}-\theta_{1-3})}}$$

Variable:

- F_{piston}: The pushing or pulling force by piston,[N]
- L_{force} : Perpendicular distance from fixed axis (P1) to force line (L4),[mm]
- P_{piston} : gauge air pressure in piston,[Pa]
- D_{piston} : ball diameter of piston,[mm]
- P_1 : Joints between two pieces of actuator arm
- P_2 : Joints between actuator's forearm and piston
- P_3 : Joints between actuator's arm and piston
- L_1: Length of line segment between P_2 and P_1,[mm]
- L_2: Length of line segment between P_3 and P_1,[mm]
- θ_{1-2} : angle between actuator's forearm and arm (Line L_2 and L_3),[∘]
- θ_{1-3} : angle between lines L_1 and L_3, [∘]

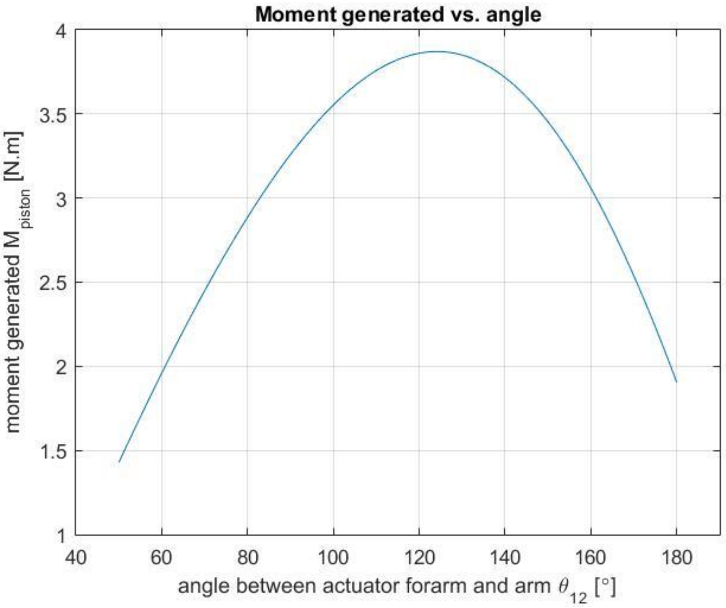


Figure 22: Moment About the Elbow vs Angle of Device

FMEA (FAILURE MODES EFFECTS ANALYSIS)

Item Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Current Design Controls	Detec	R.P.N.	Recommended Action(s)
Piston									
Generate moments by inflation/ deflation	Leak	Less efficient	7	Fatigue failure	2	Test and validate method.	8	112	Better manufacturing process
	Explosion	No moment generated. Noise.	9	Non-uniformity of the thickness of the actuator.	2	Test and validate method.	2	36	Use strong material
Tubes									
Transports air	Dis-connection	No moment generated.	10	Clumsy usage, bad connections	7	Minimize extrusion of tubes off of the body.	9	630	Research different connection method
	Leak	Less efficient expansion	7	Fatigue failure	5	Use air-tight tape.	8	280	Research robust tube
	Too much resistance	Slow operation	3	Too small tube	1	Choose correct width of tubes.	6	18	Avoid thin tube

Item Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Current Design Controls	Detec	R. P. N.	Recommended Action(s)
Sleeve									
Holds the device in right place	Slipping	Less moment transferred to the arm Change in orientation of moment generation.	4	Wrong material selection	6	Test and validate method.	1	24	Search for better materials and different ways to fix the device in position
	Over-pressure (Tightness)	Affects blood circulation	4	Wrong material selection	2	Test and validate method.	1	8	Search for flexible material.
Linkages									
Hold rigidity of design and transfer moment to the arm.	Screws come loose	Design is no longer solid, and will generate zero to little force.	8	Overuse and no maintenance.	4	Choose correct bolts and nuts.	4	128	Continued maintenance after correct installation.
	Fracture	Could dismantle device or cause minor injuries.	9	If too much pressure is applied from an external force. (misuse)	3	Choose strong and elastic enough material.	3	81	Careful eye on material, medium-gentle usage of device.

Item Function	Potential Failure Mode	Potential Effect(s) of Failure	Sev	Potential Cause(s) / Mechanism(s) of Failure	Occur	Current Design Controls	De tec	R. P. N.	Recommended Action(s)
Silicon Molding									
These molds will serve as arm supports. The wearer will have one on the bicep and around the wrist, while a Velcro strap will fasten up the device to the arm.	Screws become loss	The support will detach from the frame of device.	4	Improper installion and/or continued use without refastening.	3	Test and validate method.	1	24	Provide enough working room to ensure the fastening of the screws.
	The mold rips	No longer support the arm properly, and the user's arm will be directly on the Velcro sleeve.	4	Over bending the mold, or large experienced shearing forces	3		1	8	Use a more durable Silicone.

RISK ANALYSIS

Hazard	Hazardous Situations	Likelihood	Impact	Level	Technical Performance	Cost	Action to minimize hazard
Tube Disconnection	When using the device, tubes can be disconnected from the piston. The disconnected tube can be caught on some objects. Air or tube also can damage patient’s eye.	Very likely	Minor	3	Significant degradation in technical performance.	Budget increase or unit cost increase.	Better technology for connection.
Piston Explosion	When using the device, high pressure can cause the piston to explode.	Remote	Serious	2	Significant degradation in technical performance.	Budget increase or unit cost increase.	Stronger material for piston. eg. metal instead of plastic
Pinching Between Linkages	When returning to the flexed position, the skin on the harm could be caught in a pinch from the connection of the linkages.	Likely	Minor	2	No change in performance.	Budget increase or unit cost increase.	Fixing a cupped orthotic to rest the elbow that seals to the inside walls of the linkages.

Hazard	Hazardous Situations	Likelihood	Impact	Level	Technical Performance	Cost	Action to minimize hazard
Tight Sleeve	If the sleeve is too tight, it can slow down blood circulation. Also the movement of the arm is limited.	Likely	Minor	2	Moderate degradation in technical performance.	Budget increase or unit cost increase.	More flexible sleeve.
Sharpness of the Material that is in Contact with the Arm	When moving the arm, user could scrap it on the surface and edges of the linkages.	Likely	Minor	2	No change in performance.	Budget increase or unit cost increase.	Round or file the edges of the material, or change or layer the material with a soft one, such as silicon.

CURRENT CHALLENGES

The current status of our design fulfill many of our desire requirements for our device; however, there are still several remaining unresolved issues. The first unresolved issue is limitation in motion. Since we use joints, which has one degree of freedom, for bar connection, there is limitation in motion which the end user may feel uncomfortable. In order to solve this problem, we are using Solidworks and our engineering knowledge from other designing course to provide wider range of motion in device and still remain power efficient. For example, we are concerning about using ball and socket joint.

Another remain unresolved issue is slip between device and an arm. As the device operate to reach fully extension position, there is slip occurrence due to the geometry and location of the device with respect to the arm. Thus, engineering analysis regarding dynamics and material property is needed to whether change the structure formation of the current device design or use the feature of slip in our device.

Lastly, portability is another remain unresolved issue that we need to encounter. One of our important goal for this device is portability so that the end users can use in their daily lives. However, because of the rigid material used for frames and pistons, it is likely to have high weight which reduce the portability to many of stroke survivors. Thus, we need engineering analysis and approaches regarding material strength, solid mechanic in terms of mathematically finding force applied to our device and find correct materials to used that can minimize both the volume and weight of the device.

FINAL DESIGN

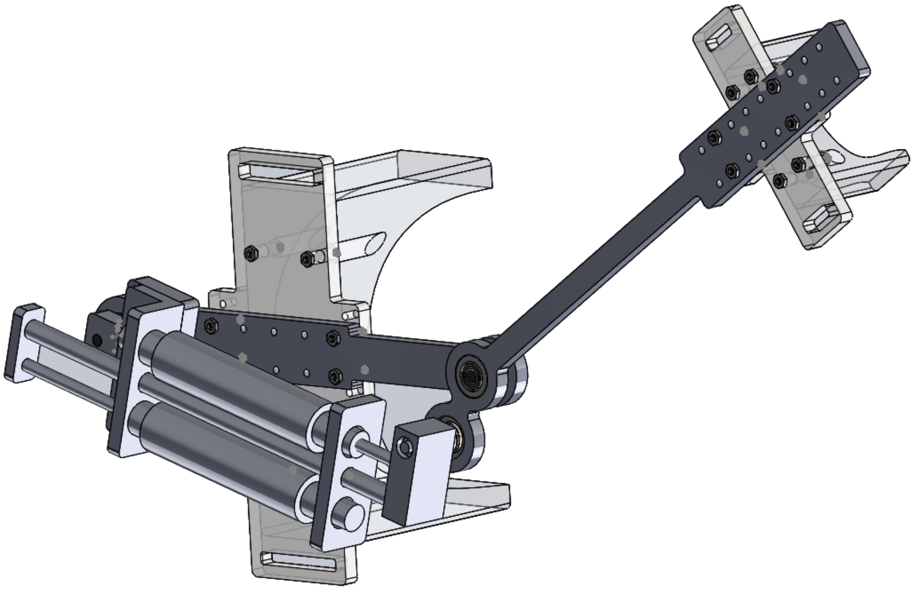


Figure 23: Full CAD Design of Prototype

Changes (Edit)

After submitting our design to our sponsor again, we were assigned an additional criterion. Not only should the device be backdrivable, but a double acting actuator such as our air cylinder (which would provide sufficient force to both extend and flex the arm) was to be eliminated. Namely, only the extension of the rod in the air cylinder would be acceptable to actuate motion of the arm. Thus, at minimum, two single-acting actuators were necessary. This added requirement produced numerous problems to our designing process. Because of our selection of air cylinders was sufficient for actuation, we decidedly moved forward with adding another cylinder to the device, as shown in Fig. 23. The added difficulty that came with a cylinder that would face in an opposite direction was creating a linkage system that would actuate motion for the arm to move from the extended position to the fully flexed. Upon redesigning a feasible concept on SolidWorks, which placed two cylinders below the arm, we quickly discovered that the range of achievable motion of the arm was significantly decreased. This is most likely due to our linkage designing, however, the more intricate the linkages became, the more the time in manufacturing, weight of the device, and cost of the design increased. We then redesigned the device to mount on the side of the arm, which is a highly problematic area to design for. As the concern for slipping and a higher priority of the weight would be amplified when the device is fixed to this area.

Model Description (Edit)

After our latest meeting with our sponsor, our team became more informed for materials that would be appropriate to use in the composition of our device. Needing the device to secure onto the side of the arm, it became a balancing act with reducing weight, maintaining physical integrity of the device, yet most importantly having functionality and wearability. A list of the device's components can be found on pages 59-60. The overall design of our prototype was highly dependent on the selection of materials that would compose our device. CAD screenshots of our prototypes assembly of components can be found in Appendix G. The main frame of the device resembles that of the human skeletal system of the arm, with two rigid links made of 6061 aluminum that will lay along the upper- and forearm. The human arm will be in direct contact with a rounded silicone molding which will be fastened with Velcro straps. These silicone moldings will be fixed to very durable Delrin plastic bases, and this unit of silicone and Delrin will serve as adjustable fixtures for the user. This will allow for people of different arm lengths to wear the prototype comfortably. One aluminum rod will be between the two air cylinders, connecting their rods, so that when one air cylinder is in upstroke, the other in down stroke (essence of backdrivability). This design, mechanically, should be capable to actuate a desirable 135˚ of motion of the arm.

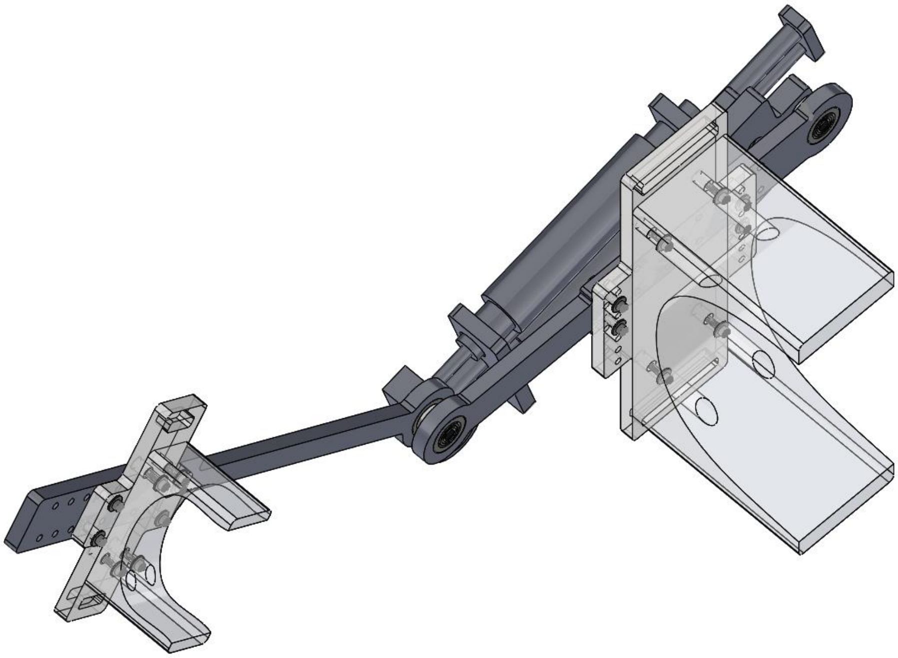


Figure 24: Another Full CAD Design Screenshot

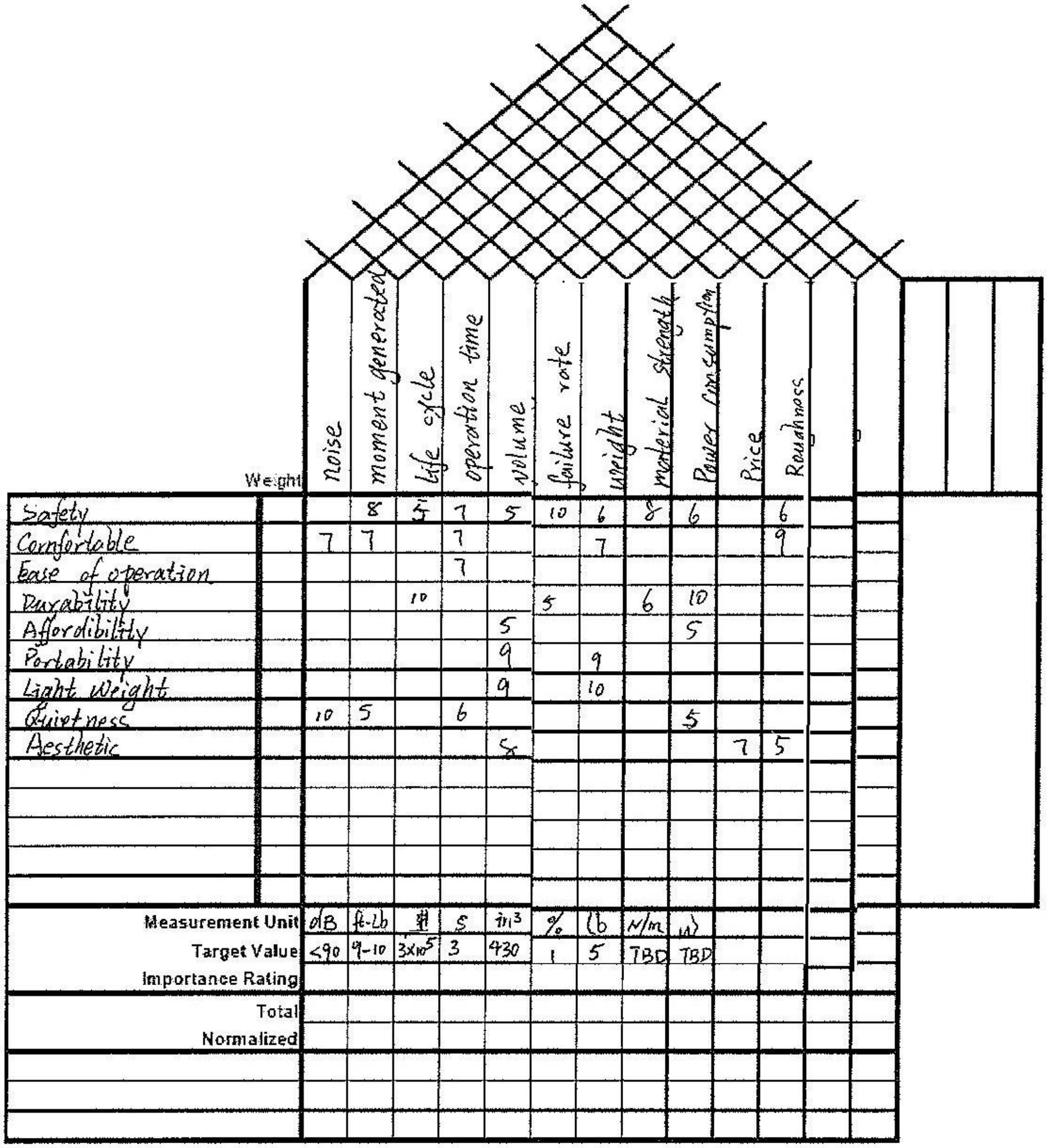
Material Comparisons

Our team is very much still in the prototyping stages, and on a daily basis we are comparing materials that would function better than what we currently have or idealize for the design. To begin, we have four main components of the device: linkages, spacers, an actuator, and a sleeved-system. Beginning with perhaps the most challenging, are the linkages. These can be composed of a number of different materials, but in addition to holding certain standards to ensure functionality, our team has to accommodate for the end-user for a material selection which works best for them. The linkages will serve as the bulk of material in this design, thus keeping it lightweight yet durable is key. That immediately rules out the possibility of using metals. Our team believes the use of acrylic or PP would suit best for our device. Both materials can be laser cut, and both offer great durability. However our team is more inclined towards a PP plastic, because it is approximately 20% less dense, is more elastic/flexible, and we have the budget to purchase it. To hold the spacing and maintain overall shape of our device, we will need to use spacers. Typically in our other x50 labs, our teams use tubed aluminum for spacers. We contemplated other soft materials such as rubber, however at least for the prototyping stage that we are in, we may need to go through many iterations for a final product. Rubbers may marginally decrease the overall weight of the device, but they are far more expensive and would require more careful manufacturing to install on our device. The use of the Airpel air cylinder we have is great two-fold. Firstly, the HaptiX lab that we are working with has many air cylinders of this brand and good grade, so free of charge. Additionally, these specific actuators (theoretically) will generate sufficient force that is required from our device. Finally, our sleeved system is what poses the most problems. We must deal with the weight, shifting rotationally, and slipping up and down the arm of the device. To combat this we need a system that can be worn and hold the device in correction orientation. There are a myriad of compressive garments available, most of which are a spandex and polyester composition, but that may not be enough for our project. We would need multiple layers of said material, which would greatly increase costs, or add a ratcheting system. The ratcheting system we would like to implement would be similar to that observed in ski boots. Thus, a plastic winding contraption that could tighten the device to the arm, while also enabling some customization for the user.

CONCLUSION

Upon completion of manufacturing and assembly, our team was left with a device that could be independently worn on the arm and actuate motion along a desired range of motion. At the beginning of the semester we were tasked with creating a prototype that could achieve 2.1 ft.lb moment, actuate across 135º, operate in under 3 seconds, weigh under 5lbs, fit within 430in^3, and be created for under $400. Our team were able to not only achieve these values but often surpassed our expectations. Our design is not perfect however. We achieved about 80% of our most desirable range of motion, our feedback system could be improved for the wearer if gas powered is the mode of operation. Additionally, if this project were to be continued in future semesters we would have recommendations for areas of improvement. Specifically, the fixed pneumatic cylinders would need re-engineering, for the structure is too rigid. Utilizing ball bearings would solve this problem, and would minimize the wasted power that does not contribute to the linear forces which create the actuation of the arm. Furthermore, swapping out the aluminum connecting rod for a high-grade steel one, would greatly reduce the friction that sometimes occurs in the current design, also leading to greater power generated to the arms. As far as safety, more testing with the influence of the pressure in relation to the jarring forces to the human body would need to be further explored. Though our team designed against hyperextension of the arm, the whiplash effect that could occur at high pressures is would need to be safeguarded by a pressure relief system/mechanism, which is currently not implemented.

Appendix A: Quality Function Development



	Weight	noise	moment generated	life cycle	operation time	volume	failure rate	weight	material Strength	Power consumption	Price	Roughness
Safety			8	5	7	5	10	6	8	6		6
Comfortable		7	7		7			7				9
Ease of operation					7							
Durability				10			5		6	10		
Affordibility						5				5		
Portability						9		9				
Light Weight						9		10				
Quietness		10	5		6					5		
Aesthetic						5					7	5
Measurement Unit		dB	ft-Lb	#	s	in³	%	lb	N/m	w		
Target Value		<90	9-10	3x10⁵	3	430	1	5	TBD	TBD		
Importance Rating												
Total												
Normalized												

Figure A: Quality Function Development

Appendix B: 20 Concept Designs

Concept 1: Two balloons on top and bottom inside sleeve

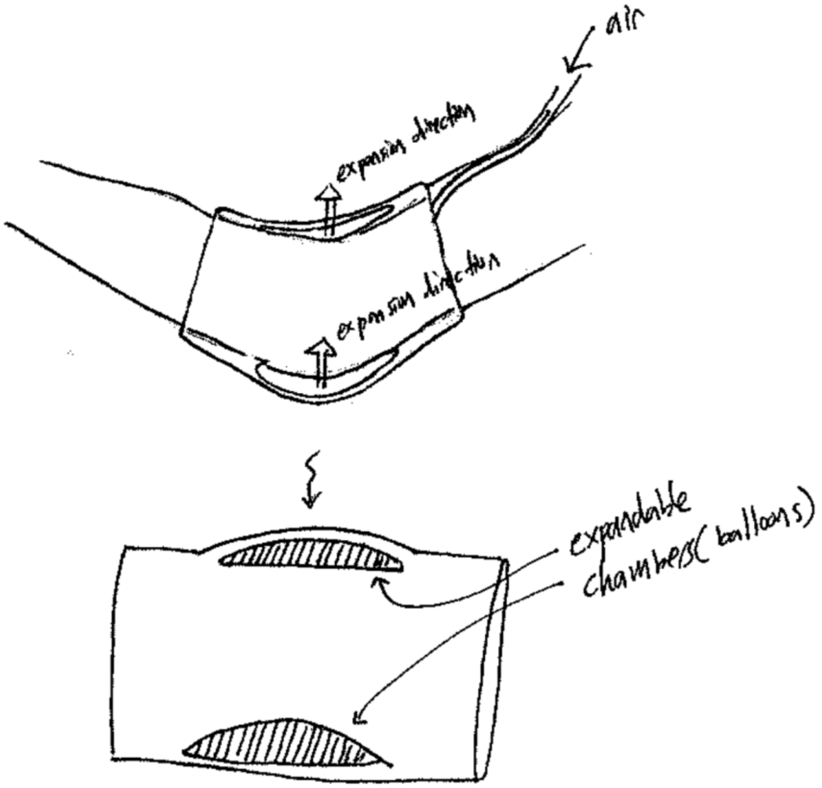


Figure B1

This concept relies on the mechanical properties of balloons. The sleeve is used to hold two balloons in intended position of the arm and also to enhance the comfort of the device. When the two inserted balloons are inflated, the volume of balloons will increase and provide moment on the arm. Eventually, the moment generated due to inflation of the balloon will assist the movement of an arm to its full extension position.

Concept 2: Worm sleeve

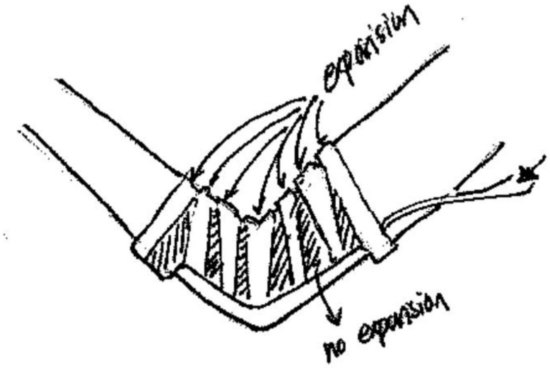


Figure B2

The worm sleeve is an idea that primarily depends on high air pressure. It consists of multiple ring shape air chambers each connected with air tubes. When manufacturing air chambers with silicone, we can use fiberglass to control the direction of expansion when they are inflated. By using this mechanism, the air chamber will push each other due to its axial direction expansion, and the pushing forces between air chamber will generate moment on the arm.

Concept 3: Air actuator along the arm muscle

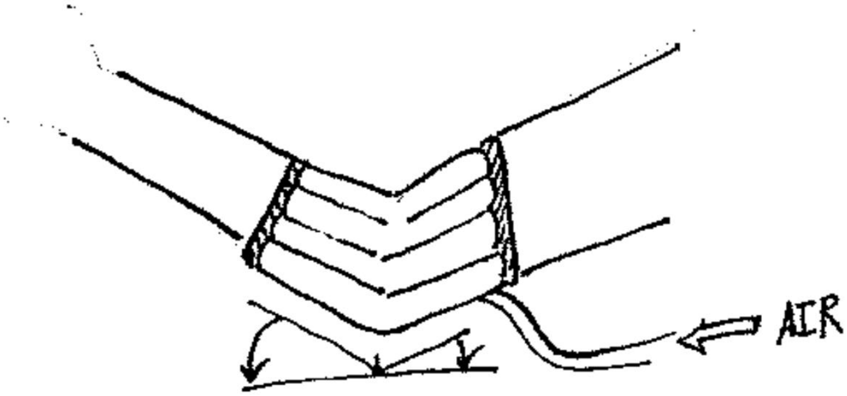


Figure B3

The concept of air actuator along the arm muscle primary use the mechanical property of air chamber. By restricting both axial and longitudinal direction expansion of the air chamber by wrapping the air chamber with fiberglass, all the force generated by high air pressure will be used to get back to original shape which is cylinder.

Concept 4: Fluid piston attached on the side of arm.

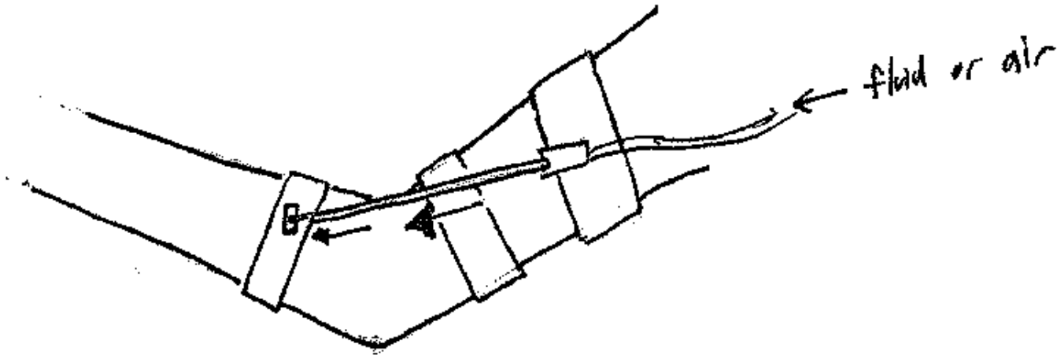


Figure B4

The concept relies on pushing force generated by fluid piston. Three vices will be used to hold the piston and piston arm. As the fluid is transferred through tube and fluid pressure increases, the piston will push piston arm which is attached to the vise on forearm. The primary advantage of this concept is the fact that all the force generated are transferred directly on to our intended position, whereas the force generated due to expansion of balloons is hard to control.

Concept 5: Vertical Air Actuator

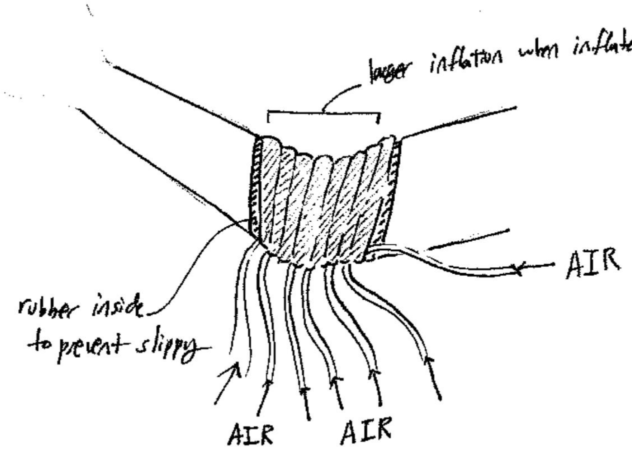


Figure B5

The primary advantage of this concept is its uncomplicated and straightforward usability. Since it is only constructed with groups of air chambers connected together with air tubes, the end user will not have hard time on learning how it operates. Moreover, because it is thoroughly made out of soft materials, such as silicone, it is light and portable which a patient can directly use in daily basis. In addition, due to its geometrical property, ring shape air chambers, the energy loss is expected to be less than other concepts that use air chamber or balloon as an actuator. Thus it will generate higher force and moment to patient’s arm. On other hands, there are some of disadvantages that must be considered. First, since the device is consisting of multiple air chambers connected side by side, the method of hold those in correct place must be solved. In short, it is hard to manufacture because numbers of air chamber are needed for each device.

Moreover, in order to expand the air chambers in axial direction, there must be high air pressure needed or we need to connect an air tube to each air chamber. In either way, the end user should carry heavy air pressure pump or the device will get too messy with many air tube attached.

Concept 6: Two Pistons

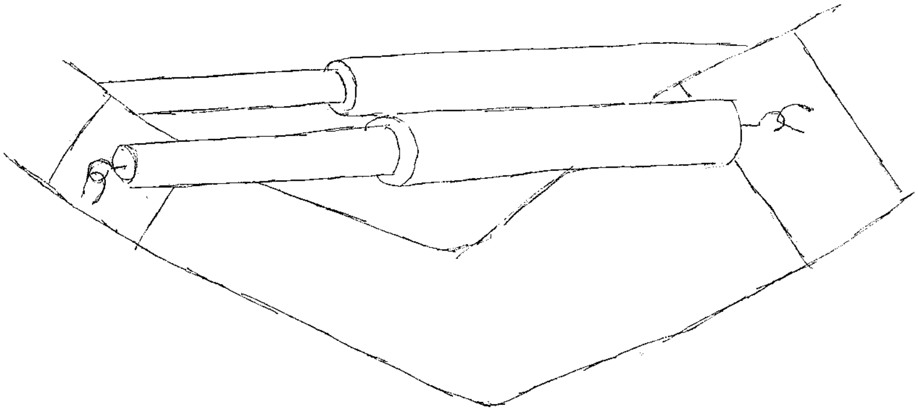


Figure B6

Two pistons are placed next to the arm. When the pistons are inflated, they are elongated. The elongations of piston will push the forearm outward, resulting in extension of the arm. The pistons are fixed with straps to the forearm and upper arm.

Concept 7: Josh's Air Tube Below the Elbow

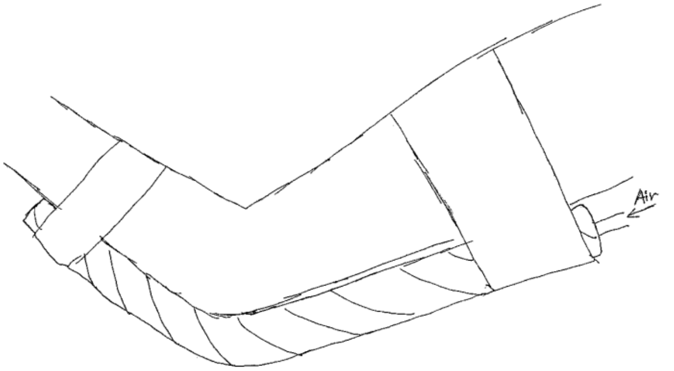


Figure B7

Our advisor Josh Bishop-Moser invented air tube that is winded up with strings in calculated shape to have desired change when it is pressurized. This design uses one of Josh's tube that contracts when pressurized. The tube is placed below the elbow. Air pressure will be applied to the tube when the arm is in bent position. The tube will contract and will pull the forearm so that the arm straightens.

Concept 8: Two of Josh's Air Tubes Next to an Arm

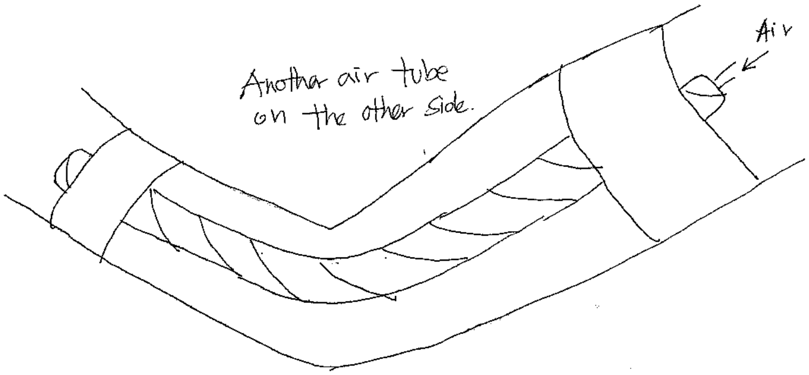


Figure B8

This concept uses other kind of air tube that Josh invented. It uses two of Josh's air tube that elongates when it is pressurized. The air tubes are placed next to an arm. When air is pressurized, they will push the arm outward to give extension to the arm.

Concept 9: Air Bag below the Elbow

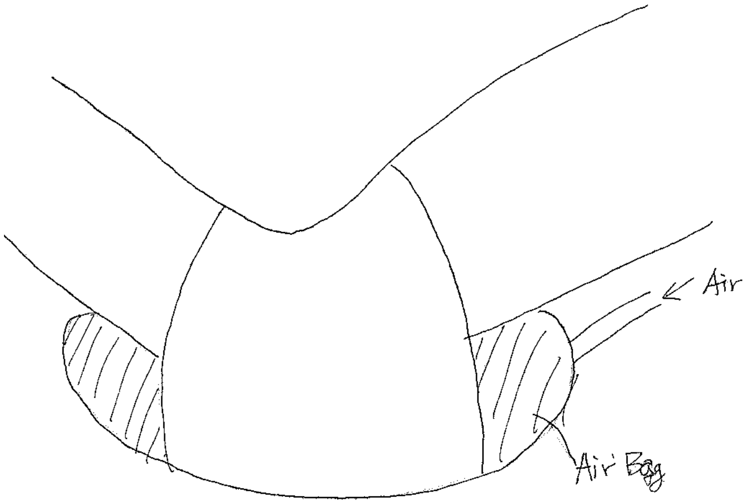


Figure B9

An air bag is placed under the elbow. When the airbag is inflated, the part that is bent due to the bent shape of the arm will expand, pushing the elbow since the air bag tends to expand radially. By pushing the elbow, the arm will be straightened.

Concept 10: Mini Balloons

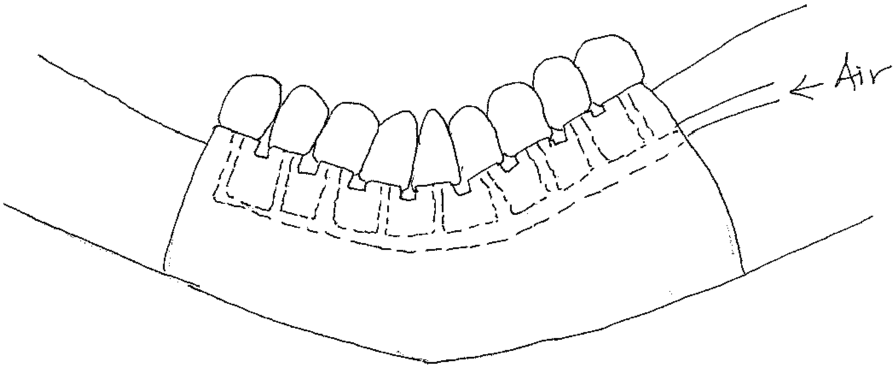


Figure B10

There are several small “balloons” that are aligned in parallel. When air pressure is applied to the device, the balloons are inflated all together. They will eventually pushing each other, providing expanding motion for the impaired arm.

Concept 11: Artificial Muscle Driven Actuator

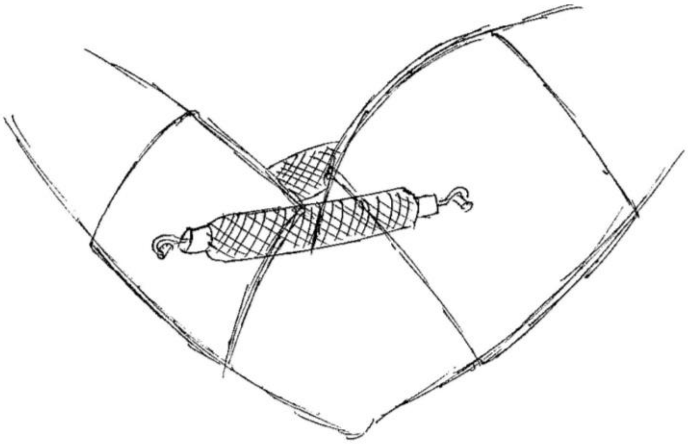


Figure B11

Artificial muscle is a kind to actuator that can transfer potential energy in fluid to linear shrinking motion. This function is very similar to real muscle. So in this design, we attach three muscle to the back surface of arm, so that when compressed air is inflated, the muscle can assist the motion of arm just like real muscle.

Concept 12: Double-Chamber Sleeve

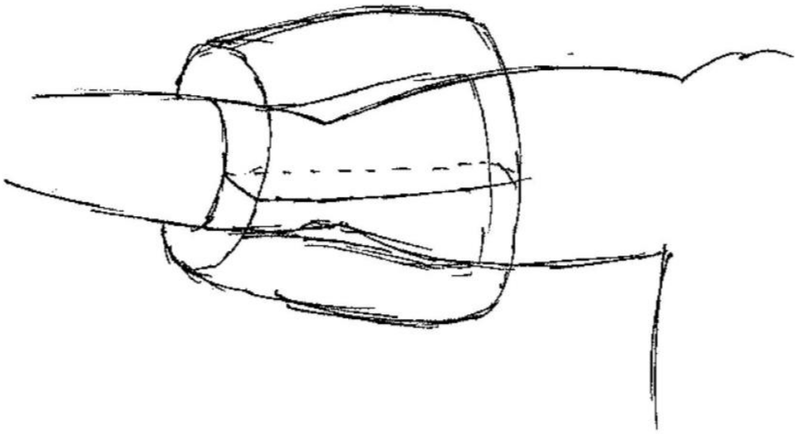


Figure B12

The double-chamber sleeve is basically a cylindrical sleeve consists of two parallel air bag which has been made into specific shape before assembling. The difference between this and two-balloon sleeve is that for double-chamber actuator, two air bags they for a sleeve without the assistance of additional materials such as cloths or latex. The advantage of this design is that it will be lighter, while the difficulties of manufacturing also increase.

Concept 13: Metal-Ring Worm Sleeve

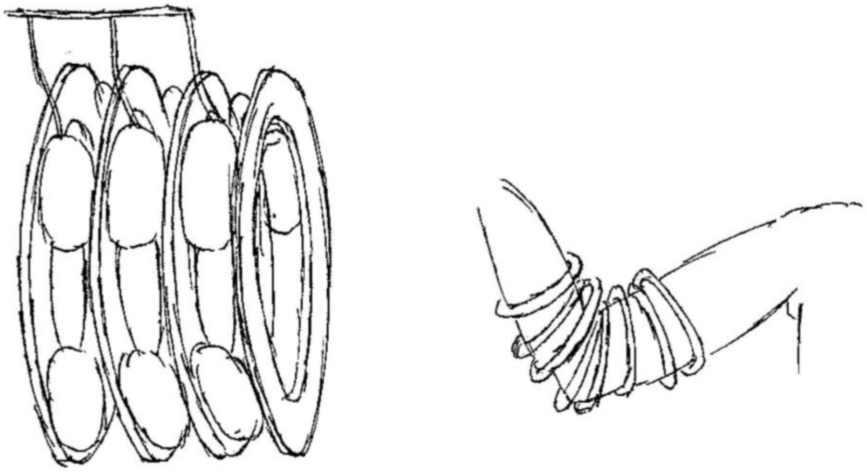


Figure B13

Metal-ring sleeve is a worm-like actuator. It consists of a series of parallel metal-rings, between which four tiny air-balloons are glued. Each line of balloons are connected together and also connected to air pump. Balloon are controlled independently between each lines. When one line of balloons are inflated, these balloon will therefore push the rings away from each other. This kind of off-axis extension will eventually cause sleeve to bend to one direction. So when human can put on one sleeve on their elbow. We can achieve the assistance in motion by controlling the inflating of four lines of balloons.

Concept 14: Drum-Pile Actuator

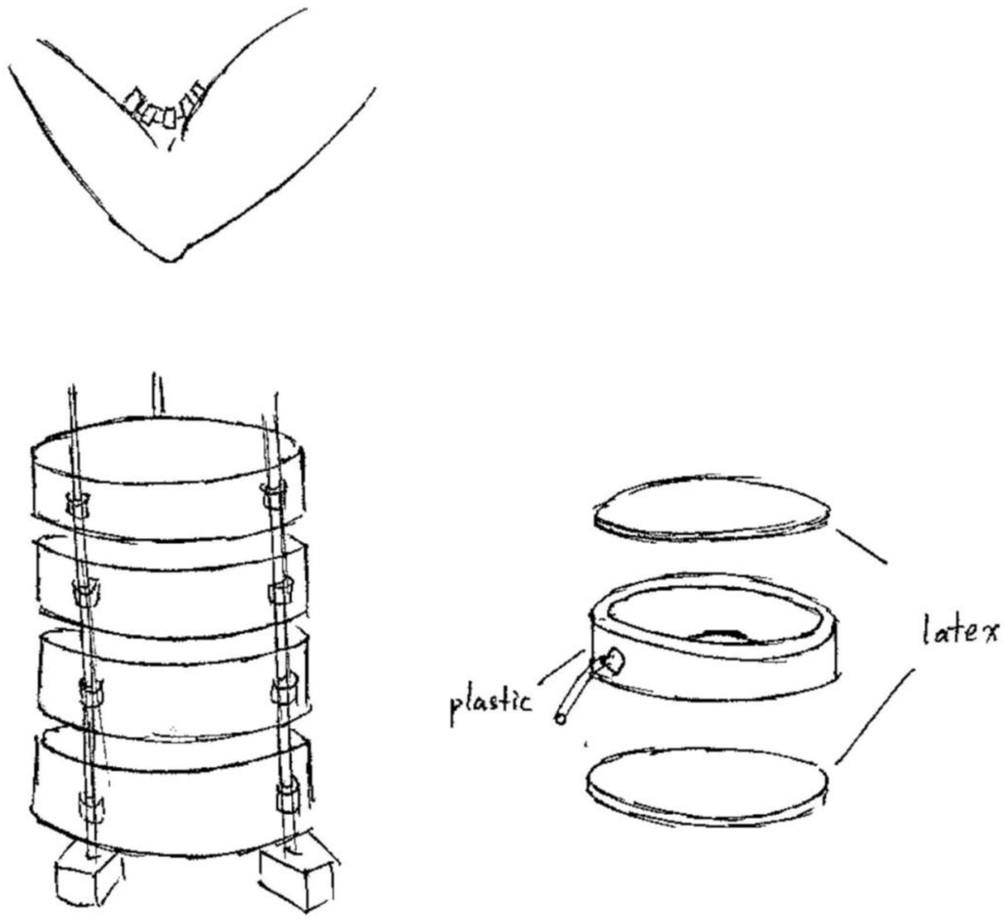


Figure B14

This actuator consists of a piles of drums-like air chambers. For each “drum”, there are two thin latex covered on each ends. When the “drum” is inflated, its two latex coverings will tends to expend, which when in a piles, the total pile of actuator will expending linearly. Now there are three constraint string attached on the surface of the drum pile, 120 degrees away from each other’s. The string serves as a constraint that can prevent the expending of drum-pile near it. This off-axis constraint will also eventually cause the bending of actuator. The outstanding feature of this kind of actuator is that, through the combination of string-constraint, different motion of actuator can be achieved. When n strings are attached, up to 2^n can be generated.

Concept 15: Origami Actuator

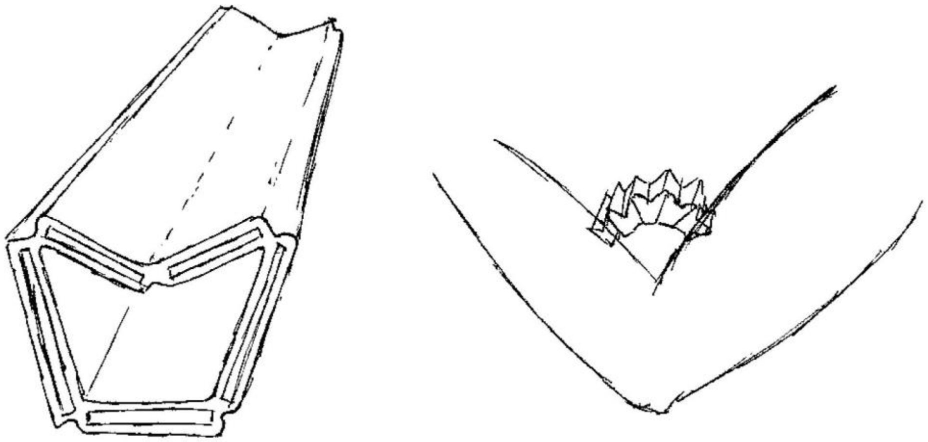


Figure B15

Origami actuator is a kind of actuator with rigid surface that can achieve certain kind of motion when inflated. It’s actually a novel field in pneumatic actuator designing. One example of origami actuator is shown here, the actuator consists of 5 pieces of rectangular boards which are embedded in silicon coating. When inflated, the pressured air inside can push two side board to extend. When connected in parallel, angular motion will be generated.

Concept 16: Piston-Cylinder Linkage

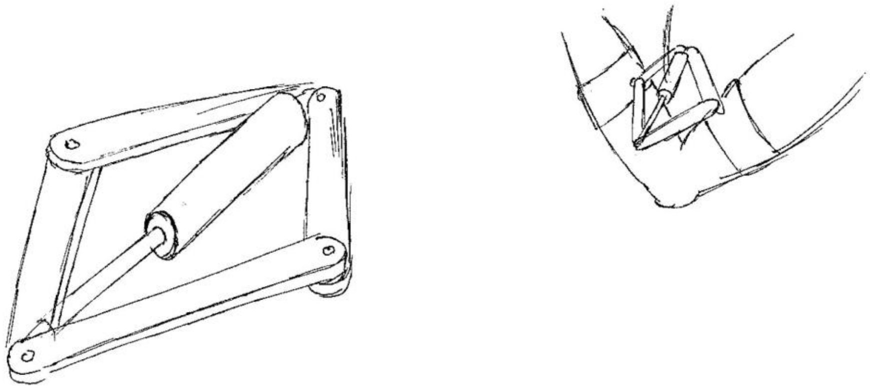


Figure B16

This piston-cylinder linkage actuator consists of one piston-cylinder and four bars which are connected as is shown in Fig. B16. The two symmetric joints can be connected to the sleeve on arm. Piston-cylinder can transform air pressure into force and linkage structure can change the direction for 90 degrees so that it can extend arm.

Concept 17: Body Power Design

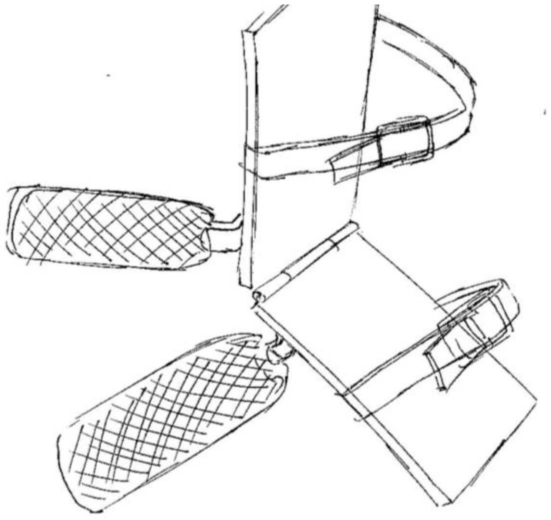


Figure B17

The body power structure doesn't include an external actuator, but instead, let user to control the motion of harmed arm by the healthy one. As is shown in the Fig. B17, two paddles are connected by a link, and each paddle have one handler on it. For instance, if patient want to extend his or her right arm, what he needs to do is only to grab the handler on the device, and his or her right forearm can extend.

Concept 18: Improved electro-stimulator

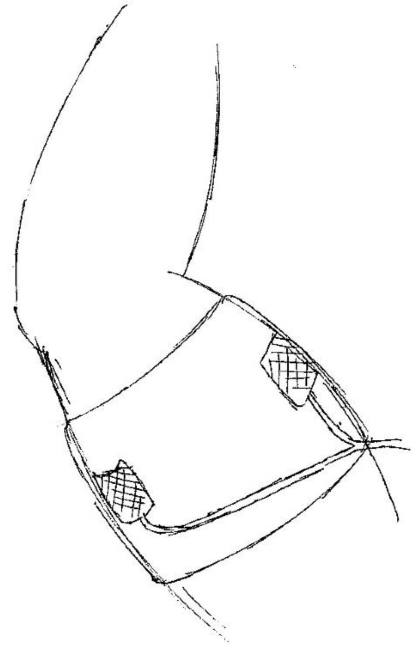


Figure B18

This is the electro stimulator design. Comparing to previous design, it has an additional sleeve that can make the device more comfortable to wear and more stable during operation. In addition, all the wires are clustered so less wires will projected out, which makes the device simpler for end users.

Concept 19: Dual Motor with Pulley on the Arm

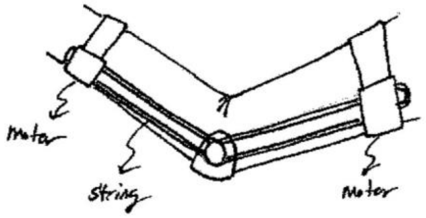


Figure B19

The device of this concept uses pulling force created by string, pulley, and motor. The motors are attached at each forearm and upper arm and pulley is installed at the side of an elbow. The arm will extend or bend depends on which motor provide pulling force to the string. Thus, the main advantage of this concept is backdrivability which other concepts with balloons and air pressures are hard to achieve. However, since it requires electrical motor, it has downside in terms of weight and portability.

Concept 20: Dual String and Motors

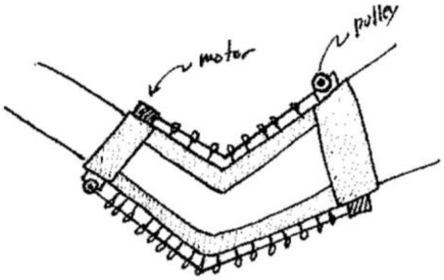


Figure B20

This concept relies on pulling force generated by motor and string. Two motors are attached on upper portion of upper arm and under portion of forearm. In addition, sleeves are used to hold hooks which the strings are passing through. Each motor and pulley are controlled independently. For example, if a user wants to expand the arm, he needs to operate motor on his upper arm so that the force generated by motor pull the string and arm is extended. This main advantage of this device is backdrivability and the primary disadvantage is weight and noise due to operation of motor.

Concept 21: Conveyor-motor

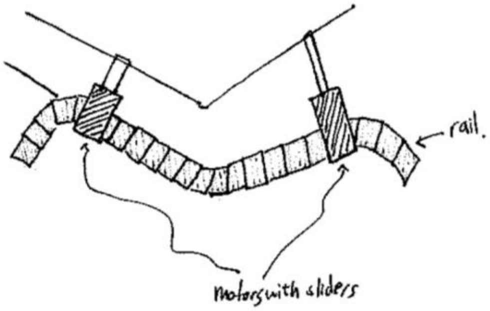


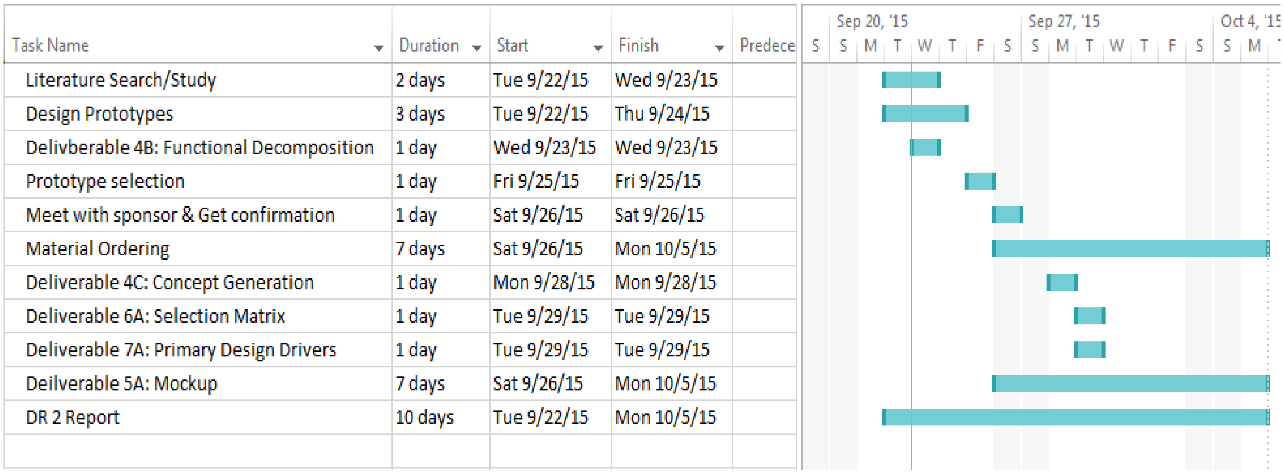
Figure B21

In this servomotor-conveyor concept, we use conveyor belt to take the place of string in previous servomotor-string concepts. Since conveyor belt provide larger contact area compared with string, it is predicted to be more stable. Thus, the main advantage of this concept comparing with other string-motor concept is the stability. On the other hand, the major disadvantage is larger energy consumption which results larger motor or battery.

Appendix C: Project Plans

DR2 PROJECT PLAN

By the time of Design Review 2, we plan to finish the actuator design and purchase materials we need for the project. Also, we will spend time on deliverables.

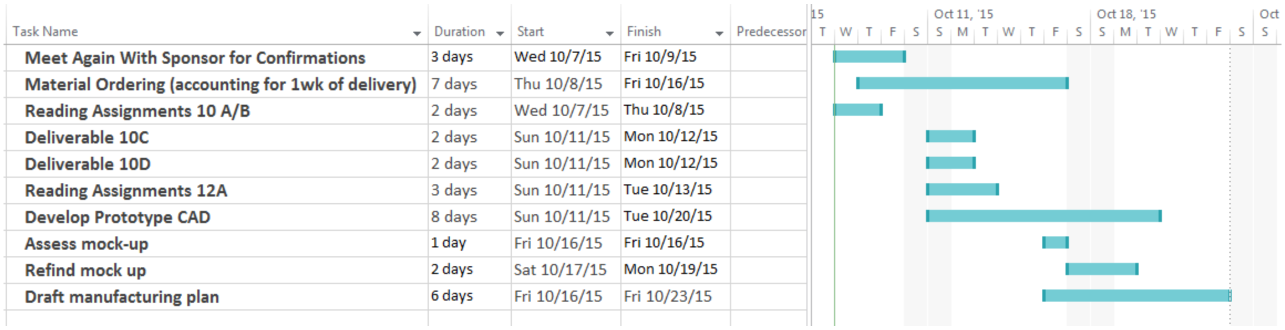


Task Name	Duration	Start	Finish	Predece
Literature Search/Study	2 days	Tue 9/22/15	Wed 9/23/15	
Design Prototypes	3 days	Tue 9/22/15	Thu 9/24/15	
Delivberable 4B: Functional Decomposition	1 day	Wed 9/23/15	Wed 9/23/15	
Prototype selection	1 day	Fri 9/25/15	Fri 9/25/15	
Meet with sponsor & Get confirmation	1 day	Sat 9/26/15	Sat 9/26/15	
Material Ordering	7 days	Sat 9/26/15	Mon 10/5/15	
Deliverable 4C: Concept Generation	1 day	Mon 9/28/15	Mon 9/28/15	
Deliverable 6A: Selection Matrix	1 day	Tue 9/29/15	Tue 9/29/15	
Deliverable 7A: Primary Design Drivers	1 day	Tue 9/29/15	Tue 9/29/15	
Deilverable 5A: Mockup	7 days	Sat 9/26/15	Mon 10/5/15	
DR 2 Report	10 days	Tue 9/22/15	Mon 10/5/15	

Figure C1: Project Gantt Chart for Design Review 2

DR3 PROJECT PLAN

By the time of Design Review 3, we plan to meet with our sponsor to discuss about our mockup. We will be preparing to build the prototype.

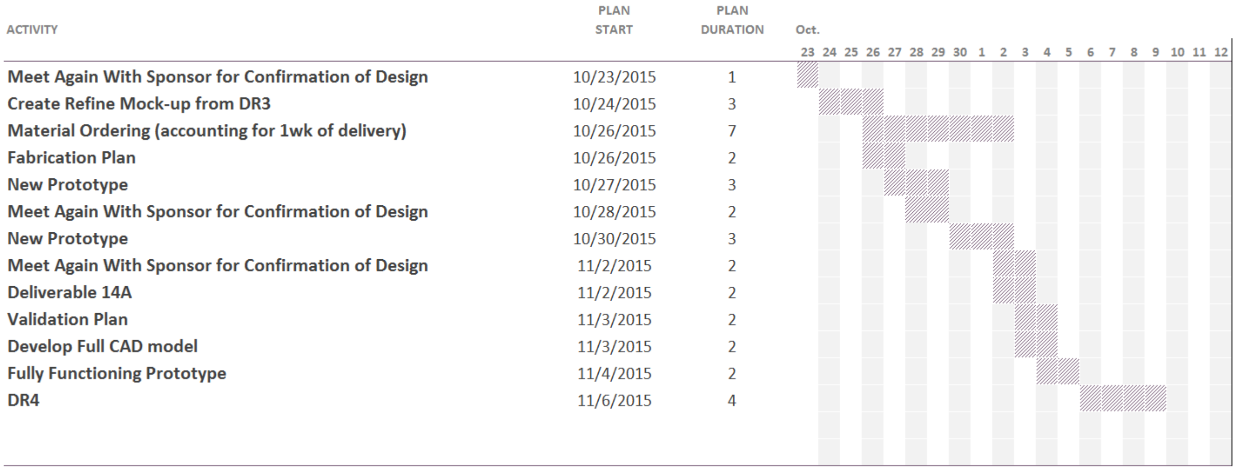


Task Name	Duration	Start	Finish	Predecessor
Meet Again With Sponsor for Confirmations	3 days	Wed 10/7/15	Fri 10/9/15	
Material Ordering (accounting for 1wk of delivery)	7 days	Thu 10/8/15	Fri 10/16/15	
Reading Assignments 10 A/B	2 days	Wed 10/7/15	Thu 10/8/15	
Deliverable 10C	2 days	Sun 10/11/15	Mon 10/12/15	
Deliverable 10D	2 days	Sun 10/11/15	Mon 10/12/15	
Reading Assignments 12A	3 days	Sun 10/11/15	Tue 10/13/15	
Develop Prototype CAD	8 days	Sun 10/11/15	Tue 10/20/15	
Assess mock-up	1 day	Fri 10/16/15	Fri 10/16/15	
Refind mock up	2 days	Sat 10/17/15	Mon 10/19/15	
Draft manufacturing plan	6 days	Fri 10/16/15	Fri 10/23/15	

Figure C2: Project Gantt Chart for Design Review 3

DR4 PROJECT PLAN

By the time of Design Review 4, we plan to have our final design that meets all the requirements. We are also planning to build the prototype.

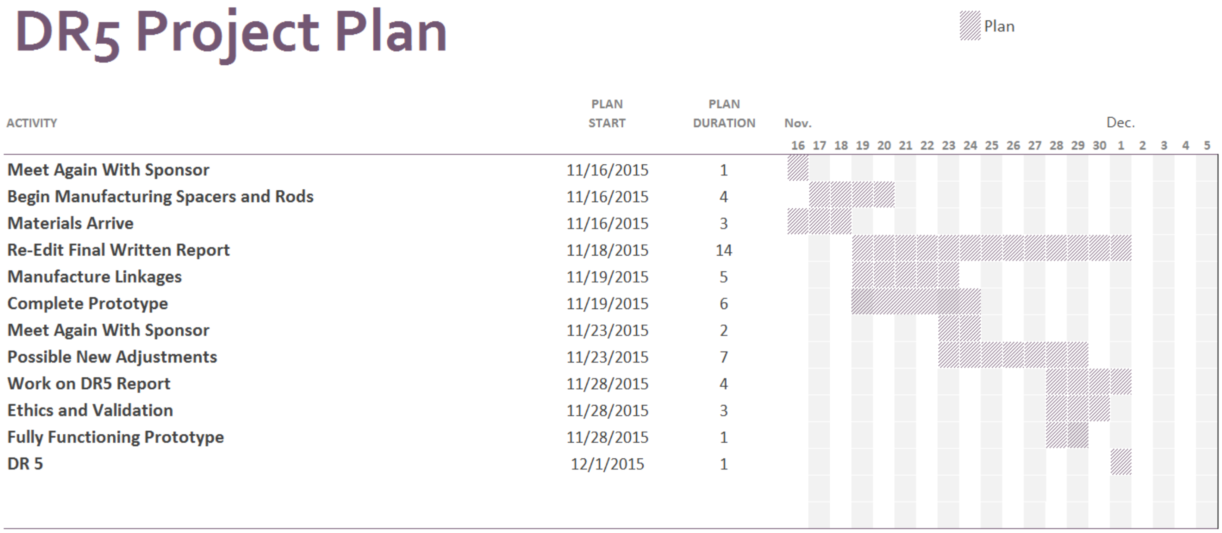


ACTIVITY	PLAN START	PLAN DURATION
Meet Again With Sponsor for Confirmation of Design	10/23/2015	1
Create Refine Mock-up from DR3	10/24/2015	3
Material Ordering (accounting for 1wk of delivery)	10/26/2015	7
Fabrication Plan	10/26/2015	2
New Prototype	10/27/2015	3
Meet Again With Sponsor for Confirmation of Design	10/28/2015	2
New Prototype	10/30/2015	3
Meet Again With Sponsor for Confirmation of Design	11/2/2015	2
Deliverable 14A	11/2/2015	2
Validation Plan	11/3/2015	2
Develop Full CAD model	11/3/2015	2
Fully Functioning Prototype	11/4/2015	2
DR4	11/6/2015	4

Figure C3: Project Gantt Chart for Design Review 4

DR5 PROJECT PLAN

By the time of Design Review 5, we plan to finish manufacturing and assembling final design that meets all the requirements.



DR5 Project Plan

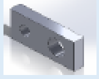
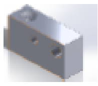
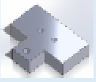
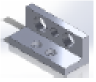
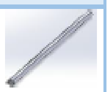
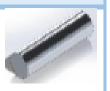
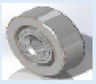
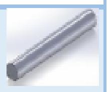
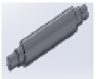
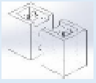
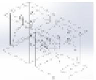
▨ Plan

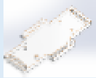
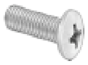
ACTIVITY	PLAN START	PLAN DURATION
Meet Again With Sponsor	11/16/2015	1
Begin Manufacturing Spacers and Rods	11/16/2015	4
Materials Arrive	11/16/2015	3
Re-Edit Final Written Report	11/18/2015	14
Manufacture Linkages	11/19/2015	5
Complete Prototype	11/19/2015	6
Meet Again With Sponsor	11/23/2015	2
Possible New Adjustments	11/23/2015	7
Work on DR5 Report	11/28/2015	4
Ethics and Validation	11/28/2015	3
Fully Functioning Prototype	11/28/2015	1
DR 5	12/1/2015	1

Appendix D: Concept Comparisons

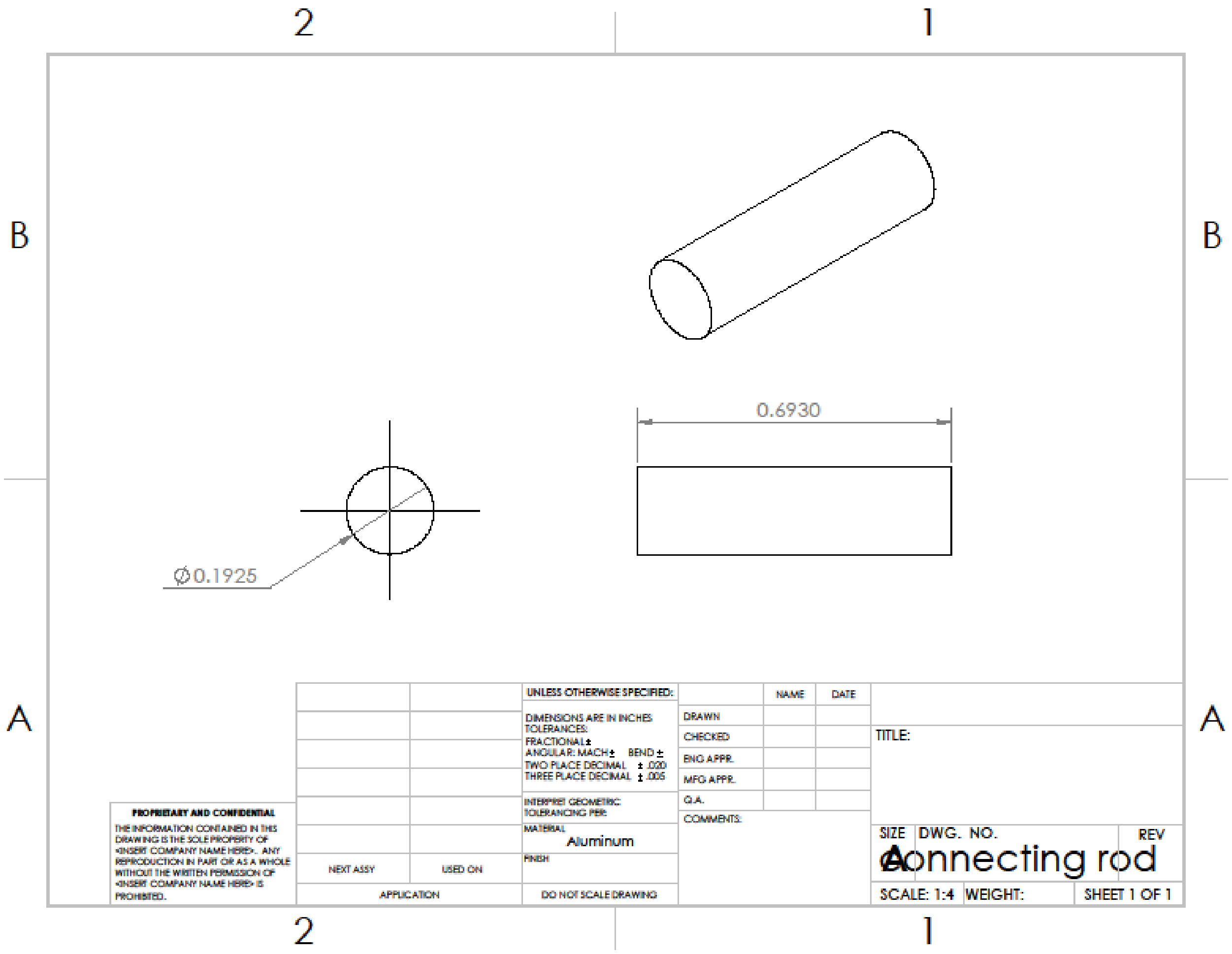
	Description ->	airbag	Piston + Linkage	2 pistons	Josh's	sleeve with two actuators	vertical air actuators	Stringed Pulleys	Electrodes on "Triceps"
Design Parameter	Weight	"Standard" Design	Design Concept 2	Design Concept 3	Design Concept 4	Design Concept 5	Design Concept 6	Design Concept 7	Design Concept 8
Noise	1	0	-1	-1	-1	0	-1	0	N/A
Moment generated	5	0	1	1	0	1	1	2	N/A
Life Cycle	4	0	-2	-2	-2	3	-1	-2	N/A
Operation Time	3	0	-1	-2	0	-2	-1	0	N/A
Volume	4	0	-2	-2	-1	3	2	1	N/A
Weight	3	0	-2	-2	-3	3	1	-1	N/A
Material Strength	2	0	3	2	2	-1	-2	0	N/A
Power Consumption	2	0	1	1	2	0	0	-2	N/A
Price	3	0	-1	-2	2	2	2	-3	N/A
Roughness	3	0	-1	-4	-3	-2	-2	-1	N/A
SUM		0	-19	-36	-17	30	4	-13	#VALUE!

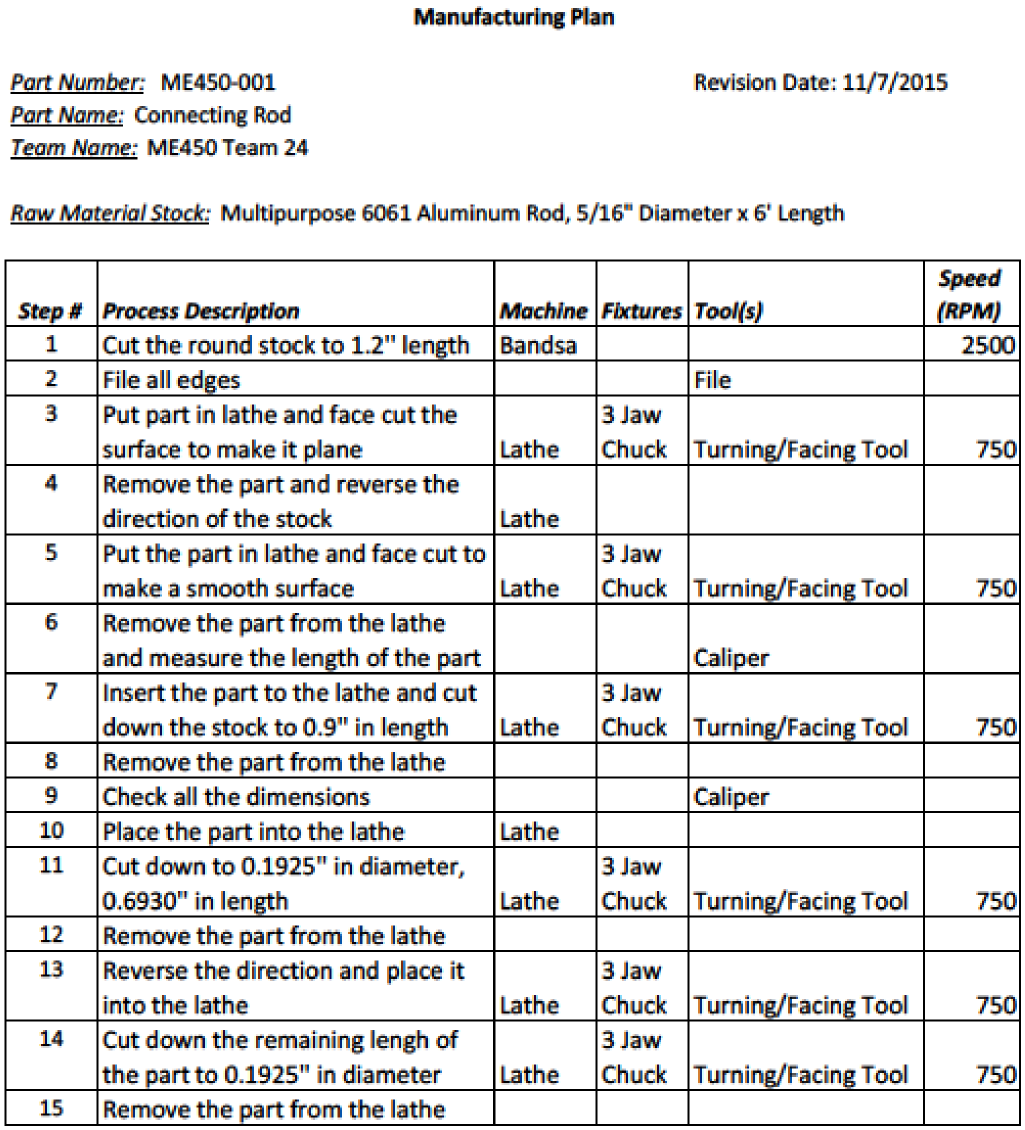
Appendix E: Bill of Materials

Part	Part Name	Part Number	Supplier	Cost ($)	Picture
1	Bar connector back	Multipurpose 6061 Aluminum, 1/2" Thick, 6" Width, 1' Length (8975K219)	McMaster-Carr	29.24	
2	Front Bar connector	Multipurpose 6061 Aluminum, 1/2" Thick, 6" Width, 1' Length (8975K219)	McMaster-Carr	Included in 1	
3	Base Plate	Multipurpose 6061 Aluminum, 1/2" Thick, 6" Width, 1' Length (8975K219)	McMaster-Carr	Included in 1	
4	Piston Block(Back)	Multipurpose 6061 Aluminum, Rectangular Bar, 1" x 1", 1/2' Long (9008K14)	McMaster-Carr	Included in 1	
5	Piston Block (front)	Multipurpose 6061 Aluminum, 1/2" Thick, 6" Width, 1' Length (8975K219)	McMaster-Carr	4.03	
6	Center Bar	Multipurpose 6061 Aluminum Rod, 5/16" Diameter x 6' Length (8974K23)	McMaster-Carr	12.68	
7	Connecting Rod (Base to upper arm)	Multipurpose 6061 Aluminum Rod, 5/16" Diameter x 6' Length (8974K23)	McMaster-Carr	Included in 6	
8	Connecting Rod	Multipurpose 6061 Aluminum Rod, 5/16" Diameter x 6' Length (8974K23)	McMaster-Carr	Included in 6	
9	Fore arm bearing	Steel Ball Bearing, Plain Open for 3/16" Shaft Diameter, 11/16" OD, 1/4" Wide (6383K11)	McMaster-Carr	3.28 each	
10	Fore arm Frame	Multipurpose 6061 Aluminum with Certification, Precision Ground Blank, 1/4" Thick, 12" x 18" Size	McMaster-Carr	given	
11	Piston and fore arm axis	Multipurpose 6061 Aluminum Rod, 5/16" Diameter x 6' Length (8974K23)	McMaster-Carr	Included in 6	
12	Air Cylinder Piston	Airport Airpel Anti-stiction Air Cylinder Double-Acting (E16D2.0U)	Airpot Corporation	given	
13	Thrust Ball bearing (between base and upper arm)	Steel Thrust Ball Bearing, Steel Washers, for 3/16" Shaft Diameter, 1/2" OD (6655K12)	McMaster-Carr	2.09 each	
14	Upper Arm frame	Multipurpose 6061 Aluminum with Certification, Precision Ground Blank, 1/4" Thick, 12" x 18" Size	McMaster-Carr	given	
15	Mold lower	ABS Plastic	University of Michigan 3-D Printing Lab	TBD	
16	Mold Upper	ABS Plastic	University of Michigan 3-D Printing Lab	TBD	
17	Nut	Zinc Aluminum Coated Steel Thin Hex Nut, Grade 8, 5/16"-18 Thread Size, 1/2" Wide, 3/16" High	McMaster-Carr	8.68pkg	

18	Lower Silicone Base Plate	White Delrin Acetal Resin Sheet, 3/16" Thick, 24" x 24" (8574K74)	McMaster-Carr	70.66	
19	Upper Silicone Base Plate	White Delrin Acetal Resin Sheet, 3/16" Thick, 24" x 24" (8574K74)	McMaster-Carr	Included in 20	
20	Screws	Type 316 Stainless Steel Pan Head Phillips Machine Screw, 10-32 Thread, 1/2" Length (91735A829)	McMaster-Carr	4.98 pkg	
21	Locknuts	Low-Strength Steel Thin Nylon-Insert Locknut, Zinc-Plated, 10-32 Thread Size, 3/8" Wide, 11/64" High	McMaster-Carr	3.18 pkg	
22	Nuts for cylinders	Type 316 Stainless Steel Hex Nut, 7/16"-20 Thread Size, 11/16" Wide, 3/8" High (94804A335)	McMaster-Carr	4.70 pkg	
23	Nuts	Class 04 Steel Thin Hex Nut - DIN 439B, Zinx Plated, M3x0.5 Thread Size, 5.5mm Wide, 1.8mm High	McMaster-Carr	3.10 pkg	
24	Washers	Type 316 Stainless Steel Flat Washer, M3 Screw Size, 3.2mm ID, 7.0mm OD (90965A130)	McMaster-Carr	7.50 pkg	
25	Screws	Class 12.9 Socket Head Cap Screw, Zinc-Plated Aly Steel, M3 Thread, 16mm Long, .5mm Pitch	McMaster-Carr	3.90 pkg	
26	Silicon Support (Upper Arm)	Dragon Skin 10 Medium Trial Size	Smooth-On	30.1	
27	Silicon Support (Fore Arm)	Dragon Skin 10 Medium Trial Size	Smooth-On	30.1	

Appendix F: Manufacturing Drawings and Plans



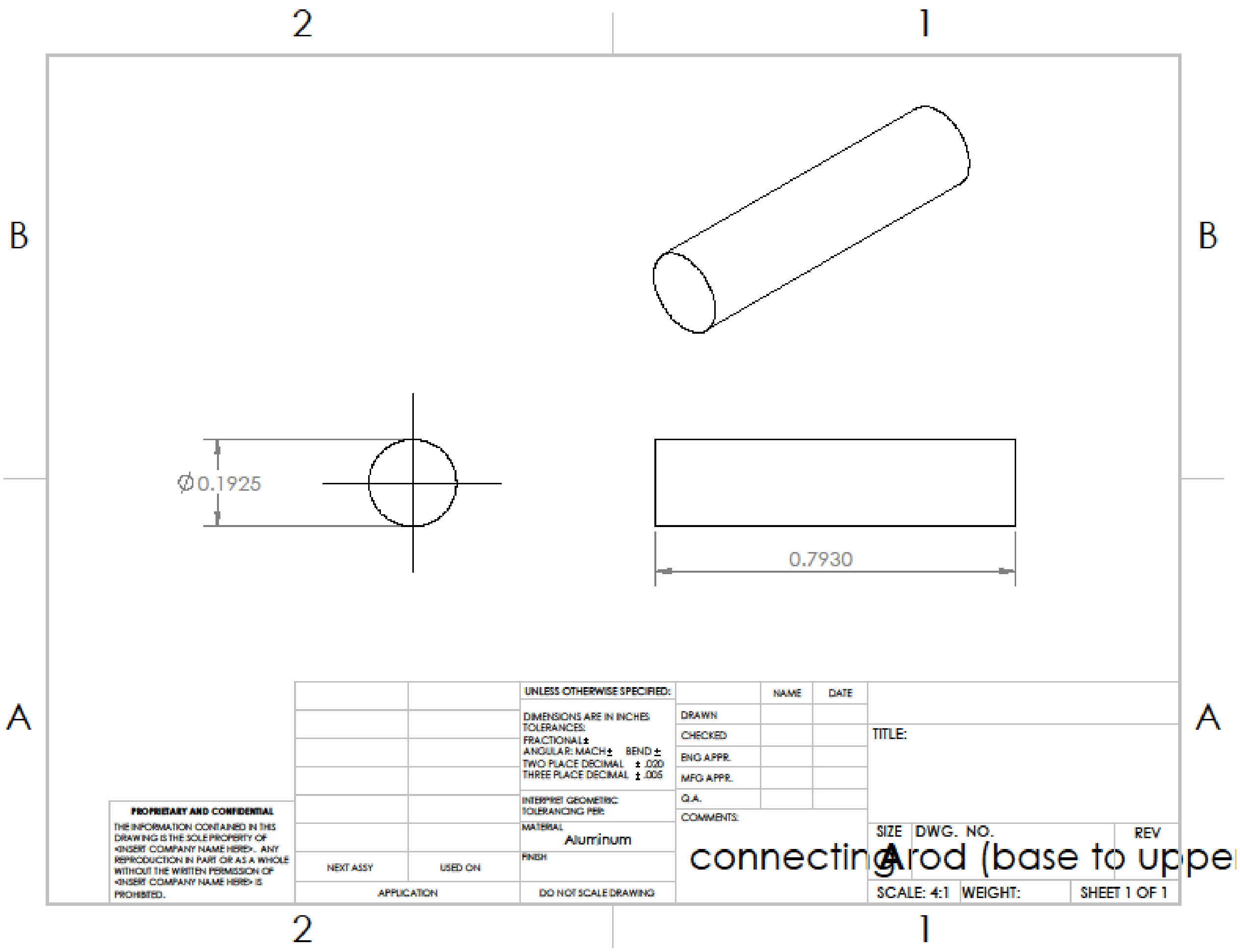


Manufacturing Plan

Part Number: ME450-001 Revision Date: 11/7/2015
Part Name: Connecting Rod
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum Rod, 5/16" Diameter x 6' Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut the round stock to 1.2" length	Bandsa			2500
2	File all edges			File	
3	Put part in lathe and face cut the surface to make it plane	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
4	Remove the part and reverse the direction of the stock	Lathe			
5	Put the part in lathe and face cut to make a smooth surface	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
6	Remove the part from the lathe and measure the length of the part			Caliper	
7	Insert the part to the lathe and cut down the stock to 0.9" in length	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
8	Remove the part from the lathe				
9	Check all the dimensions			Caliper	
10	Place the part into the lathe	Lathe			
11	Cut down to 0.1925" in diameter, 0.6930" in length	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
12	Remove the part from the lathe				
13	Reverse the direction and place it into the lathe	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
14	Cut down the remaining lengh of the part to 0.1925" in diameter	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
15	Remove the part from the lathe				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INTERPRET GEOMETRIC TOLERANCING PER:
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connecting rod (base to uppe
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SHEET 1 OF 1
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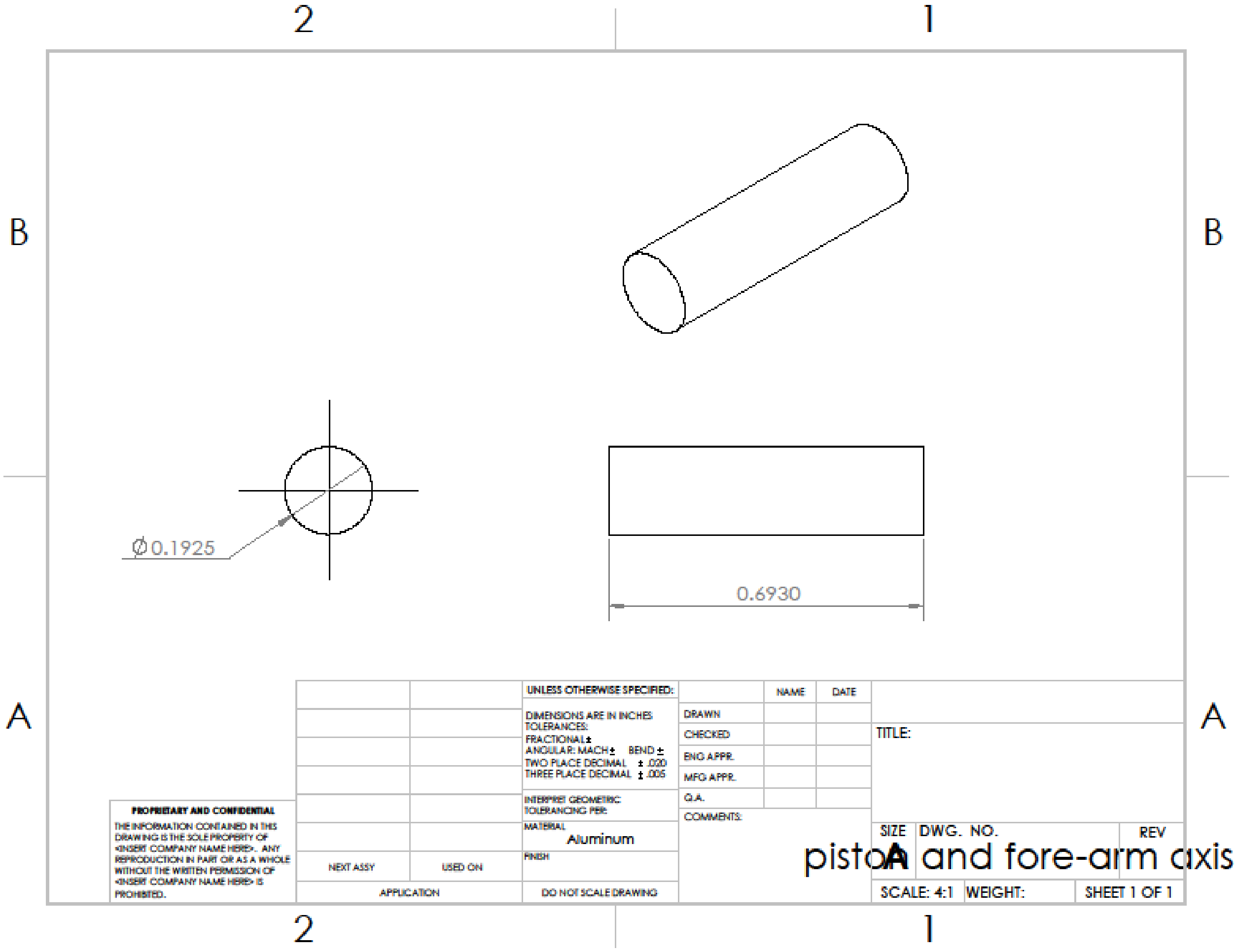
Manufacturing Plan

Part Number: ME450-002 Revision Date: 11/7/2015
Part Name: Connecting Rod (base to upper arm)
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum Rod, 5/16" Diameter x 6' Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut the round stock to 1.4" length	Bandsaw			2500
2	File all edges			File	
3	Put part in lathe and face cut the surface to make it plane	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
4	Remove the part and reverse the direction of the stock	Lathe			
5	Put the part in lathe and face cut to make a smooth surface	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
6	Remove the part from the lathe and measure the length of the part			Caliper	
7	Insert the part to the lathe and cut down the stock to 1.2" in length	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
8	Remove the part from the lathe				
9	Check all the dimensions			Caliper	
10	Place the part into the lathe	Lathe			
11	Cut down to 0.1925" in diameter, 0.7930" in length	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
12	Remove the part from the lathe				
13	Reverse the direction and place it into the lathe	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
14	Cut down the remaining lengh of the part to 0.1925" in diameter	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
15	Remove the part from the lathe				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ANGULAR: MACH ± BEND ±
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THREE PLACE DECIMAL ± .005
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piston and fore-arm axis
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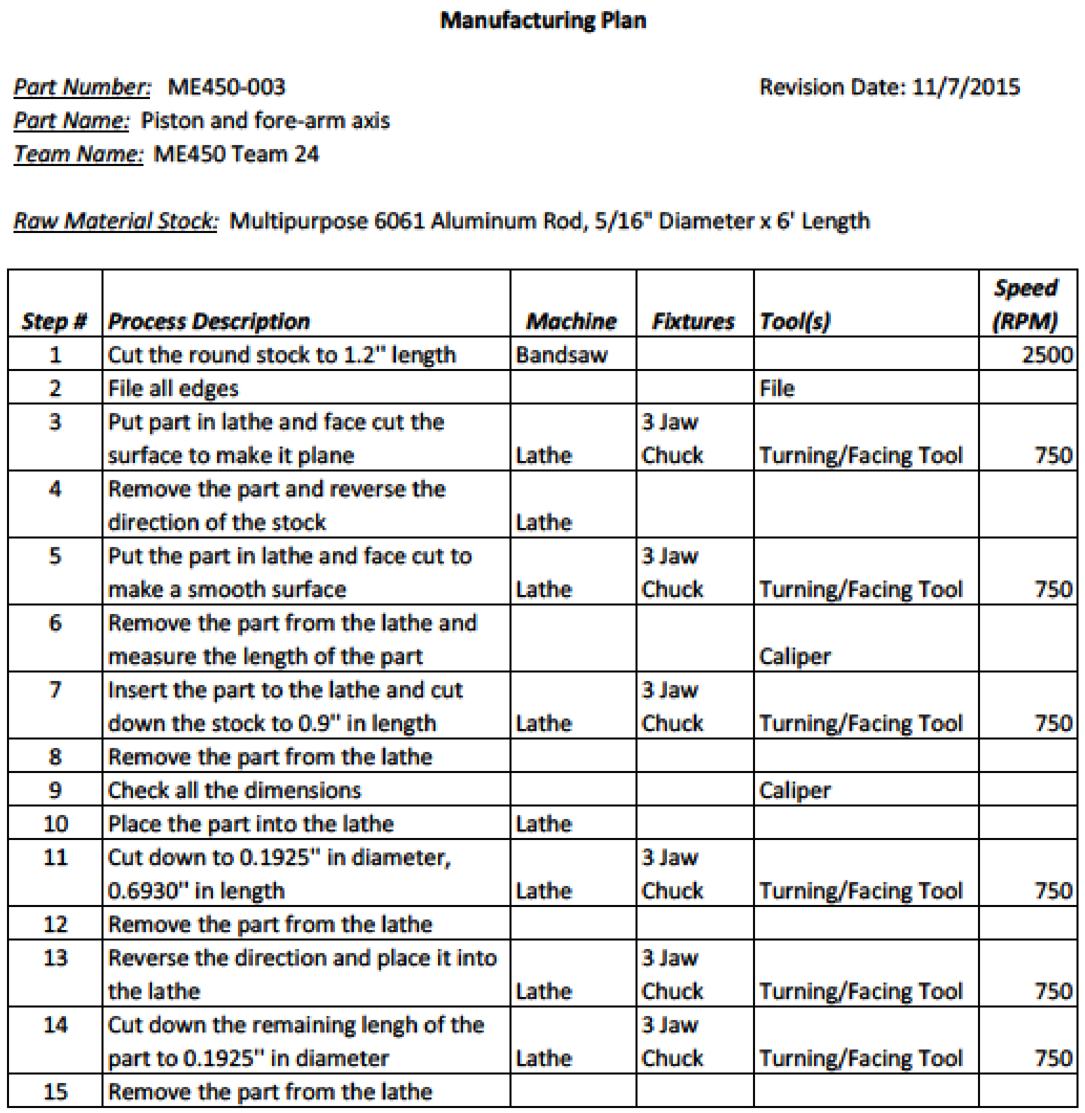
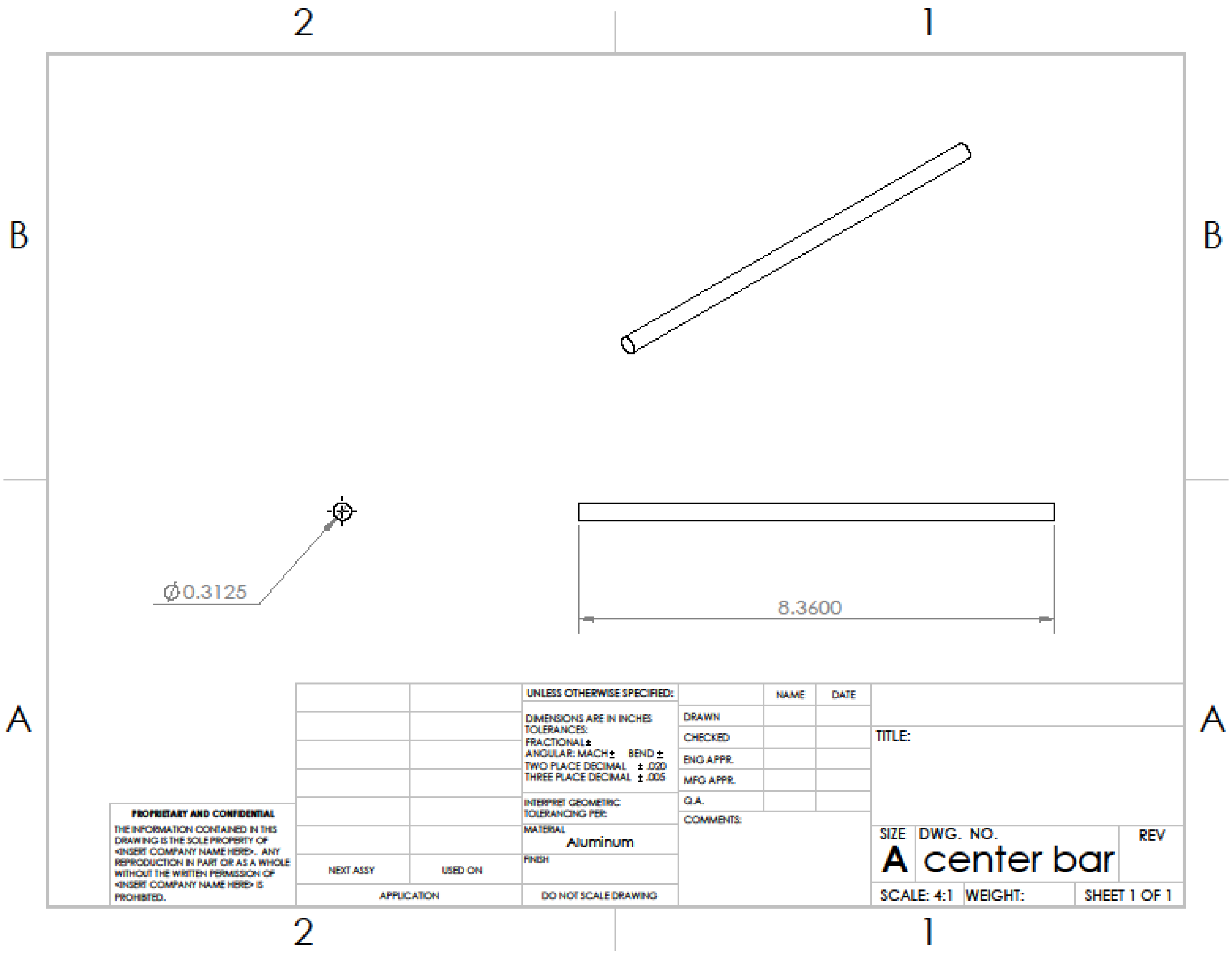


Manufacturing Plan

Part Number: ME450-003 Revision Date: 11/7/2015
Part Name: Piston and fore-arm axis
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum Rod, 5/16" Diameter x 6' Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut the round stock to 1.2" length	Bandsaw			2500
2	File all edges			File	
3	Put part in lathe and face cut the surface to make it plane	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
4	Remove the part and reverse the direction of the stock	Lathe			
5	Put the part in lathe and face cut to make a smooth surface	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
6	Remove the part from the lathe and measure the length of the part			Caliper	
7	Insert the part to the lathe and cut down the stock to 0.9" in length	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
8	Remove the part from the lathe				
9	Check all the dimensions			Caliper	
10	Place the part into the lathe	Lathe			
11	Cut down to 0.1925" in diameter, 0.6930" in length	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
12	Remove the part from the lathe				
13	Reverse the direction and place it into the lathe	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
14	Cut down the remaining lengh of the part to 0.1925" in diameter	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
15	Remove the part from the lathe				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UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± .020
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
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DO NOT SCALE DRAWING
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center bar
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SCALE: 4:1
WEIGHT:
SHEET 1 OF 1
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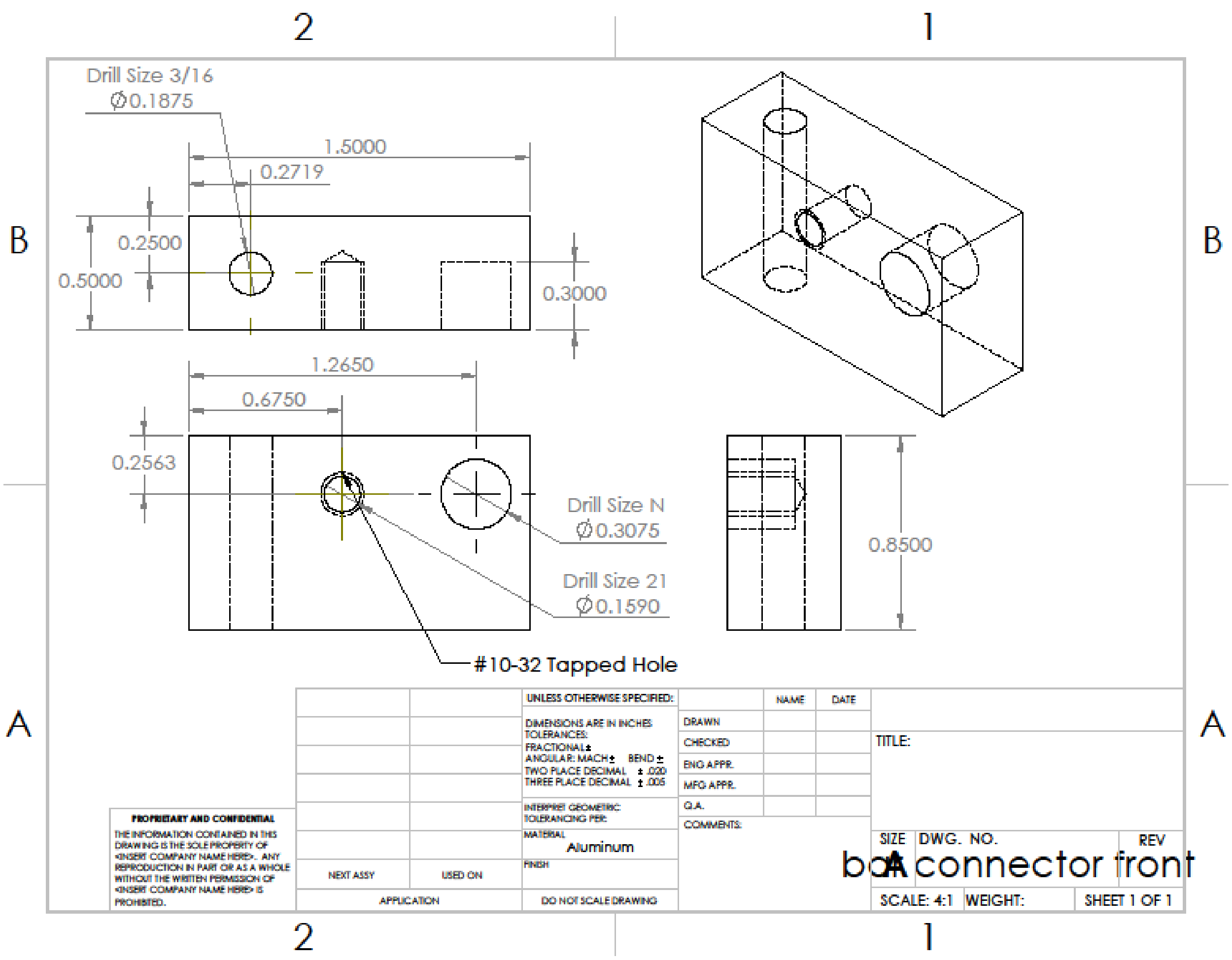
Manufacturing Plan

Part Number: ME450-004 Revision Date: 11/7/2015
Part Name: Center bar
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum Rod, 5/16" Diameter x 6' Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut the round stock to 8.8" length	Bandsaw			2500
2	File all edges			File	
3	Put part in lathe and face cut the surface to make it plane	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
4	Remove the part and reverse the direction of the stock	Lathe			
5	Put the part in lathe and face cut to make a smooth surface	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
6	Remove the part from the lathe and measure the length of the part			Caliper	
7	Insert the part to the lathe and cut down the stock to 8.6" in length	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
8	Remove the part from the lathe				
9	Check all the dimensions			Caliper	
10	Place the part into the lathe	Lathe			
11	Cut down to 8.360" in length	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
12	Remove the part from the lathe				
13	Reverse the direction and place it into the lathe	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
14	Cut down the remaining lengh	Lathe	3 Jaw Chuck	Turning/Facing Tool	750
15	Remove the part from the lathe				


2
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Drill Size 3/16
∅0.1875
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0.2719
0.2500
0.5000
0.3000
1.2650
0.6750
0.2563
Drill Size N
∅0.3075
Drill Size 21
∅0.1590
0.8500
#10-32 Tapped Hole
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±.020
THREE PLACE DECIMAL ±.005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
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REV
box connector front
SCALE: 4:1
WEIGHT:
SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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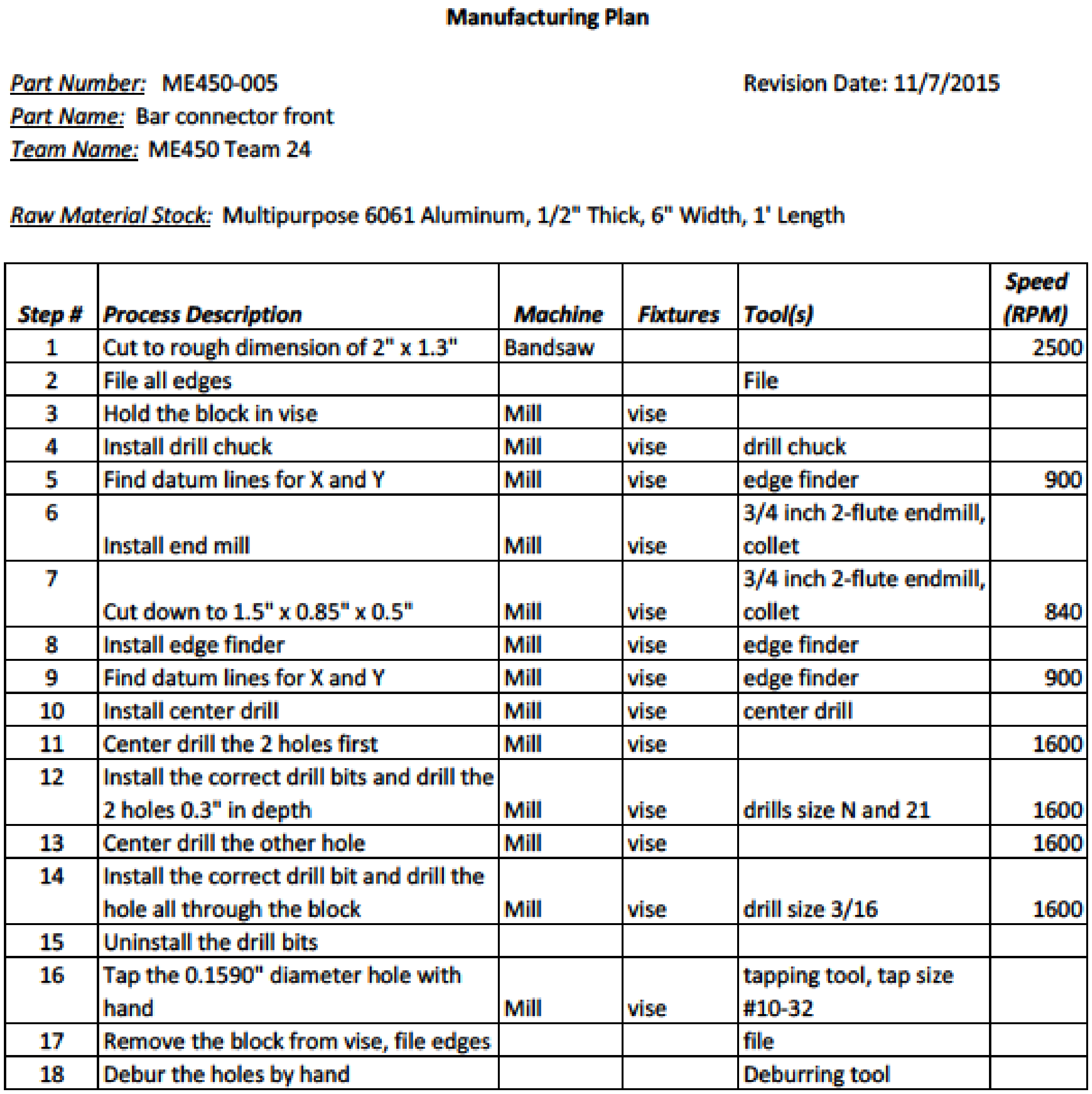
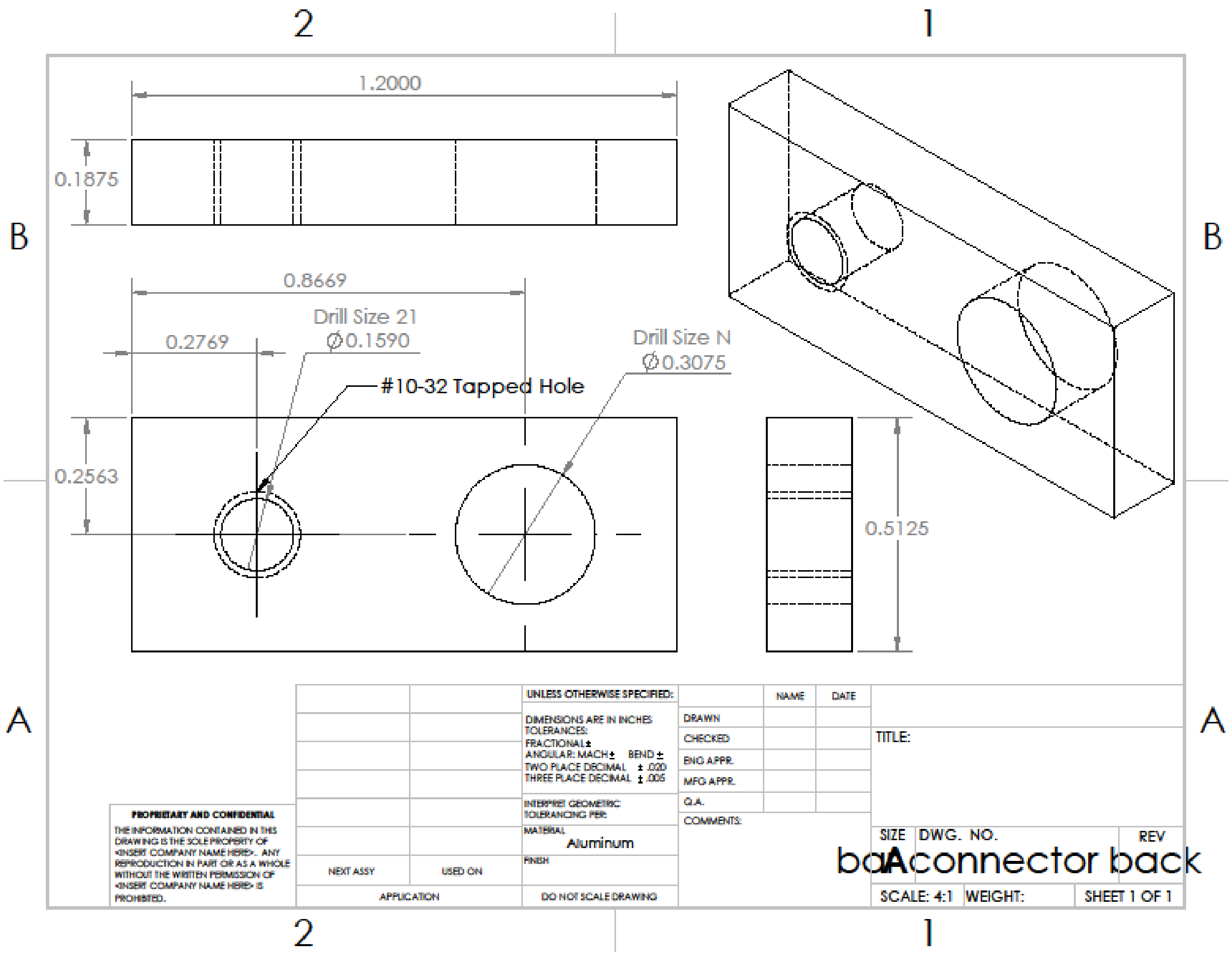


Manufacturing Plan

Part Number: ME450-005 Revision Date: 11/7/2015
Part Name: Bar connector front
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum, 1/2" Thick, 6" Width, 1' Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut to rough dimension of 2" x 1.3"	Bandsaw			2500
2	File all edges			File	
3	Hold the block in vise	Mill	vise		
4	Install drill chuck	Mill	vise	drill chuck	
5	Find datum lines for X and Y	Mill	vise	edge finder	900
6	Install end mill	Mill	vise	3/4 inch 2-flute endmill, collet	
7	Cut down to 1.5" x 0.85" x 0.5"	Mill	vise	3/4 inch 2-flute endmill, collet	840
8	Install edge finder	Mill	vise	edge finder	
9	Find datum lines for X and Y	Mill	vise	edge finder	900
10	Install center drill	Mill	vise	center drill	
11	Center drill the 2 holes first	Mill	vise		1600
12	Install the correct drill bits and drill the 2 holes 0.3" in depth	Mill	vise	drills size N and 21	1600
13	Center drill the other hole	Mill	vise		1600
14	Install the correct drill bit and drill the hole all through the block	Mill	vise	drill size 3/16	1600
15	Uninstall the drill bits				
16	Tap the 0.1590" diameter hole with hand	Mill	vise	tapping tool, tap size #10-32	
17	Remove the block from vise, file edges			file	
18	Debur the holes by hand			Deburring tool	



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Drill Size 21
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#10-32 Tapped Hole
Drill Size N
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0.5125
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ± .020
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
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baconnector back
SCALE: 4:1
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SHEET 1 OF 1
PROPRIETARY AND CONFIDENTIAL
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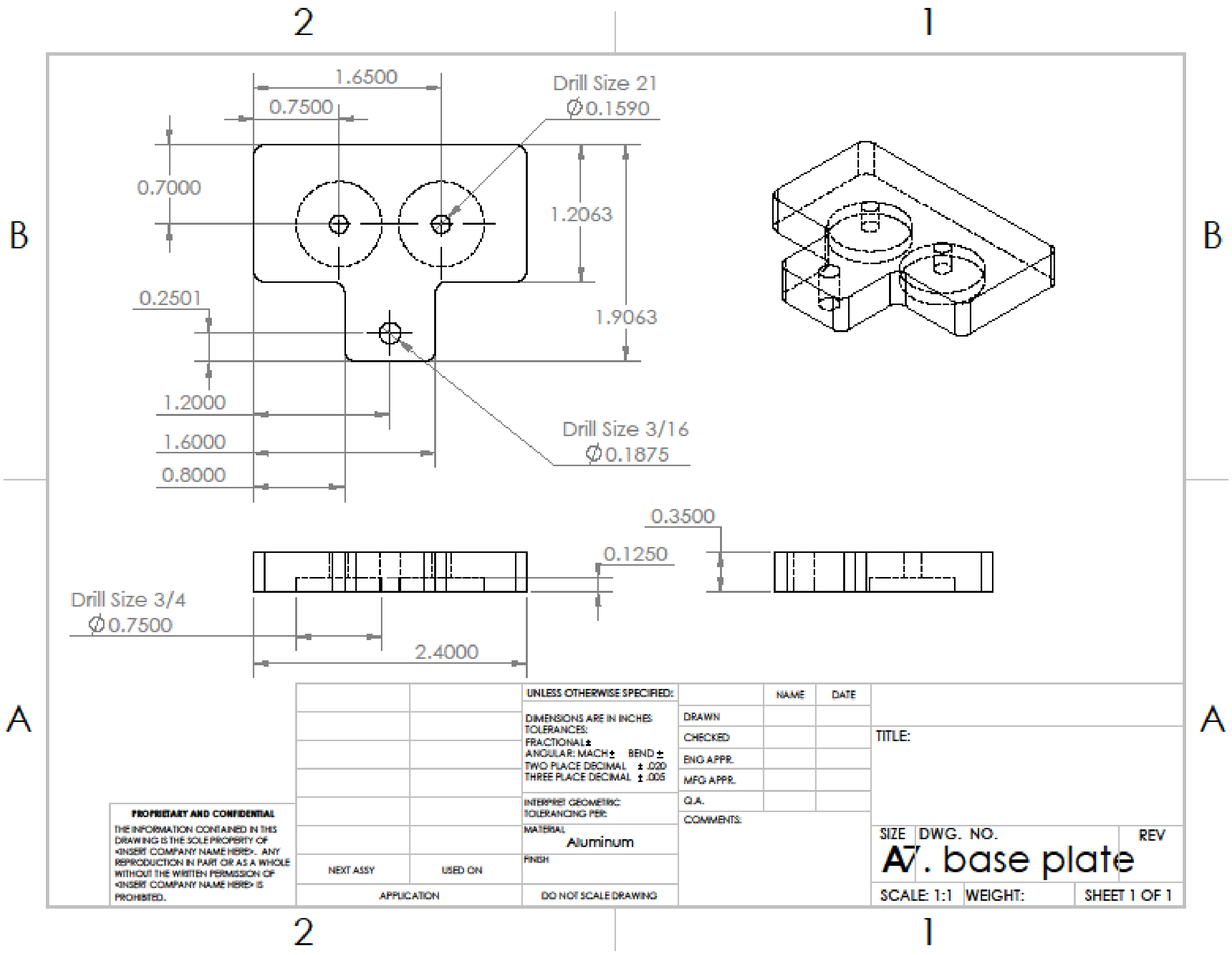
Manufacturing Plan

Part Number: ME450-006　　Revision Date: 11/7/2015
Part Name: Bar connector back
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum, 1/2" Thick, 6" Width, 1' Length

Step #	***Process Description***	***Machine***	***Fixtures***	***Tool(s)***	***Speed (RPM)***
1	Cut to rough dimension of 1.6" x 1"	Bandsaw			2500
2	File all edges			File	
3	Hold the block in vise	Mill	vise		
4	Install drill chuck	Mill	vise	drill chuck	
5	Find datum lines for X and Y	Mill	vise	edge finder	900
6	Install end mill	Mill	vise	3/4 inch 2-flute endmill, collet	
7	Cut down to 1.2" x 0.5125" x 0.1875"	Mill	vise	3/4 inch 2-flute endmill, collet	840
8	Install edge finder	Mill	vise	edge finder	
9	Find datum lines for X and Y	Mill	vise	edge finder	900
10	Install center drill	Mill	vise	center drill	
11	Center drill the 2 holes	Mill	vise		1600
12	Install the correct drill bits and drill the 2 holes through the block	Mill	vise	drills size N and 21	1600
13	Uninstall the drill bits				
14	Tap the 0.1590" diameter hole with hand	Mill	vise	tapping tool, tap size #10-32	
15	Remove the block from vise, file edges			file	
16	Debur the holes by hand			Deburring tool	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1.6500
0.7500
Drill Size 21
Ø0.1590
0.7000
1.2063
0.2501
1.9063
1.2000
1.6000
0.8000
Drill Size 3/16
Ø0.1875
0.3500
0.1250
Drill Size 3/4
Ø0.7500
2.4000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ± .020
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
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MFG APPR.
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COMMENTS:
TITLE:
SIZE
DWG. NO.
REV
A7. base plate
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
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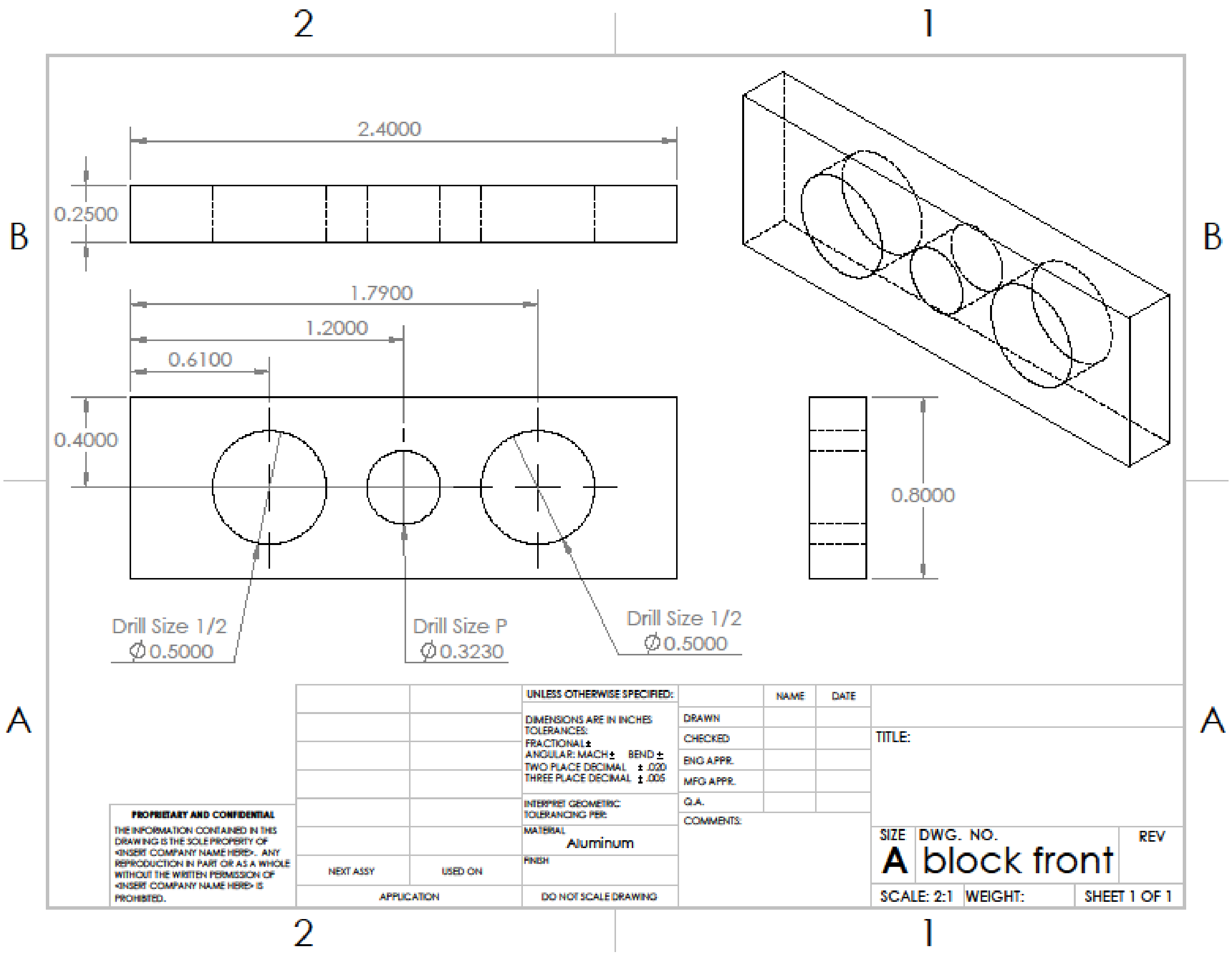
Manufacturing Plan

Part Number: ME450-007 Revision Date: 11/7/2015
Part Name: Base plate
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum, 1/2" Thick, 6" Width, 1' Length

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut to rough dimension of 3" x 2.4"	Bandsaw			2500
2	File all edges			File	
3	Hold the block in vise	Mill	vise		
4	Install drill chuck	Mill	vise	drill chuck	
5	Find datum lines for X and Y	Mill	vise	edge finder	900
6	Install end mill	Mill	vise	3/4 inch 2-flute endmill, collet	
7	Cut down to 2.4" x 1.9063" x 0.35"	Mill	vise	3/4 inch 2-flute endmill, collet	840
8	Install edge finder	Mill	vise	edge finder	
9	Find datum lines for X and Y	Mill	vise	edge finder	900
10	Install center drill	Mill	vise	center drill	
11	Center drill the 3 holes	Mill	vise		1600
12	Install drill size 21 and cut the two holes all through the part	Mill	vise	drills size 21	1600
13	Install drill size 3/16 and cut the hole all through the part	Mill	vise	drills size 3/16	1600
14	Remove the part from the vise ,flip it over, and hold the block in vise	Mill	vise		
15	Install edge finder	Mill	vise	edge finder	
16	Find datum lines for X and Y	Mill	vise	edge finder	900
17	Instal drill size 3/4 and cut the two holes 0.1250" in depth	Mill	vise	drills size 3/4	1600
18	Remove the block from vise, file edges			file	
19	Debur the holes by hand			Deburring tool	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Drill Size 1/2
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Drill Size P
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Drill Size 1/2
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ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ± .020
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
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ENG APPR.
MFG APPR.
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TITLE:
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block front
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WEIGHT:
SHEET 1 OF 1
NEXT ASSY
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APPLICATION
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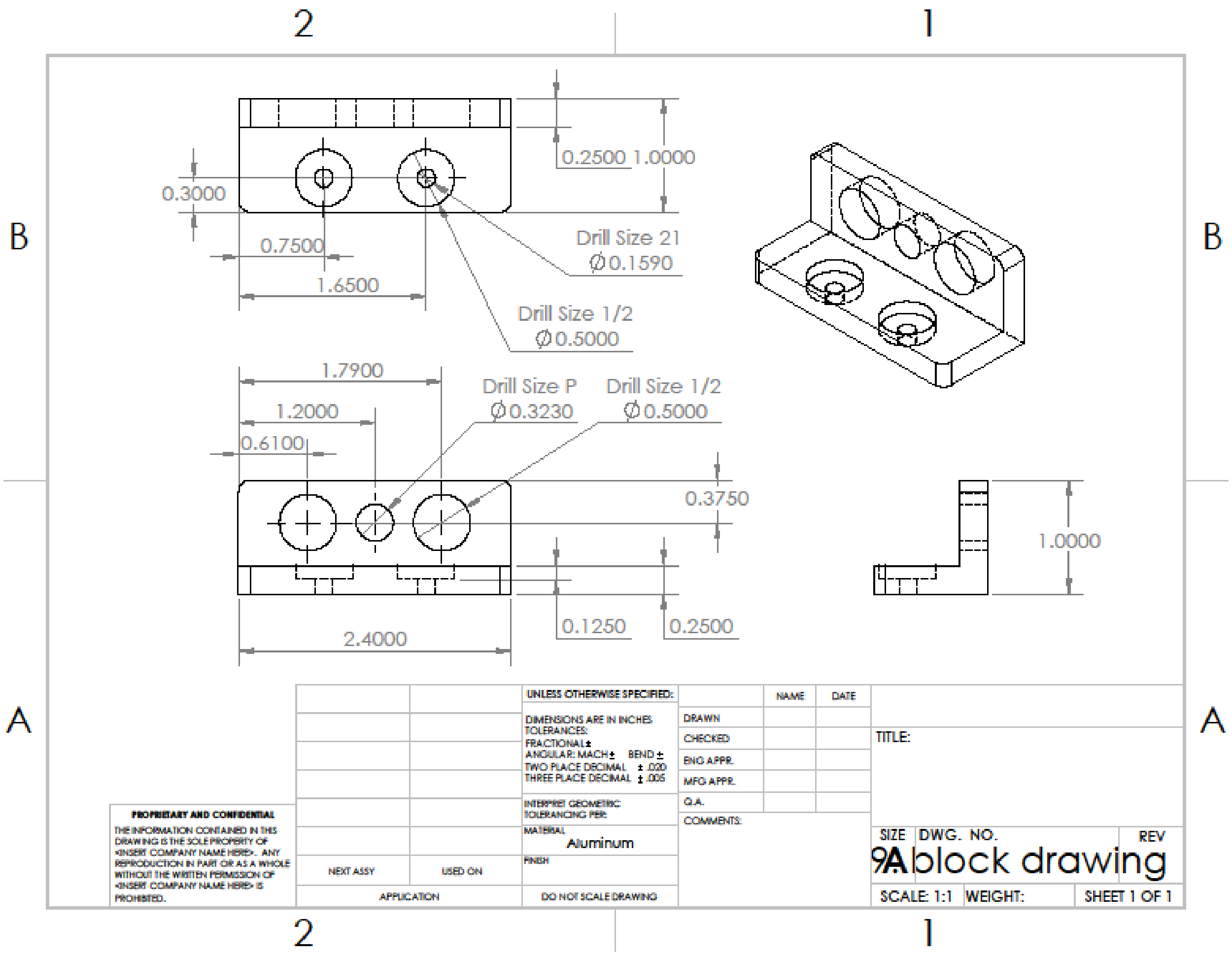
Manufacturing Plan

Part Number: ME450-008 Revision Date: 11/7/2015
Part Name: Block front
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum, 1/2" Thick, 6" Width, 1' Length

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut to rough dimension of 3" x 1.2"	Bandsaw			2500
2	File all edges			File	
3	Hold the block in vise	Mill	vise		
4	Install drill chuck	Mill	vise	drill chuck	
5	Find datum lines for X and Y	Mill	vise	edge finder	900
6	Install end mill	Mill	vise	3/4 inch 2-flute endmill, collet	
7	Cut down to 2.4" x 0.8" x 0.25"	Mill	vise	3/4 inch 2-flute endmill, collet	840
8	Install edge finder	Mill	vise	edge finder	
9	Find datum lines for X and Y	Mill	vise	edge finder	900
10	Install center drill	Mill	vise	center drill	
11	Center drill the 3 holes	Mill	vise		1600
12	Install the correct drill bits and drill the 3 holes through the block	Mill	vise	drills size 1/2 and P	1600
13	Remove the block from vise, file edges			file	
14	Debur the holes by hand			Deburring tool	



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UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ± .020
THREE PLACE DECIMAL ± .005

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Aluminum

FINISH

DO NOT SCALE DRAWING

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ENG APPR.		
MFG APPR.		
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COMMENTS:

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SIZE	DWG. NO.	REV
A	9 block drawing	

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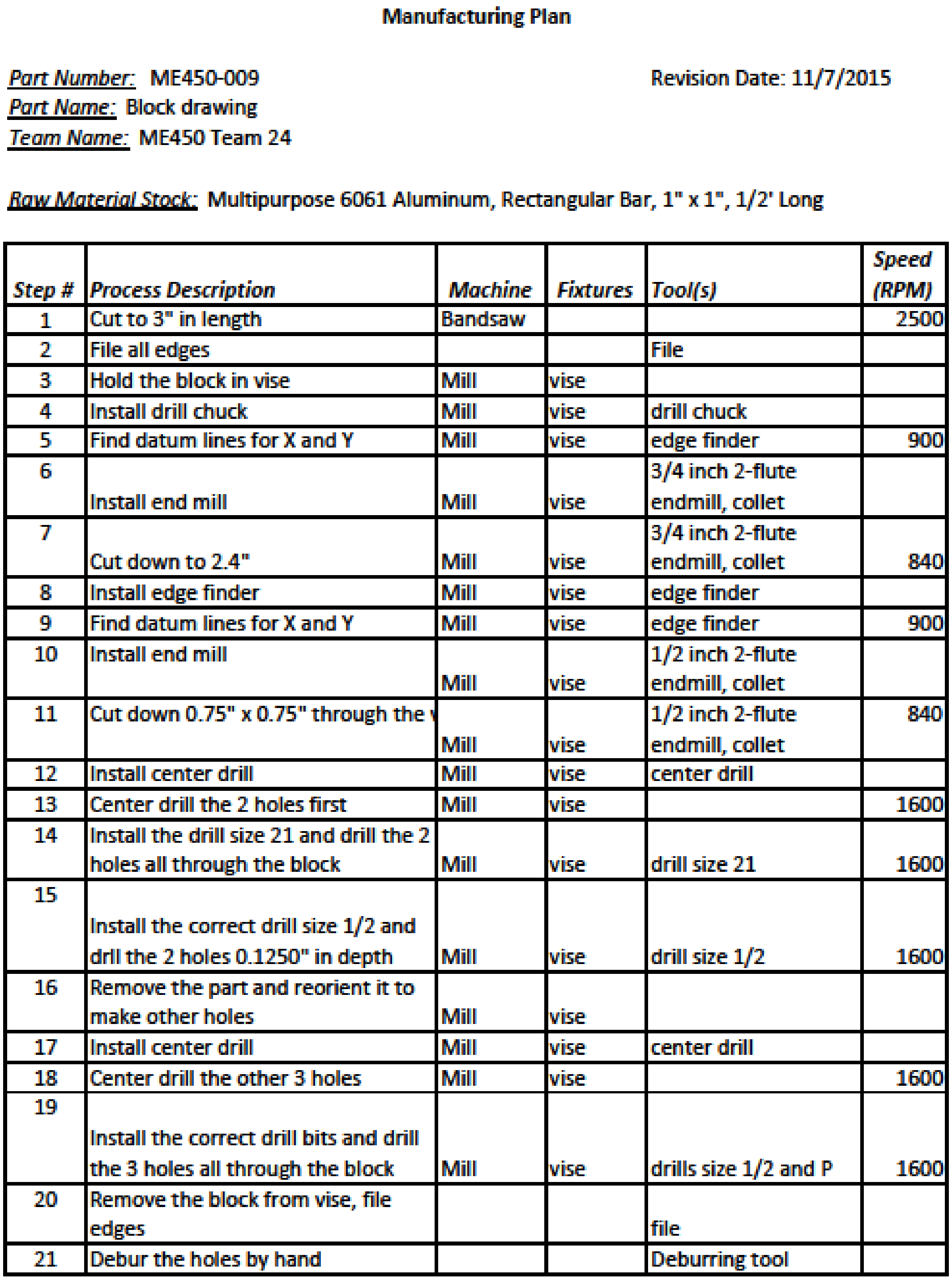
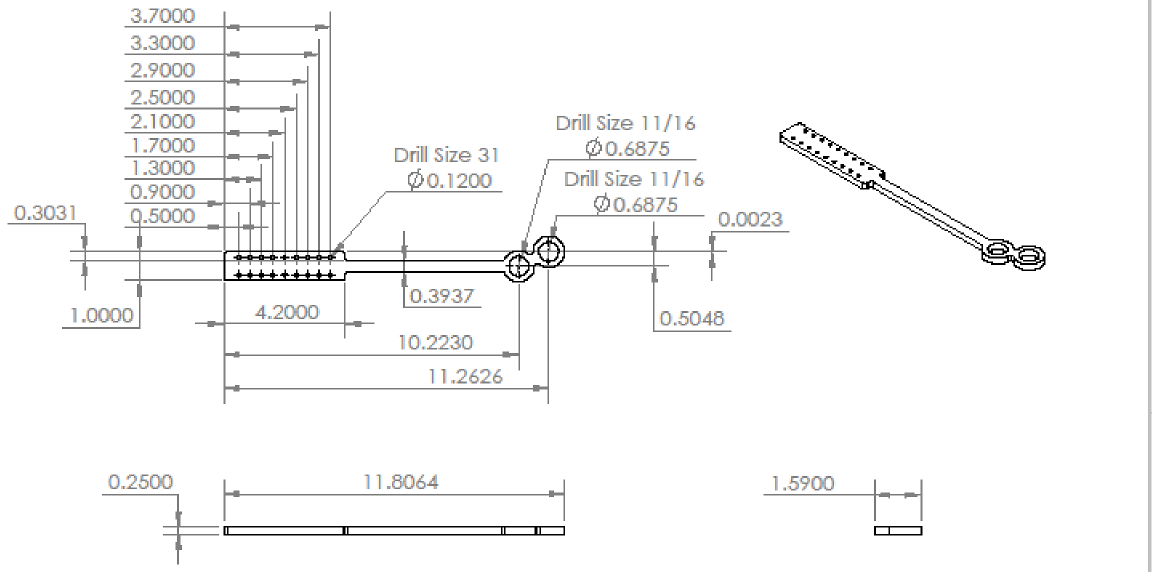


Manufacturing Plan

Part Number: ME450-009 Revision Date: 11/7/2015
Part Name: Block drawing
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum, Rectangular Bar, 1" x 1", 1/2' Long

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut to 3" in length	Bandsaw			2500
2	File all edges			File	
3	Hold the block in vise	Mill	vise		
4	Install drill chuck	Mill	vise	drill chuck	
5	Find datum lines for X and Y	Mill	vise	edge finder	900
6	Install end mill	Mill	vise	3/4 inch 2-flute endmill, collet	
7	Cut down to 2.4"	Mill	vise	3/4 inch 2-flute endmill, collet	840
8	Install edge finder	Mill	vise	edge finder	
9	Find datum lines for X and Y	Mill	vise	edge finder	900
10	Install end mill	Mill	vise	1/2 inch 2-flute endmill, collet	
11	Cut down 0.75" x 0.75" through the	Mill	vise	1/2 inch 2-flute endmill, collet	840
12	Install center drill	Mill	vise	center drill	
13	Center drill the 2 holes first	Mill	vise		1600
14	Install the drill size 21 and drill the 2 holes all through the block	Mill	vise	drill size 21	1600
15	Install the correct drill size 1/2 and drill the 2 holes 0.1250" in depth	Mill	vise	drill size 1/2	1600
16	Remove the part and reorient it to make other holes	Mill	vise		
17	Install center drill	Mill	vise	center drill	
18	Center drill the other 3 holes	Mill	vise		1600
19	Install the correct drill bits and drill the 3 holes all through the block	Mill	vise	drills size 1/2 and P	1600
20	Remove the block from vise, file edges			file	
21	Debur the holes by hand			Deburring tool	



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APPLICATION		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± .020 THREE PLACE DECIMAL ± .005	DRAWN		
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		MATERIAL Aluminum	ENG APPR.		
		FINISH	MFG APPR.		
		DO NOT SCALE DRAWING	Q.A.		
			COMMENTS:		

TITLE:

SIZE A DWG. NO. 10. foreArm(right) (change REV

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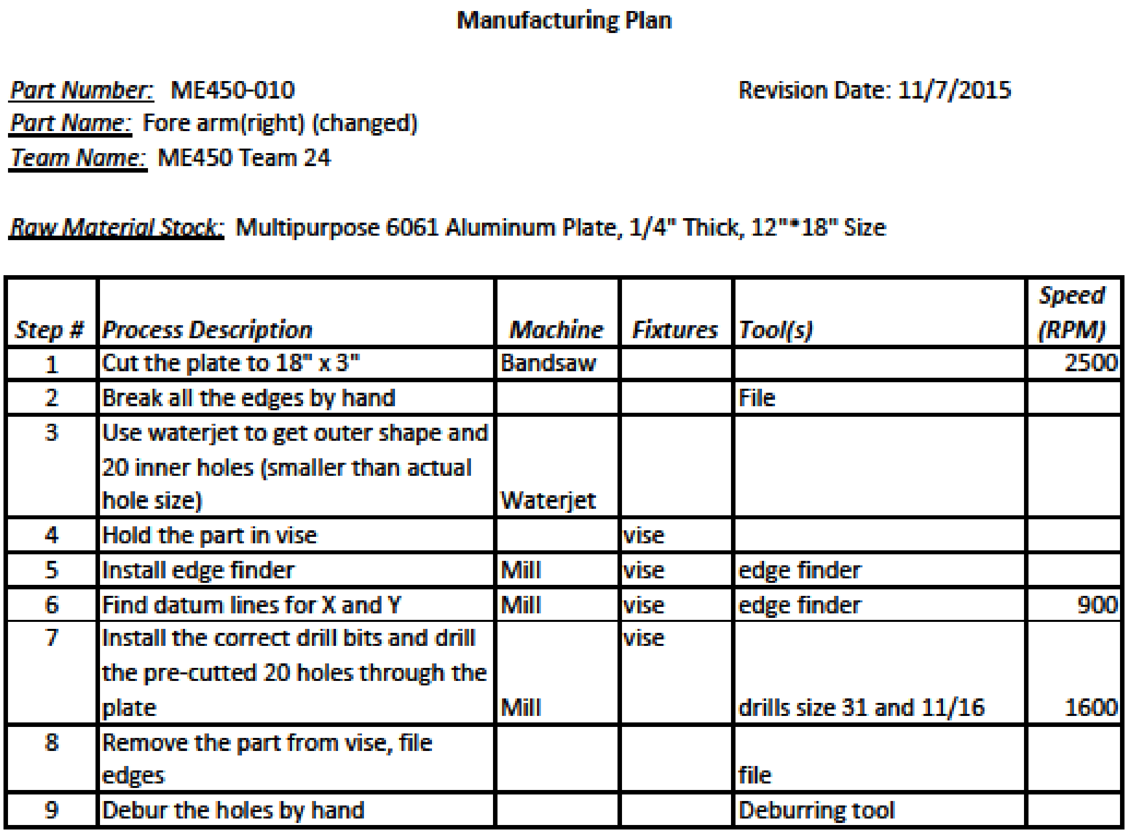
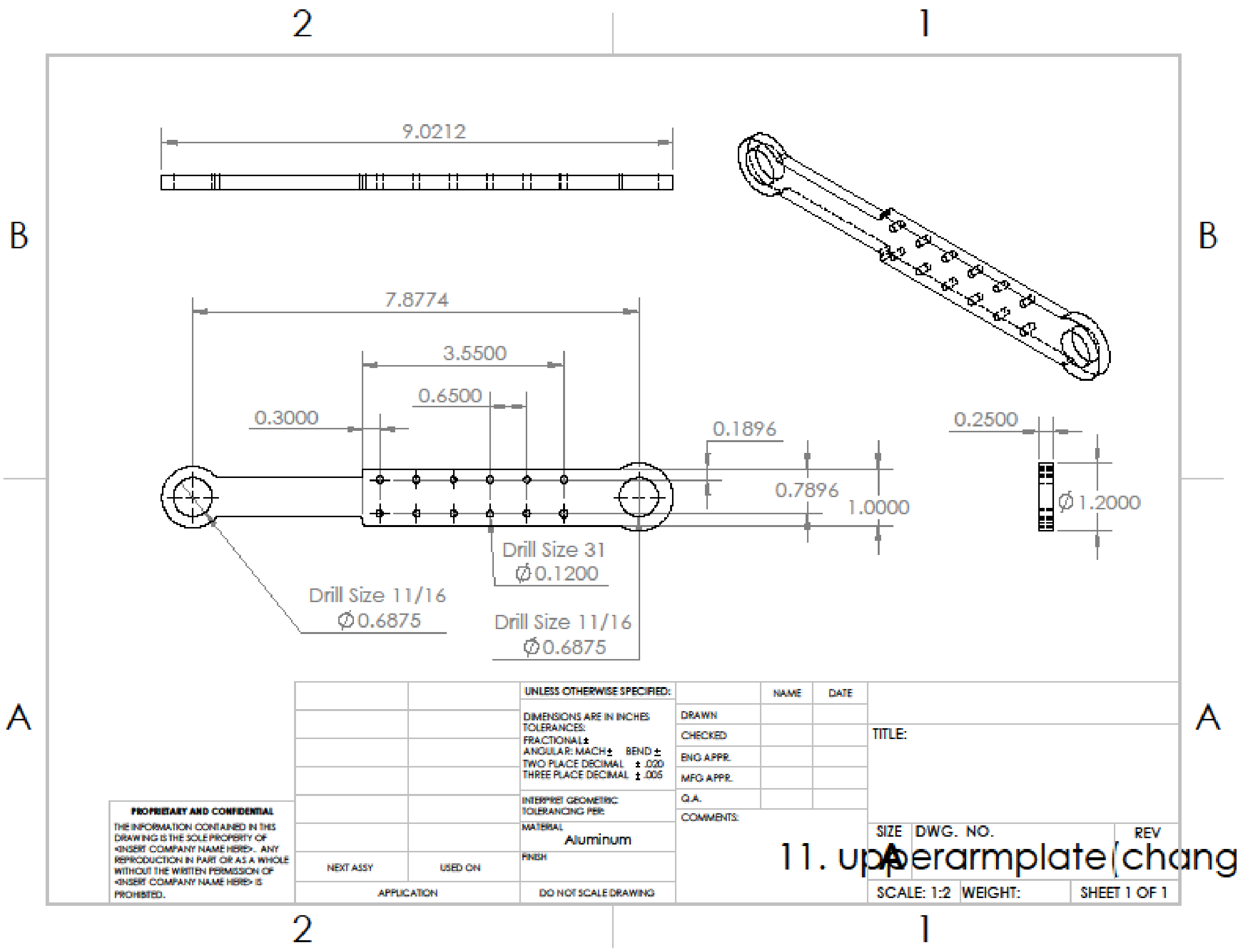


Manufacturing Plan

Part Number: ME450-010 Revision Date: 11/7/2015
Part Name: Fore arm(right) (changed)
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum Plate, 1/4" Thick, 12"*18" Size

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut the plate to 18" x 3"	Bandsaw			2500
2	Break all the edges by hand			File	
3	Use waterjet to get outer shape and 20 inner holes (smaller than actual hole size)	Waterjet			
4	Hold the part in vise		vise		
5	Install edge finder	Mill	vise	edge finder	
6	Find datum lines for X and Y	Mill	vise	edge finder	900
7	Install the correct drill bits and drill the pre-cutted 20 holes through the plate	Mill	vise	drills size 31 and 11/16	1600
8	Remove the part from vise, file edges			file	
9	Debur the holes by hand			Deburring tool	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B
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Ø1.2000
Drill Size 31
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Drill Size 11/16
Ø0.6875
Drill Size 11/16
Ø0.6875
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ± .020
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Aluminum
FINISH
NEXT ASSY
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REV
11. upperarmplate(chang
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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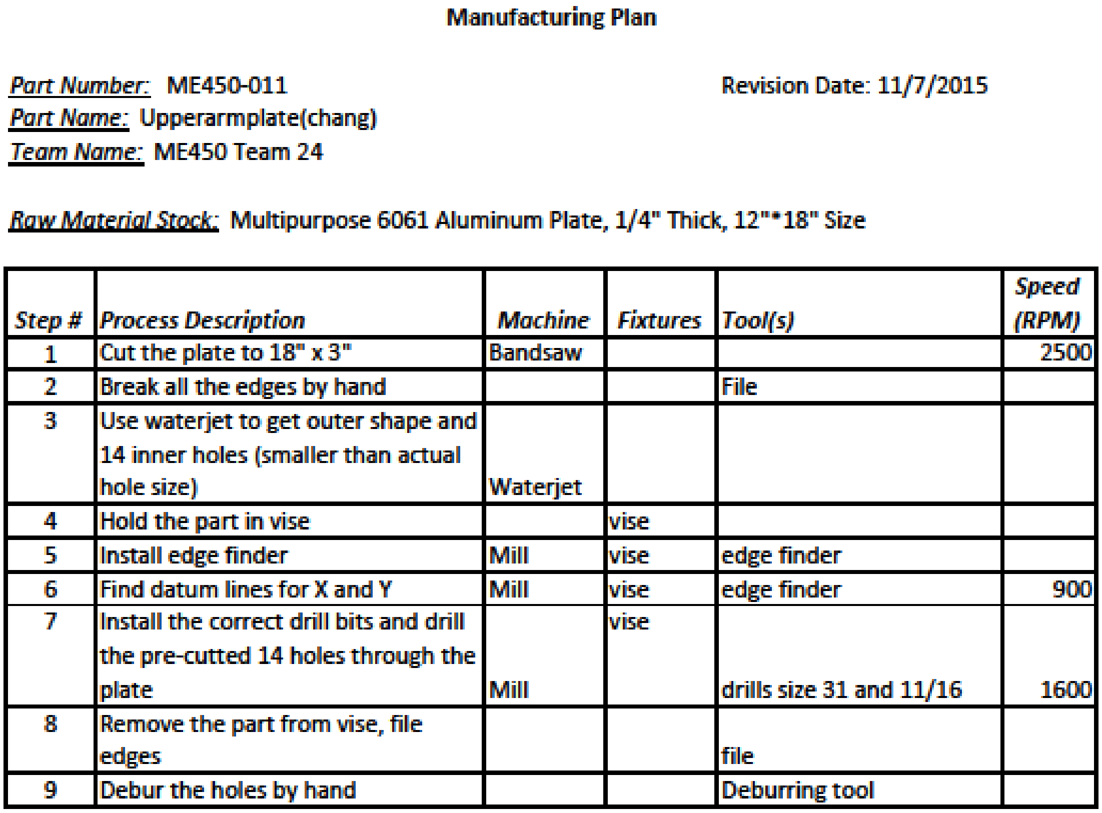
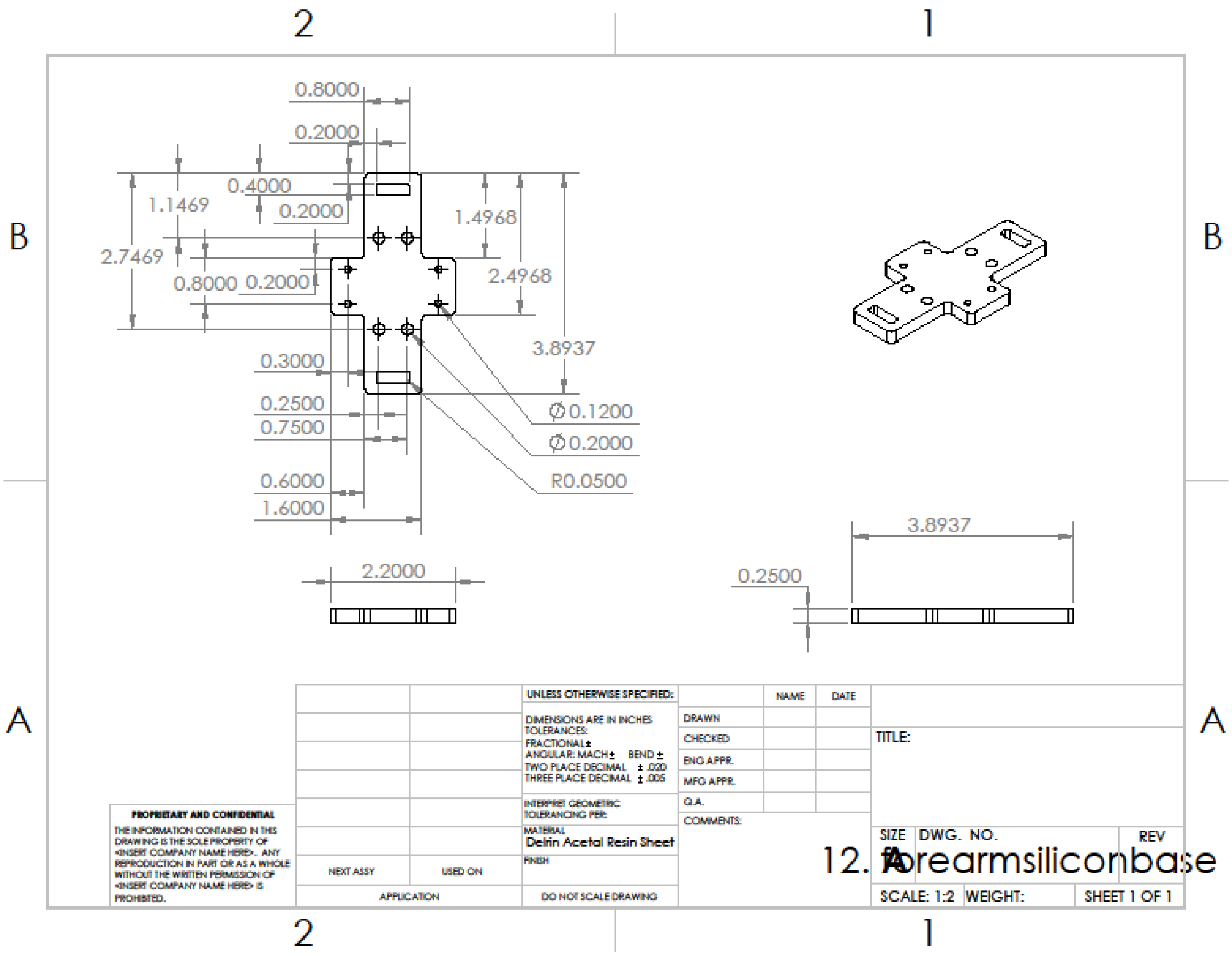


Manufacturing Plan

Part Number: ME450-011 Revision Date: 11/7/2015
Part Name: Upperarmplate(chang)
Team Name: ME450 Team 24

Raw Material Stock: Multipurpose 6061 Aluminum Plate, 1/4" Thick, 12"*18" Size

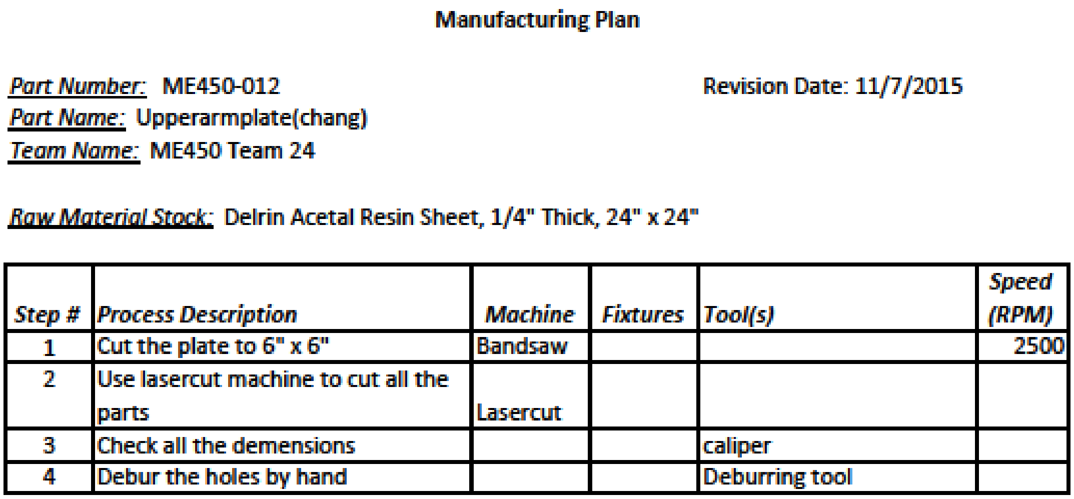
Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut the plate to 18" x 3"	Bandsaw			2500
2	Break all the edges by hand			File	
3	Use waterjet to get outer shape and 14 inner holes (smaller than actual hole size)	Waterjet			
4	Hold the part in vise		vise		
5	Install edge finder	Mill	vise	edge finder	
6	Find datum lines for X and Y	Mill	vise	edge finder	900
7	Install the correct drill bits and drill the pre-cutted 14 holes through the plate	Mill	vise	drills size 31 and 11/16	1600
8	Remove the part from vise, file edges			file	
9	Debur the holes by hand			Deburring tool	



Delrin Acetal Resin Sheet

A

12. forearmsiliconbase

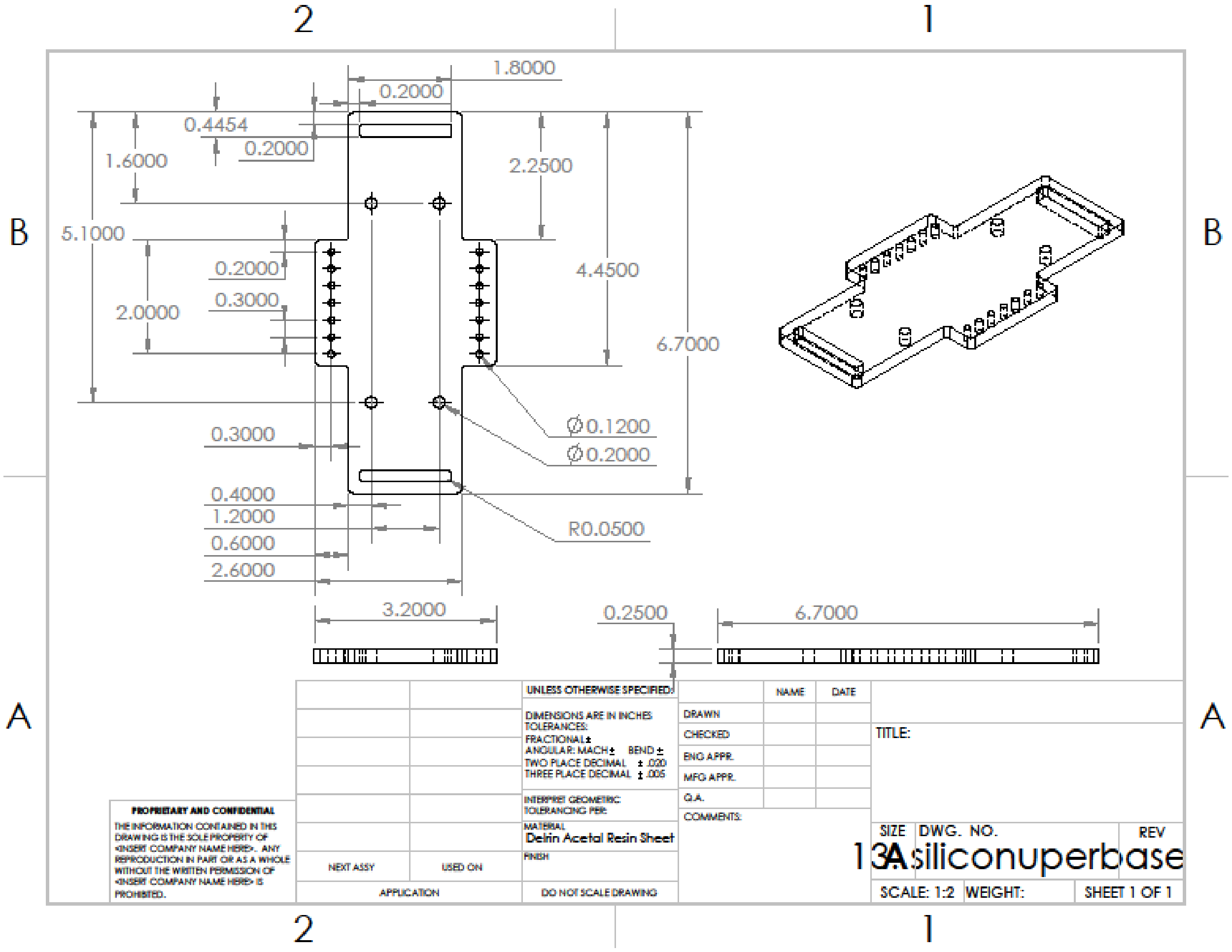


Manufacturing Plan

Part Number: ME450-012 Revision Date: 11/7/2015
Part Name: Upperarmplate(chang)
Team Name: ME450 Team 24

Raw Material Stock: Delrin Acetal Resin Sheet, 1/4" Thick, 24" x 24"

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut the plate to 6" x 6"	Bandsaw			2500
2	Use lasercut machine to cut all the parts	Lasercut			
3	Check all the demensions			caliper	
4	Debur the holes by hand			Deburring tool	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∅0.1200
∅0.2000
0.4000
1.2000
R0.0500
0.6000
2.6000
3.2000
0.2500
6.7000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ± .020
THREE PLACE DECIMAL ± .005
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
Delrin Acetal Resin Sheet
FINISH
DO NOT SCALE DRAWING
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MFG APPR.
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COMMENTS:
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A
13siliconuperbase
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
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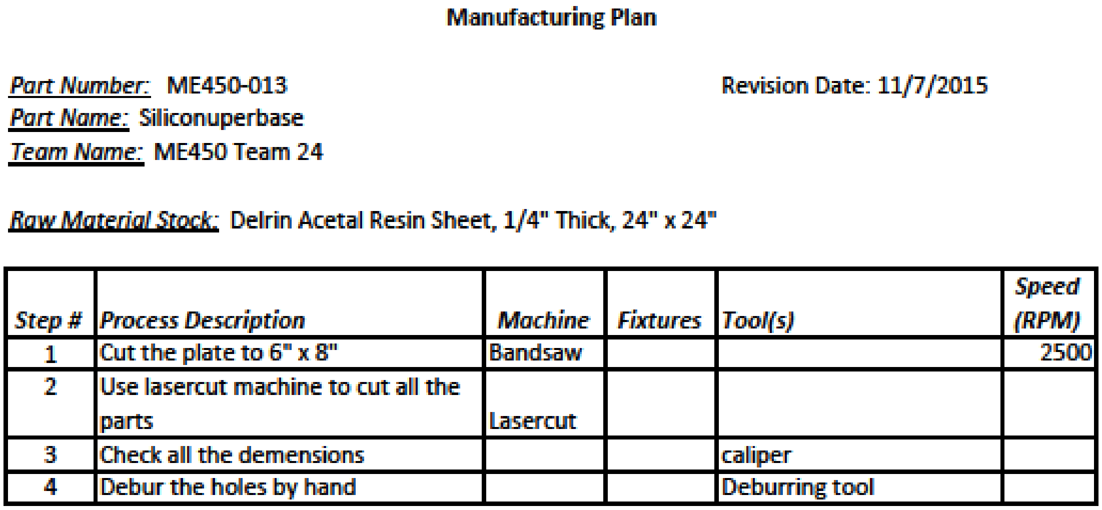


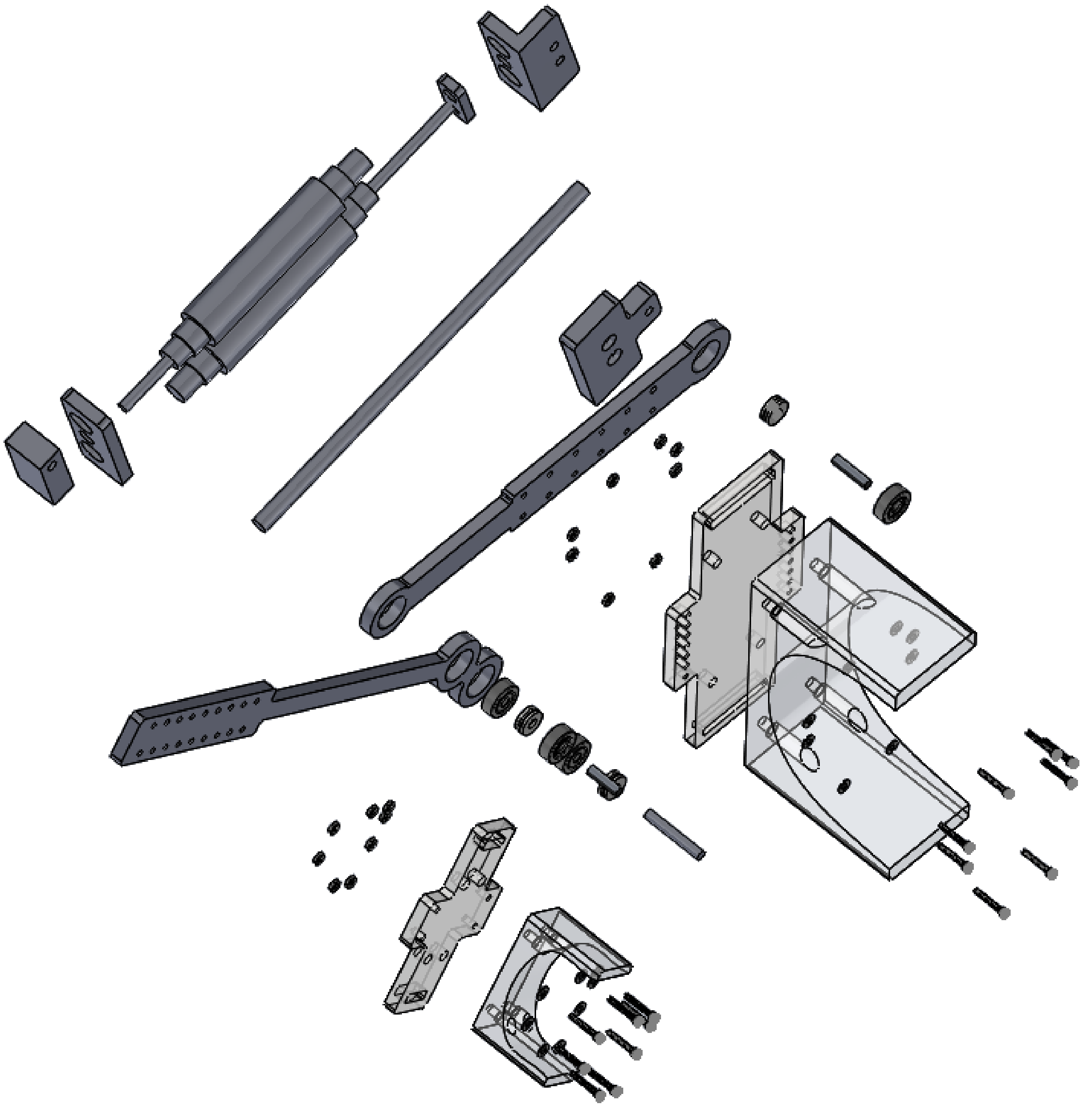
Manufacturing Plan

Part Number: ME450-013 Revision Date: 11/7/2015
Part Name: Siliconuperbase
Team Name: ME450 Team 24

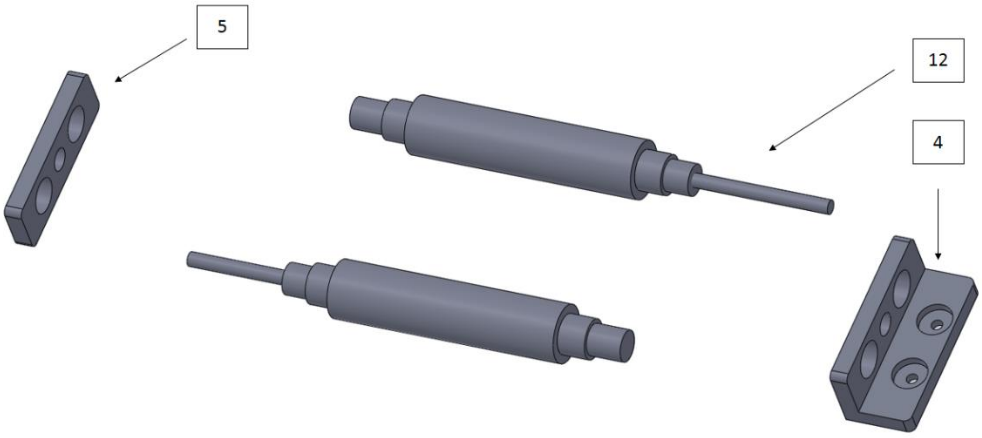
Raw Material Stock: Delrin Acetal Resin Sheet, 1/4" Thick, 24" x 24"

Step #	*Process Description*	*Machine*	*Fixtures*	*Tool(s)*	*Speed (RPM)*
1	Cut the plate to 6" x 8"	Bandsaw			2500
2	Use lasercut machine to cut all the parts	Lasercut			
3	Check all the demensions			caliper	
4	Debur the holes by hand			Deburring tool	

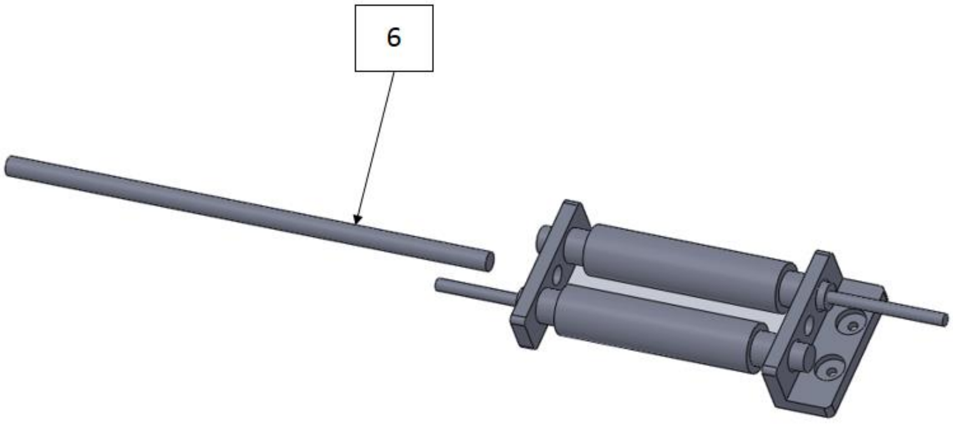
Appendix G: Explosion Diagram



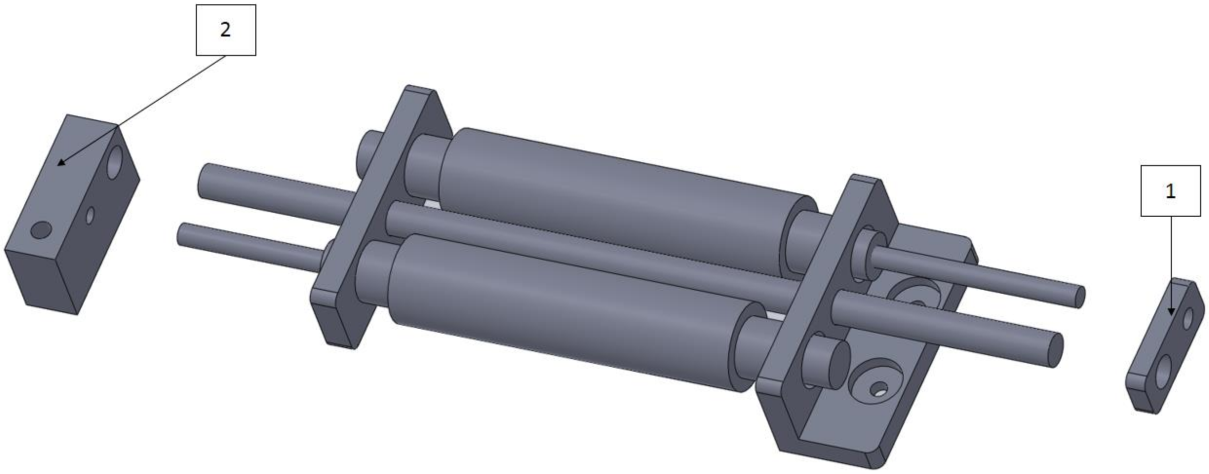
Appendix H: Assembly Process



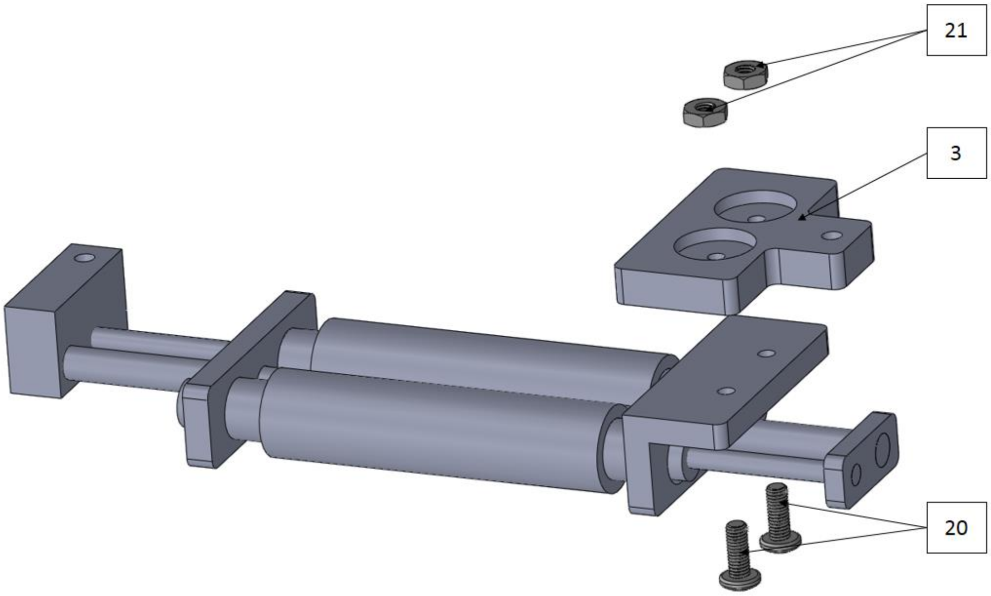
The two air cylinders (12) will be fixed into front and back aluminum housings (4,5) on each of their ends.



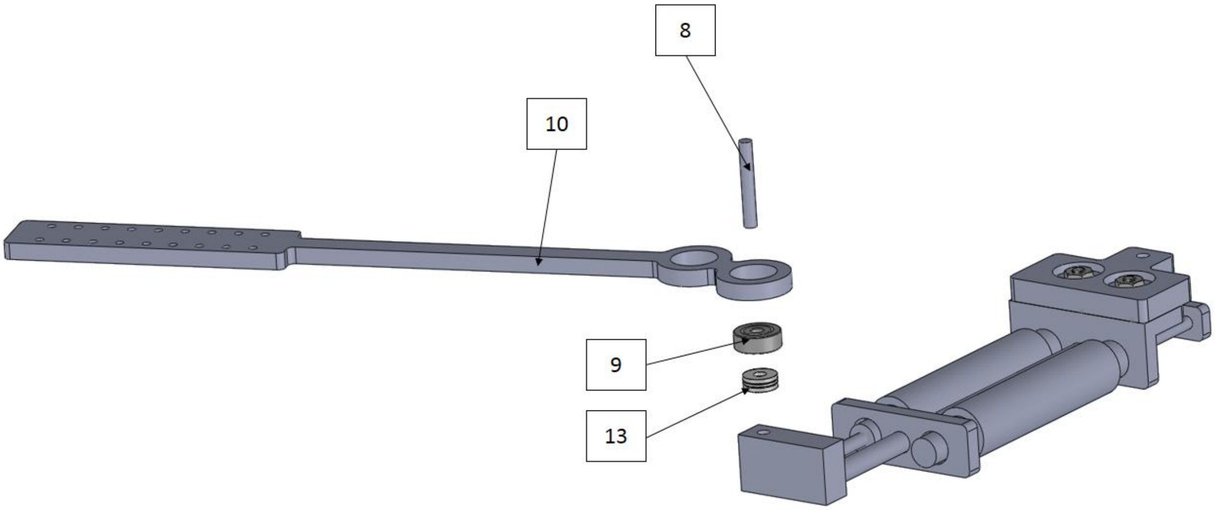
The front and back aluminum housings (4,5) will also hold and function as guide rails of center aluminum rod (6).



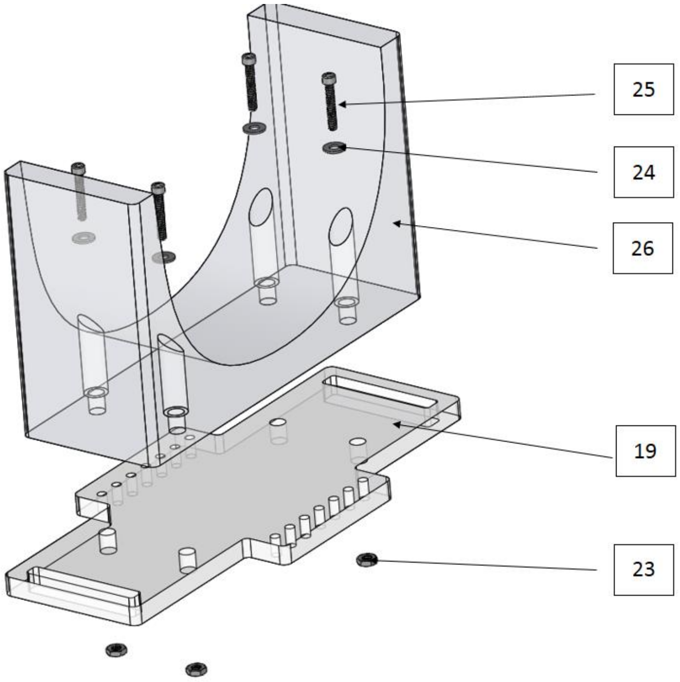
The center aluminum rod (6) and pistons of two air cylinders are connected by front bar connector (2) and back bar connector (1).



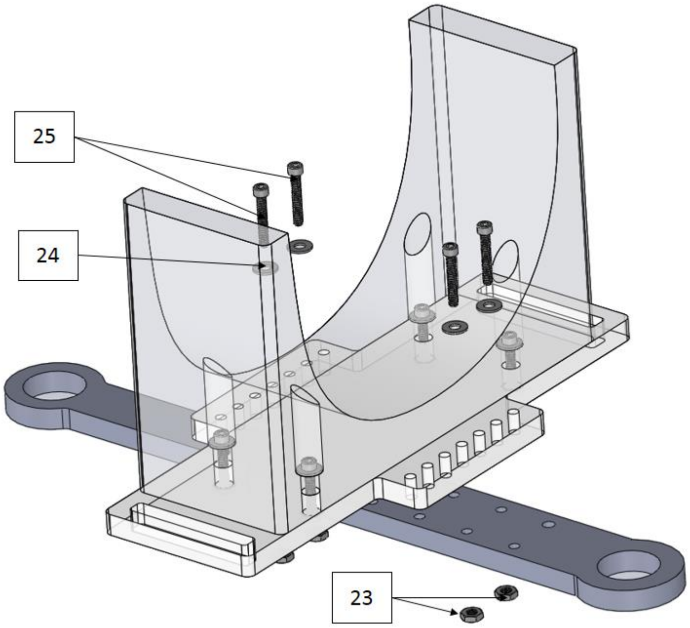
Base plate (3) is attached on back piston block (4) by using screws (20) and nuts (21). This base plate will function as a connector between air cylinders and upper arm frame.



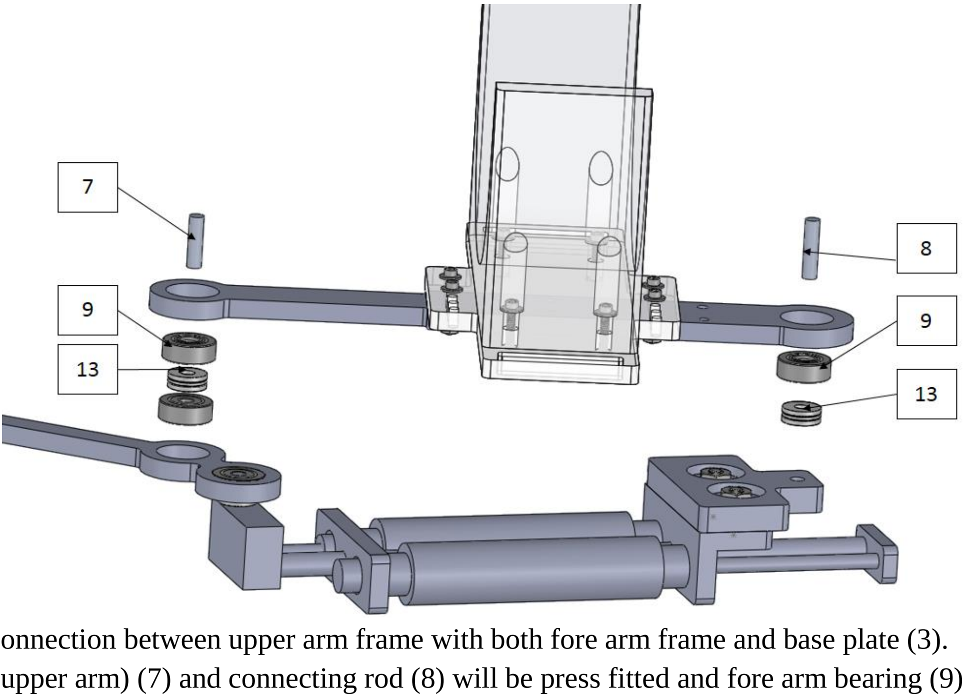
Front bar connector (2) is connected to fore arm frame (10) by connecting rod (8) via press-fit. In between fore arm frame and front bar connector, fore arm bearing (9) and thrust ball bearing (13) are placed to minimize the friction between two solids.



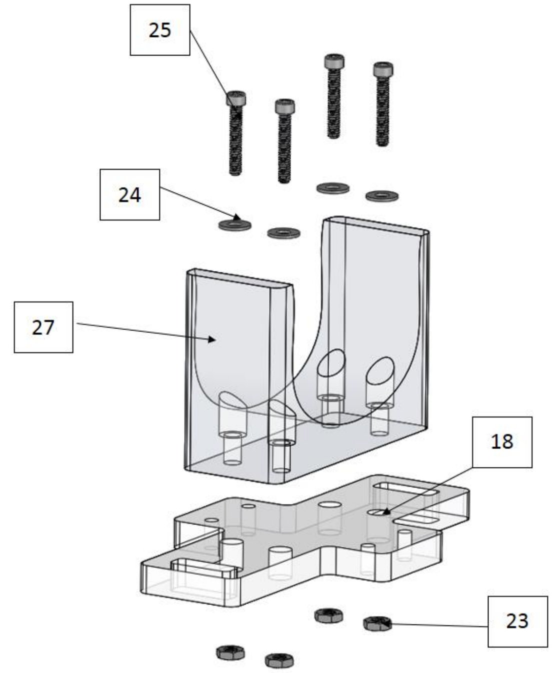
Upper silicone base plate (19) and silicone support (upper arm) (26) are connected rigidly with screws (25), washers (24), and Nuts (23).



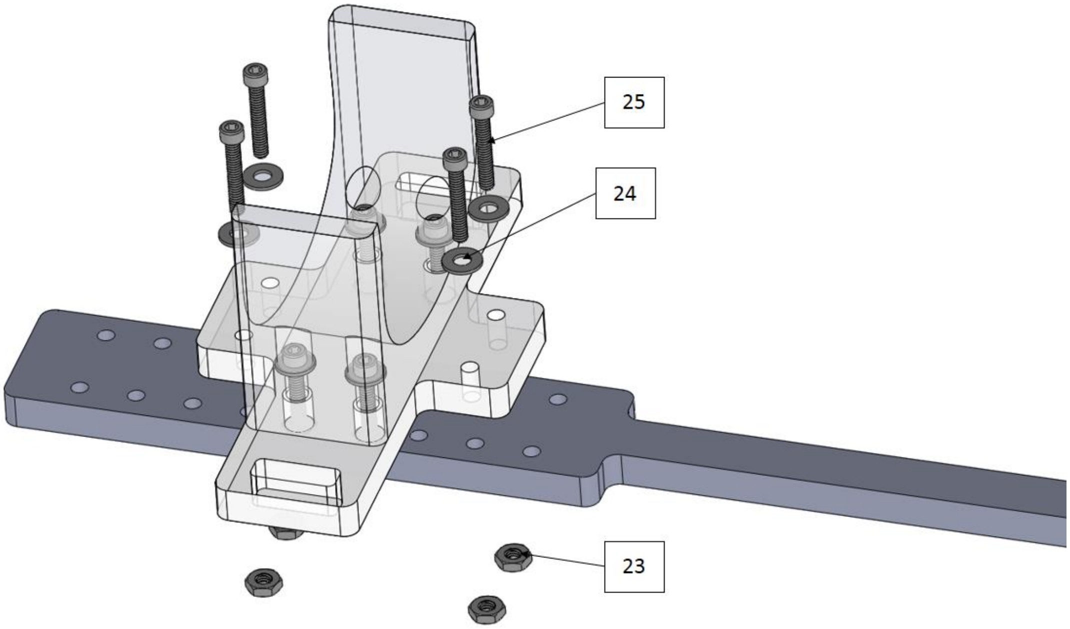
The combination of upper silicone base plate and silicone support (upper arm) is now connected with upper arm frame (14) by using screws (25), washers (24) and nuts (23).
This step is adjustable by the users based on their preference and size. As everyone has different sized arm lengths, the unit of the Derlin plastic and silicone mold can be screwed in
various positioning alone the forearm linkage.



This is connection between upper arm frame with both fore arm frame and base plate (3). Connecting rod (base to upper arm) (7) and connecting rod (8) will be press fitted and fore arm bearing (9) and thrust ball bearing (between base and upper arm) (13) are used to reduce the friction.



We will incorporate through holes through our silicone support (fore arm) for the screws (25) to go through and secure the molding with onto the lower silicone base plate (18). This configuration allows a better attachment of the molding to the aluminum linkage device.



Finally, the combination which is completed on previous step is connected with fore arm frame (10) via screws (25), washers (24) and nuts (23).

Appendix I: Validation Protocol

With our fully assembled device, our team was able to now empirically test whether or not our prototype met our target values for engineering specifications that were given to us at the beginning of the semester. Namely, these parameters include the moment that is generated about the elbow, weight, volume, range of motion, price, and operation time of the device.

Moment

A main component of our prototype is the ability to actuate movement of the human arm. This can only be achieved through a sufficient moment generated about the elbow. To quantify our device's exerted forces we calculated the theoretical values of the moment generated along the path of motion of the device. As seen in Fig. I1, at 40psi, our device's minimum moment generated is larger than that of the moment required from our original target value of 2.1 ft.lb. Additionally, all authors of this document can attest that this device, in use, has the capability to generate large forces that far exceed that of 2.1ft.lb about the elbow. Our team will be using another indirect method, which will calculate the minimum moment that the device generates [25]. **S**tudy shows that men's forearm plus hand weight is approximately 2.5% of one's body weight, and 2.0% for women's. Our heaviest member on our team weighs 185lbs, and with a estimation of .4ft being the center of mass from the elbow along the forearm, he requires approximately a 1.85ft.lb. max moment to actuate along the full range of motion. At 25psi our device was able to accomplish this actuation from fully flexed to extended, back to the fully flexed position again.

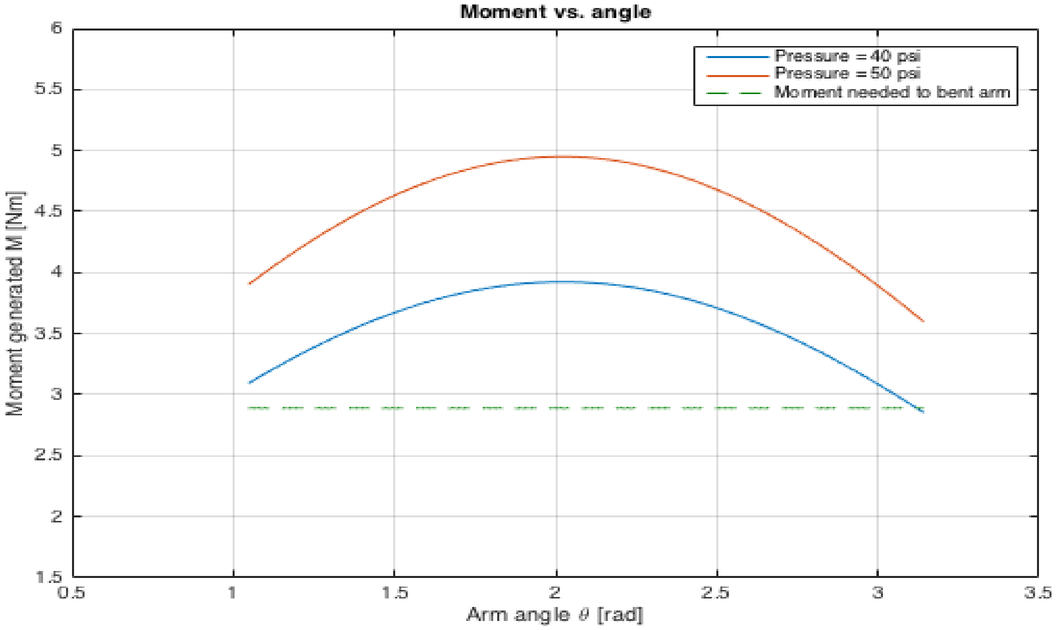


Figure I1: Moment About the Elbow vs Angle of Device

Weight and Volume

Creating a portable and easily maneuverable device are desirable traits for our design team. Our device is to be worn by the end-user, possibly for extended periods of time (a few hours), so keeping weight at a minimum is optimal. Our team targeted for a design that was under 5lbs. We used a 5000g WeighMax scale to record our weight, which came in at 2lbs and 6.6oz. For the volume of our device, we were tasked to achieve within 430in^3. This is equivalent to a typical US size 9 shoe box. After full assembly, our verified that our device fits inside the dimensions.

Figure I2

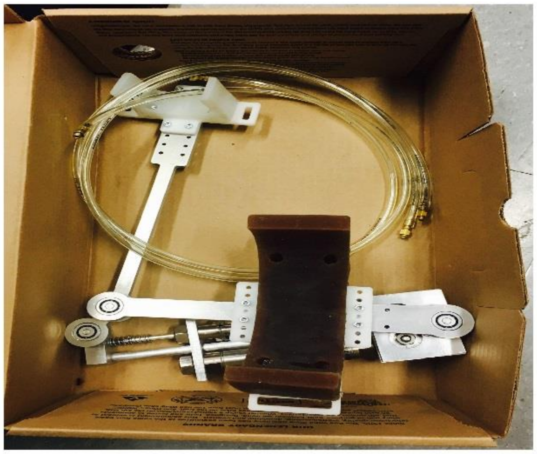


Figure I3

Price

If categorized, our prototype would be slated as a medical device. For it is primarily used for rehabilitative and muscle recovery purposes. As with medical devices, the drive to creating things better and cheaper is ever prevalent. Our team was allotted a budget of $400. Though we have just about hit that mark, we also possess a decent amount of excess material (accounting for unforeseeable factors such as remanufacturing components). After reaching full assembly and our team pro-rated the amount of material we used from all of our stock equipment and finalized a raw material price of approximately $167. This figure may not hold great significance, as there are no commercialized products in this field, only in clinical settings and research labs, however it can set a precedent for other teams that will continue our work on this project through the HaptiX Lab.

Range of Motion

Actuating movement of the arms will help recover the lost electrical signal connections that existed in the end-user from their brain to their impaired limb. If the prototype can obtain a greater range of motion this will increase the amount of motor function that is recovered by the end-user. Defining the arm at a fully extend position as 0 degrees, our team was tasked to go from 0º to 135º for a target range of motion. Our team measured this by placing a standard protractor on the outside of the device during use. After our empirical testing we measured our device reaches 20º to 130º. Thus we achieved about 80% of our target range of motion.

Operation Time

Repeatability of operation is crucial for our prototype's functionality. Without achieving full operation upon numerous repetitions, the purpose of our device (to rehabilitate the end-user) is unachieved. Because the end-user will need to operate this prototype at such high volumes, designing for an operation time that is quick enough for temporal comfort of use is highly desired. We are tasked to achieve operation across 135 degrees of motion in approximately 3 seconds. Because this number does not have to be precise, using a simple timer from a smartphone will suffice. At 30psi, we observed that the device traverses from (to) the fully flexed position to (from) the fully extended position in 0.3-0.6s. This is great news for future work, as this is far quicker than expected from the beginning of the semester.

AUTHORS

Yechan Kim

Yechan Kim is a senior student of the University of Michigan, Ann Arbor majoring in Mechanical Engineering. He was born in Republic of Korea but he lived in the Redlands, CA since his high school years. He recently gained his interest in robotic, and on last summer, he worked as a research assistant at the HaptiX lab with Prof. Brent Gillespie. During his time at the lab, he participated in technological development of soft actuator for braille and also rehabilitation robot. He currently resides in Ann Arbor.

JangWon Ko

JangWon Ko is an undergraduate student, majoring in Mechanical Engineering from University of Michigan, Ann Arbor, MI, USA. He was born in Republic of Korea and lived in Guatemala for 7 years. He served in the Republic of Korea Army for two years after his freshman year in the University of Michigan – Ann Arbor. He worked in HaptiX Lab under Professor Gillespie in University of Michigan – Ann Arbor during summer of 2015. He worked on exploring soft robotics and designing pneumatic devices for rehabilitational purpose.

Ronnie Trower

Ronnie Trower is a 5th year senior in ME with a minor in German, who hails from northeastern Michigan. In the summer of 2013, he interned with the German company, Bauerfeind AG, working in their foot orthotics development department. While more currently, he conducts research at UM’s Rehabilitation Biomechanics Laboratory under Dr. Gates. He namely focuses on upper extremity motion analysis. Ronnie has a passion for soccer, sports, and biomechanics, and hopes that one day he can become a CEO at Nike.

Zhentao Xu

Zhentao Xu is a senior student of University of Michigan, Ann Arbor, majoring in mechanical engineering. He was born in China and majored in Electrical Computer Engineering before transferring to University of Michigan. With some hand-on experience in mechatronic design and growing interests in robotics, he worked in the HaptiX Lab with Prof. Brent Gillespie during the summer of 2015. He worked on innovating soft pneumatic actuator and wearable devices.

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