Development of a Biofidelic Artificial Arm for a Martial Arts Dummy

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Abstract

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There are currently no martial art dummies or training devices that offer biofidelic recreation of human joints and resistance. Having access to this type of training tool could greatly improve a martial artist's skill in the area of joint manipulations. To fill this gap in the marketplace, one subsystem of such a device, the arm, was modeled in SolidWorks and then built for testing. Design focused on the shoulder; the rest of the arm was built primarily to test the shoulder joint. The final design was made to match 50th percentile male specifications and mimic moderate muscular resistance. The resulting prototype was shown to work well for joint locks that only involve the arm (i.e. no bending at the waist or knees). Such a device represents a first in this area.

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ACKNOWLEDGMENTS

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DEDICATION

To my many *Sensei*.

Chapter 1
INTRODUCTION

Within the martial arts world, there are two ways to practice: alone or with a partner. While solo training has many benefits, most martial artists will agree that training with a partner is far more beneficial. However, fellow martial artists are often unavailable.

The underlying purpose of this project is to provide a useful surrogate for a human training partner; that is, a dummy that will mimic the human body's size, strength, weight, and resistance. This dummy will allow a martial artist to practice various techniques (e.g. joint locks and strikes) on something that behaves more realistically than a heavy bag or empty air.

1.1 Market Background

Currently, there are several commercial products available with similar goals, but none provide accurate biofidelic response.

The first example of a training dummy is the classic Wing Chun Kung Fu wooden dummy (Figure 1.1a[1], Page 2). The horizontal pegs represent an opponent's arms and are generally struck with different parts of the body (fists, palms, arms, etc.) in order to practice strikes and toughen striking surfaces. While very traditional, this fails to provide much in the way of feedback or realism.

A more modern example, the amusingly named "Martial Arm" (Figure 1.1b[2], Page 2), offers some improvement over the Wing Chun dummy. This model provides

[1]Image source: http://www.wcarchive.com/wcasites/buickyipwingchun/wingchundummy.htm

[2]Image source: http://www.jumpusa.com/martial_arm.html

(a) Wing Chun dummy (b) The Martial Arm

Figure 1.1: Striking dummmies

resistance to techniques performed on it; however, the strength of the springs inside is excessive. Performing joint locks on the Martial Arm would require far more force than would be necessary against a human being.

The previous two examples represent dummies designed primarily for striking martial arts (boxing, karate, kung fu, etc.). They are built to withstand repeated impacts but they are only useful for punches, kicks, and other striking techniques. In contrast, the following examples are targeted more towards grappling arts (judo, ju-jutsu, wrestling, etc.).

Pro Force's 30 lb. "Grappling Man Dummy" (Figure 1.2a[3], Page 3) finally looks something like a human being. Unfortunately, it has no articulated joints. It is effectively a sand bag with arms and legs. While somewhat suitable for grappling on the ground, it would be useless for someone wishing to practice standing techniques.

The next option, Dummies Unlimited's "Grapple Man" (Figure 1.2b[4], Page 3),

[3]Image source: http://www.amazon.com/Pro-Force-Grappling-Man-Dummy/dp/B0034PSK7S

[4]Image source: http://www.dummiesunlimited.com/grappleman.htm

(a) Grappling Man dummy (b) Grapple Man dummy (c) Big Bubba dummy

Figure 1.2: Grappling dummmies

responds more like a rag doll. With no built-in resistance of any kind, it would be like wrestling with someone who is already unconscious. Looking mostly like a lighter, repurposed crash test dummy, this model fails to impress. While extremely human in appearance and articulation, it lacks realism in all other areas. It would be appropriately compared to a giant action figure: fun to play with but not particularly useful.

Finally, there is I & I Sports' "BIG Bubba II" (Figure 1.2c[5], Page 3) which claims to have "realistic, flexible joints". This time, though the limbs seem to behave somewhat more realistically, the dummy is lacking in mass and size.

In general, manufacturers of grappling dummies tend to claim that they achieve human mimicry with joints and resistance. Unfortunately for them, simply watching demonstration videos shows arms that do not behave in a realistic manner. The proposed design would fill a gap that currently exists in the market by providing a

[5]Image source: http://www.bubbadummy.com/

more realistic simulation of human appendages.

Conveniently, the end goal of this project is to produce a design that bridges the gap between the two dummy genres. While primarily focused on standing techniques, it will allow a martial artist to integrate joint locks and strikes without fear of injuring a training partner. As such a device does not currently exist, this product will fill a niche that is as yet unoccupied.

1.2 Objective

The specific goal of this project was to design an artificial arm for use in a human simulacrum for martial arts training. The main focus of the project was the shoulder, the most complex joint needed for accurate simulation of human arm motion. The rest of the arm was built as well (though the elbow, hand, and wrist are only placeholders for more complex subsystems). This allowed testing of the shoulder under appropriate usage conditions.

This dummy is to be used for the training of joint locks and restraint techniques.

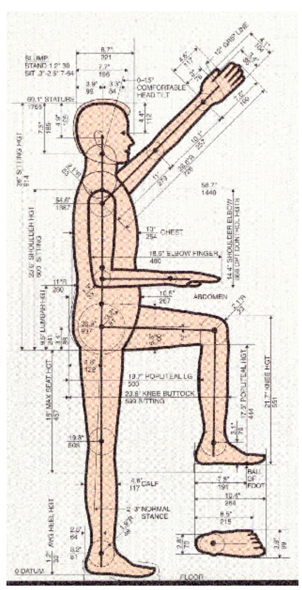

Figure 1.3: The 50th percentile male, see Appendix C for greater detail

Table 1.1: Comparison of dummy attributes

Dummy Name	**Striking**	**Grappling**	**Biofidelic Resistance**	**Biofidelic Size**	**Biofidelic Joints**
Wing Chun	X				
Martial Arm	X		X		
Grappling Man		X			
Grapple Man		X		X	X
Big Bubba		X	X		

The final design was to be lightweight (so as not to weigh more than a human arm). It will also match the dimensions, resistance, and flexibility of a fiftieth-percentile male (Figure 1.3[6], Page 4).

Per the request of the sponsor, certain stops or settings were designed to allow adjustment of joint angles and starting/return positions. That is, the arms of the dummy are supposed to be movable and poseable and will reset to the specified original positions when not in use.

Furthermore, while this project only focused on a subsystem of the final product, the sponsor desires a dummy that straddles the line between the striking and grappling dummies. The final product will resemble a heavy bag with arms and will be designed for training techniques that are performed while standing. The design of the arm had to keep this goal in mind.

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[6]Image source: http://www.adaptivemall.com/50peradmalsi.html

1.3 Project Overview

The project focused on the design of an artificial shoulder joint and culminated with production of a prototype. After completion of a thorough review of the literature on artificial shoulders and arms, a preliminary set of functional design requirements and specifications was developed. The sponsor was then consulted to review and approve the final design specifications.

Next, several different conceptual designs were developed, analyzed, and modeled. The results of the analysis served as the basis for evaluation of the conceptual designs and a final design that most closely matches the functional requirements and sponsor specifications was recommended.

The final design was modeled and tested in SolidWorks, a combined computer-aided design (CAD) and software modeling program. Biometric length, strength, and flexibility data were be obtained from literature. This allowed creation of 3D CAD drawings of the shoulder joint as well as 3D simulations of its motion.

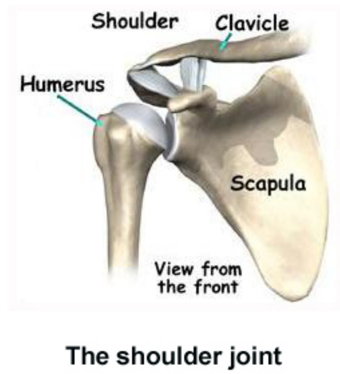
A working prototype was then constructed. Necessary parts and raw materials were ordered, or fabricated in preparation for assembly. For the sake of cost and simplicity, attempts were made to use existing parts and inexpensive materials wherever possible.

1.4 Project Deliverables

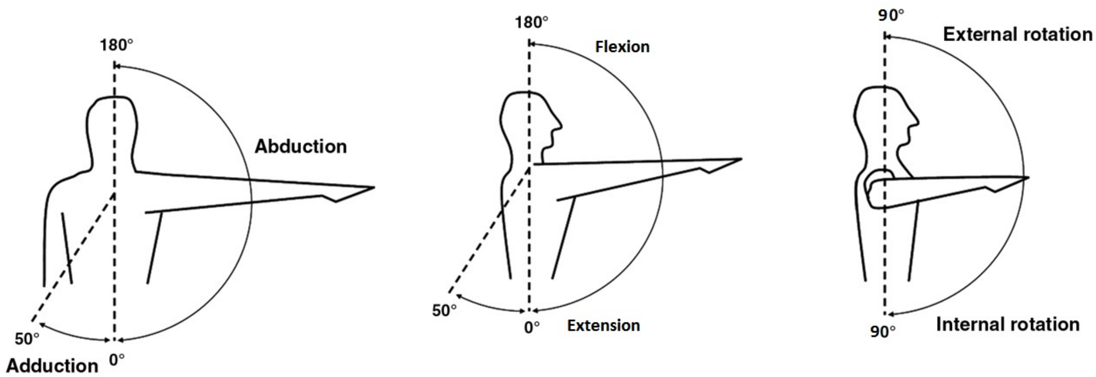
A copy of the Master's thesis will serve as the final report to the sponsor. In addition, a full set of CAD (SolidWorks) drawings of the final design will be provided on a CD-ROM, and the final design prototype will be delivered to the sponsor.

1.5 The Human Shoulder

The human shoulder is a very complex joint. Before reviewing other attempts to model the human shoulder, here is an overview of the shoulder and the terminology



(a) The human shoulder joint



(b) Human shoulder motions

Figure 1.4: The human shoulder

relating to its anatomy and motion.

The articulation of the humerus and scapula (the glenohumeral joint) creates a ball and socket which allows the human shoulder a large range of motion (figure 1.4a[7]). The acromioclavicular joint (the junction between the scapula and the clavicle) allows the arm to be lifted (abducted of flexed) over the head. The meeting between the clavicle and the sternum (the sternoclavicular joint) provides stability. Because the complex interactions between these joints, the shoulder can lift, twist, rotate, push and pull. However, unlike the hip, the "socket" is very shallow, leading to a more

[7]Image source: http://www.homebusinessandfamilylife.com/arm_bones.html

flexible but less stable joint.

The anatomical directions in which the shoulder joint can move, along with are defined in figure 1.4b[8]. This yields a simple way of discussing the movement of the shoulder in technical terms. For example, the act of bending over to touch one's toes means the shoulders flex (to approximately 90 degrees), rubbing one's tummy means the shoulder is rotated internally (approximately 90 degrees), and during jumping jacks the shoulders abduct (approximately 180 degrees) and then adduct (0 degrees). The angle definitions in figure 1.4b will be referenced throughout this document. Note also that adduction and abduction can be separated into two movements: true ad/abduction and up/downward rotation of the scapula. For simplicity's sake however, scapular motion was largely ignored during this project.

Knowledge of how the shoulder's anatomy informs attempts to replicate it mechanically. The shoulder's complex joint configuration dictates that the final design must have similar specifications (i.e. free rotation and movement over a large range of motion).

1.6 Previous Work and Similar Designs

Most previous designs represent devices that are meant either for robots or are human joint replacements. Of the two categories, the former is the more helpful. Most joint replacements presuppose the existence of muscle, bone, and connective tissue which limits their usefulness as inspiration (see Macgovern and Marra [2006] as an example of the general uses of joint replacements). In the same vein, most humanoid robotic arms are not biofidelic. They approximate the human arm and its range of motion, but rarely do so in ways that exactly match human joints. That is, robotic arms can reach all the same positions a human arm can, but they may have to travel there by different paths. The following are several examples of interesting or relevant designs.

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[8]Image source: http://www.ajronline.org/content/189/3/W128/F3.expansion.html

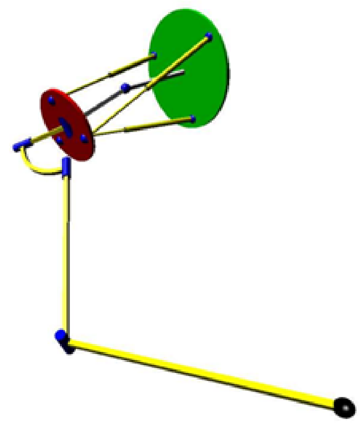


Figure 1.5: Humanoid shoulder-elbow complex from Goehler [2007], Agrawal and Dubey [2009]

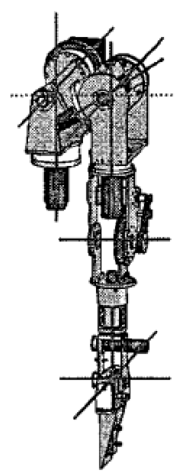


Figure 1.6: 9-DOF arm from Miwa et al. [2004]

Goehler [2007], Klopcar and Lenarcic [2001] propose a design that does an excellent job of mimicking the human shoulder's complexity (Figure 1.5, Page 9). Unfortunately, this device is designed to be motor-actuated and move under its own power. However interesting and useful it may be in the robotics community, it supplied little helpful information for this project.

Figure 1.7: Hybrid III crash test dummy

Miwa et al. [2004] provides an interesting variation on the robotic arm. Their 9 degree of freedom (DOF) arm—created as an attempt to improve emoting in robots—is cable driven, rather than directly actuated (Figure 1.6, Page 9). Furthermore, it seems to fairly accurately mimic human anatomy and proved to be a valuable source of inspiration. Indeed, the use of cabling in the prototype design can be traced to both this and the following example.

Another design that makes use of cables comes from Agrawal and Dubey [2009]. In this case, the arm is an exoskeleton intended for re-training arm motion in stroke survivors or those with muscle-related illnesses. External cables act as muscles for the arm. Like real muscles, they can only pull, giving this particular design a certain amount of biomimetic credibility.

The final designs of particular interest are the Hybrid III (Figure 1.7[9], Page 10) and THOR crash test dummies. Because of their intended purpose, these are some of the only designs available that strive for truly biofidelic representation of the human body. The Hybrid III was developed by General Motors and in 1997 it was officially adopted

[9]Image source: http://www.radenton.com/dentonatd/VESTA.html

Figure 1.8: THOR shoulder assembly

by the National Highway Traffic Safety Administration as the required dummy in all NHTSA motor vehicle safety standards. The shoulder of this dummy was "was designed for improved fidelity of shoulder belt interaction" [Humanetics, 2004] and as such is not an ideal model in this case. A Hybrid III makes use of a simplified shoulder joint consisting of two rotational bearings and a hinge, which I have dubbed the "Action Figure." This particular design has the beauty of being simple, but was deemed to be inappropriate for this project because its motion is limited in ways that proved to be important for joint-lock techniques.

The successor to the Hybrid III in the NHTSA's arsenal of crash test dummies is the THOR. The primary improvements in THOR seem to be in areas not directly related to this project (spine, pelvis, face, and instrumentation). However, the new model does incorporate an "improved shoulder design with more human-like mobility" (Figure 1.8[10], Page 11) [NHTSA, 2011]. This shoulder design, which uses a complex set of bearings and linkages, was improved and refined to include "shrugging and enhanced lateral deflection capabilities" [Haffner et al., 2001]. However, the THOR

[10]Image source: http://www.nhtsa.gov/Research/Biomechanics+&+Trauma/%3E%3ETHOR +Advanced+Crash+Test+Dummy

is designed to use the same arms as the Hybrid III, meaning the shortcomings of the action figure arm are still present.

1.7 Summary

Research into current market offerings, along with previous work by others, showed that there was a niche for a device that offered the benefits of both striking and grappling dummies. Many of the already existing products demonstrated a lack of either useful resistance or appropriate range of motion. Filling that void was one of the main goals of the design process. Also, some of the products found during background research provided inspiration for the final design. The next step was to codify the sponsor's requirements and create a design that met them.

Chapter 2

DESIGN

2.1 Selected Design Requirements

The following are excerpts from the full design requirements for the entire dummy. Only the requirements relevant to the arm and shoulder have been included. The full list of requirements, generated through discussion with the sponsor, can be found in Appendix C.

1. Minimize assembly of unit

2. Dummy to match 50th percentile male in strength, flexibility, and weight

3. Shoulder position must be poseable in three flexion/extension positions (45 degrees, 90 degrees, 135 degrees)

4. Arm as a whole must be easily poseable

5. Forearm to rotate halfway between wrist and elbow

6. Forearm to rotate 90 degrees internally and externally

7. Forearm to return to neutral after manipulation

8. Forearm positioned so wrists and hand are in neutral position (0 degrees supination/pronation)

9. Elbow to be limited to full extension (0 degrees) and maximum human flexion (140 degrees)

10. Upper arm to rotate close to shoulder, 60 degrees internally and externally

11. Upper arm to return to neutral after manipulation

12. Shoulder to allow flexion to 180 degrees and extension to -45 degrees (behind body)

13. Shoulder to return to original posed position after manipulation

Item 1 is generally something to keep in mind when designing anything that requires assembly. It was particularly important for this case, where all machining and assembly would be done by myself.

Item 2 refers to the dummy as a whole, and so must also apply to the arm subunit. The decision to use 50th percentile male specifications was made early on to provide a reasonable approximation of a human partner. Furthermore, data on that segment of the population is very easily obtainable.

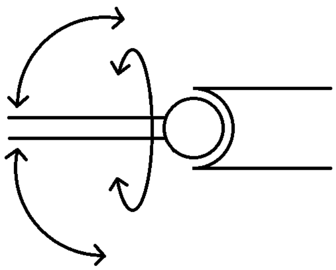
Items 3 and 4 were a large part of designing the shoulder; they are what made the design challenging and largely what will make it useful as a training tool.

Items 5-8 define the motion of the forearm under manipulation. The forearm is to rotate halfway between the wrist and elbow in order to best approximate the motions of the radius and ulna; rotation at the wrist or near the elbow would not provide quite the same accuracy. The neutral position should correspond to the relaxed position of the forearm. This position will allow the forearm to be twisted either direction, as it would be with a human opponent.

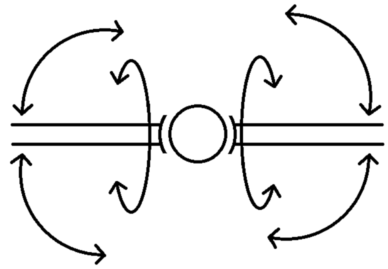
The elbow, (item 9) upper arm (items 10 and 11) and shoulder (12 and 13) follow similar guidelines to the forearm in order to ensure maximum usefulness and accuracy.

2.2 Designs Considered

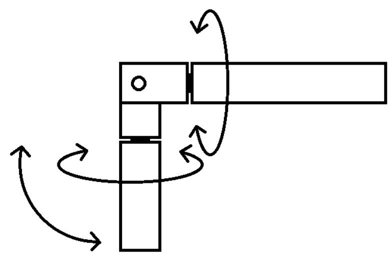
There are several options for the design of a biomimetic shoulder joint. The human shoulder (Figure 1.4a, Page 7) is effectively a ball and socket. A mechanical ball and



(a) Single ball joint



(b) Double ball joint



(c) Action figure

Figure 2.1: Designs considered for the shoulder

socket would allow the joint to move in three degrees of freedom (flexion/extension, adduction/abduction, and rotation). However, other researchers have found difficulty actuating such a device [Goehler, 2007]. This particular design (Figure 2.1, Page 15) was abandoned after no feasible (i.e. under-budget) implementations were found.

Alternatively, the ball and socket can be modeled by more complex combinations of rotational bearings and hinges. Adduction and abduction of the shoulder joint can be mimicked using a simple hinge (the “action figure”). Extension and flexion of the shoulder can be modeled with a bearing that is mounted parallel with the floor and whose axis lies along the frontal plane of the body. Rotation of the arm can be met by a combination of that bearing and a similar bearing in the upper arm. An arm with this design could assume all of the same positions as a human arm, but would sometimes have to take different paths to reach them. Replacing the shoulder hinge with a universal joint would be preferable, as it would allow for a greater freedom of motion.

Another option considered was a cable-driven arm that would use a system of weights and pulleys to provide resistance as per Miwa et al. [2004] or Agrawal and Dubey [2009]. This arm would have easily customizable resistances, as the design could draw upon currently existing technology in weight/fitness machines. Difficulties would include routing cable through or around joints as well as the possibility of changing lengths as the arm is placed into different positions. Though tempting, this design was abandoned in favor of a design with simpler implementation.

More complex methods of modeling the human shoulder, such as THOR's ability to shrug, were unnecessary for a first approximation of human shoulder motion. Ideally, the final design would perfectly mimic a human shoulder but, in the interests of cost and feasibility, sacrifices were made.

The elbow and wrist are simple hinges while wrist rotation is taken care of by a bearing in the forearm. Finally, while outside the scope of this project, it is also worth noting that, with adjustments to the resistance, a set of joints that effectively model the human arm could easily be mapped to the leg.

2.3 Design Selected

The design chosen for implementation takes inspiration from both the bearing/hinge model and the cable-driven model. The forearm and upper arm both have bearings to allow for interior and exterior rotation and are spring-loaded to provide resistance. The shoulder is a combination of two sets of concentric bearings and a universal joint. Flexion and extension resistance is provided by cabling and weights (much like a standard weight machine). Resistance to adduction is not provided, but abduction resistance is created by a spring connecting the upper arm and shoulder.

This design was chosen because of its simplicity and effectiveness. Further details, as well as the rationale behind design decisions, can be found in the following two sections.

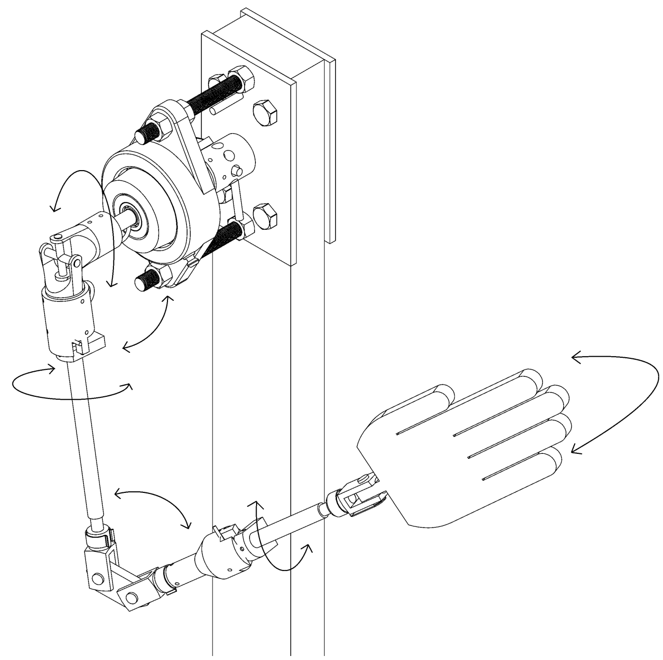


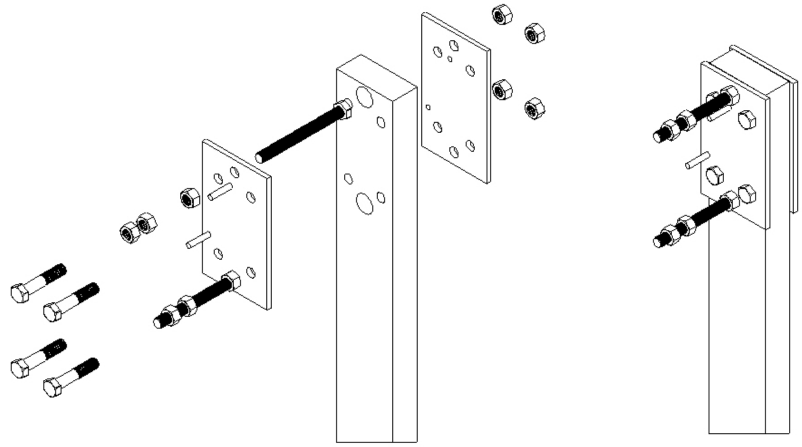
Figure 2.2: Rendering of final design in SolidWorks

2.4 Design Details

The following section describes the function of various pieces of the dummy arm. For detailed drawings, see Appendix A. For a discussion of design decisions, see the following section of design considerations.

2.4.1 The Mount Assembly

The mounting portion of the device is a simple clamping mechanism, designed to attach to a two-by-four (or similar) board. The two aluminum plates in figure 2.3, page 18 are connected by an array of four bolts to ensure a solid mating. Furthermore, those plates act as the base for the entire assembly; though only one arm was manufactured, another could easily be attached to the second plate. The two small, protruding pegs are the mechanical stops that constrain extension and flexion move-



(a) Exploded view (b) Collapsed view

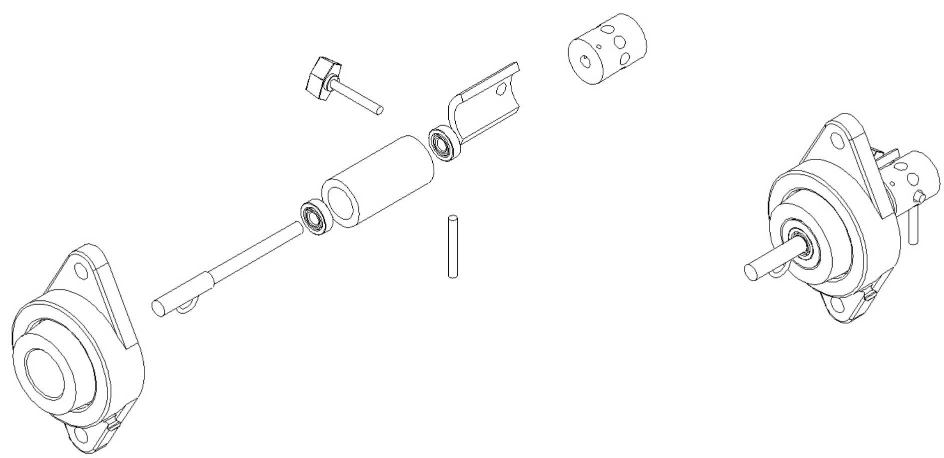
Figure 2.3: The mount assembly

ment. Finally, the two long bolts and accompanying nuts provide an attachment for the mounted bearing in the next assembly.

2.4.2 The Shoulder Assembly

The shoulder assembly (Figure 2.4, Page 19) is the main focus of this project. It provides resistance in the abduction, flexion, and extension directions and allows the arm to be posed at different angles along the flexion/extension path.

The inner axle is attached directly to the upper arm and the locking mechanism to the far right of figure 2.4a. The outer tube is connected to the partial piece of tubing which locks the tube to the inner axle via a removable pin; this pin provides the ability to pose the shoulder in increments of 45 degrees. The outer tube is stabilized by cabling and weights (not pictured) to provide resistance in the flexion/extension direction. The peg protruding from the bottom of the locking mechanism is designed to interfere with the mechanical stops on the mount and stop the arm at the limits



(a) Exploded view (b) Collapsed view

Figure 2.4: The shoulder assembly

of human flexibility.

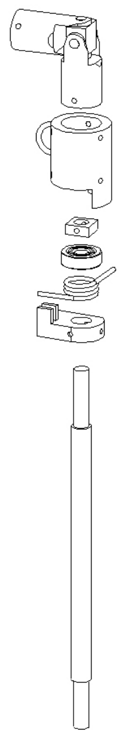
Finally, the U-bolt on the inner axle will be attached to another U-bolt on the upper arm via a spring or elastic cord to provide resistance in the abduction direction.

2.4.3 The Upper Arm Assembly

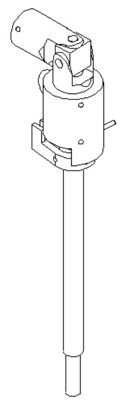
The upper arm assembly (Figure 2.5, Page 20) is simple, yet effective. The universal joint provides flexibility in two degrees of freedom. The connecting tube provides support for the bearing, a place to attach the U-bolt, and acts as a mechanical stop for the rotation motion of the upper arm. The spring provides rotation resistance and resets the arm to a neutral position when not in use. In addition to holding the spring, the lower spring lock interferes with the mechanical stops on the tube.

2.4.4 The Elbow Assembly

The elbow assembly is a simple design, intended only as a placeholder for a more complex joint that includes resistance and further options for posing. The current



(a) Exploded view



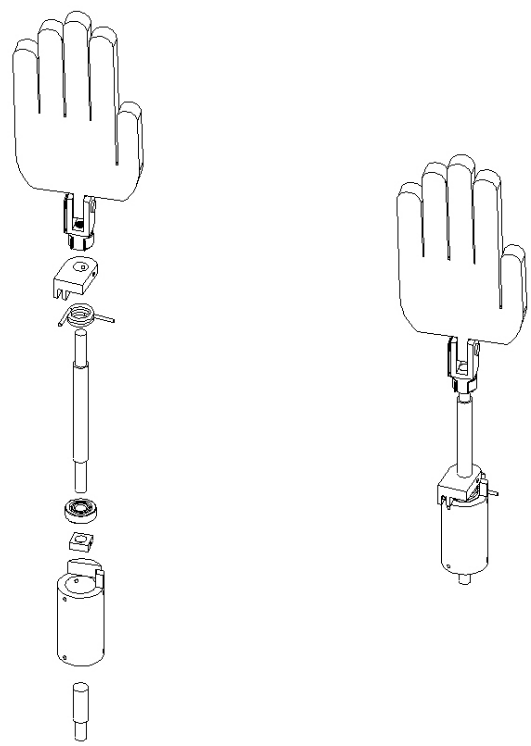
(b) Collapsed view

Figure 2.5: The upper arm assembly

design consists of two clevises attached to a simple piece of aluminum with stops that will limit motion to roughly that of a human elbow. This is an unfinished piece, only serving to connect the upper and lower arms together for the purposes of testing.

2.4.5 The Forearm Assembly

The forearm assembly (Figure 2.6, Page 21) is essentially the same as the upper arm, with the addition of a simple hinge for the hand. Much like the elbow, the wrist is an unfinished piece, only serving to provide a rough representation of a human hand.



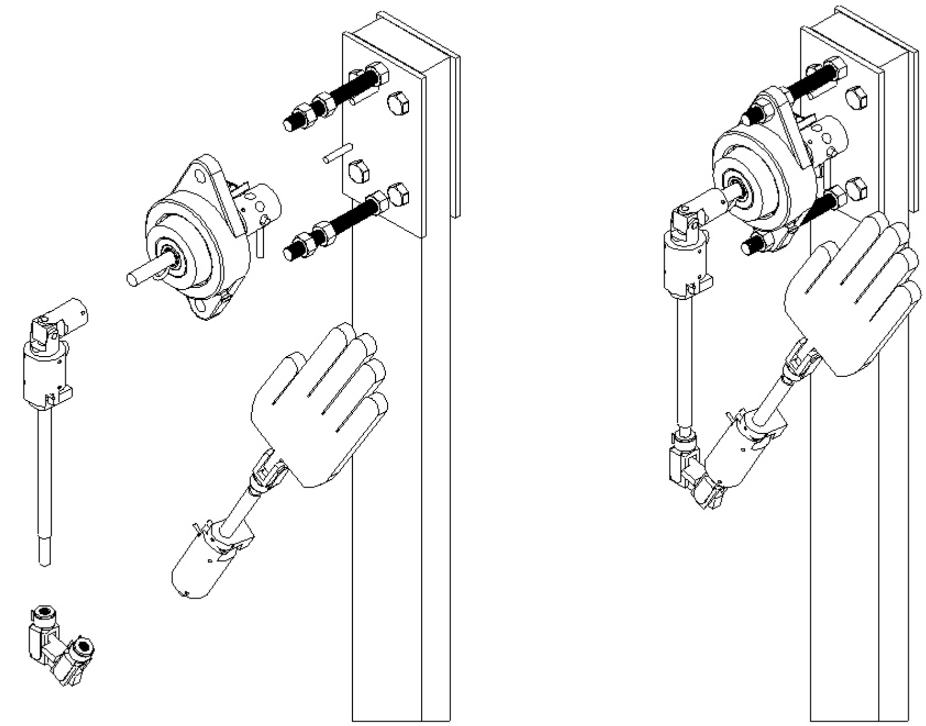
(a) Exploded view

(b) Collapsed view

Figure 2.6: The forearm assembly

2.4.6 The Final Arm Assembly

The final arm assembly (Figure 2.7, Page 22) is a simple matter of combining all the sub-assemblies.



(a) Exploded view (b) Collapsed view

Figure 2.7: The fully assembled arm

2.5 Design Considerations

In any design project decisions must be made between cost and function, or accuracy and ease. This section provides details behind some of the compromises and decisions made during this project. Improvements to the design will be discussed in the following chapter.

2.5.1 Simplicity

One of the design requirements for this project was simplicity, both in design and construction. For that reason, parts were either to be ordered off the shelf or designed to be made with minimal difficulty in a machine shop. Because of this, a great deal of effort went into adapting the design to match up with existing parts. Most of the machined parts can be created in a short time on a lathe or milling machine.

Furthermore, the design is also quite modular. Most interfaces are locked with set screws or are threaded connections. This allowed for ease in redesign or disassembly after initial construction.

2.5.2 Weight

Original plans for the dummy called for mimicking the weight of a human arm. During the investigation phase, however, it was discovered that the dead weight of an arm (approximately 10 pounds) would require an excessive amount of spring or weight resistance to control. Furthermore, in examining the arm of a Hybrid III crash test dummy, it was discovered that manipulating the full dead weight of an arm can be extremely difficult and tiring, while doing the same work with a human is not.

In light of these discoveries, the arm was made considerably lighter than 10 pounds. Currently, it weighs approximately 2 lbs. This allows the joints to be controlled with much weaker springs and less weight and makes for a much more pleasant experience for the user.

2.5.3 Resistance

At the beginning of the design process, most of the resistance was planned around the use of torsion springs. This would have allowed the joints to be compact and self-contained. However, as the design process progressed, it became clear that the only place such springs could be used appropriately was in the forearm and upper arm. In those two positions, the springs provide resistance in both directions and provide a natural neutral position. Convention dictates that torsion springs are only supposed to be torqued in the direction of their winding, but in the case of the prototype—because the loads and cycles are low—this should not pose a problem.

An elastic cord is used to constrain the ad/abduction of the shoulder. This was done to reduce cost: the elastic acts as a customizable spring, meaning that it was not necessary to purchase a dozen different springs of different lengths and sizes to achieve the correct resistance. More important, however, was the decision to provide resistance in only the abduction direction. This simplified the problem of adding resistance to the shoulder joint by making use of the assumption that anyone whose joints are being manipulated will pull their limbs toward their core (generally a wise decision when it comes to fighting a joint lock).

The spring stiffness and weight resistance were a matter of some calculation and consideration. Data about average and maximum arm strength were obtained from a NASA Report [NASA, 1995]. This data (Tables 2.1 and 2.2, Pages 25 and 26) was very useful when ordering torsion springs. But the weight of the "bone" in the arm had to be considered as well; simple static force and moment calculations were performed to ensure that the springs would provide adequate resistance without allowing excessive rotation due to gravity.

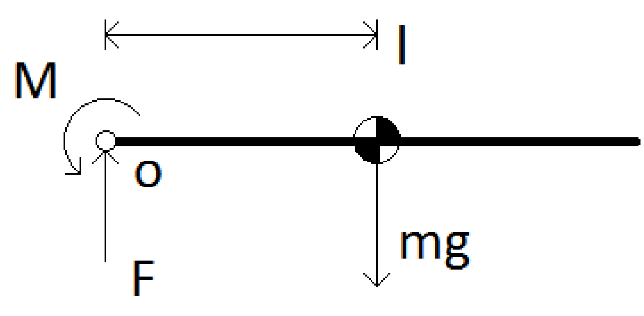
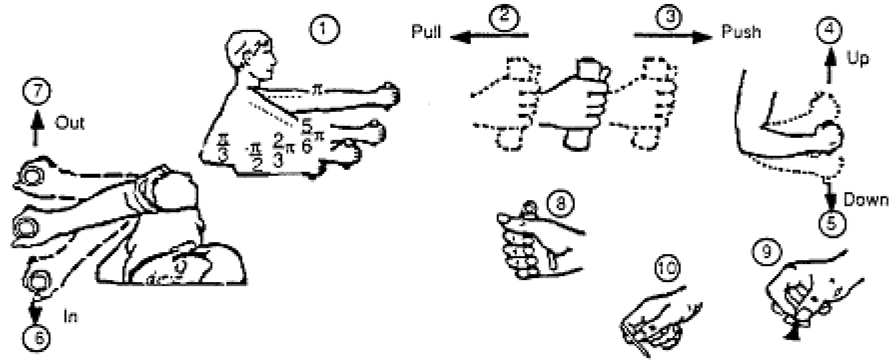


Figure 2.8: Simplified free-body diagram for upper arm

For the upper arm, the free-body diagram in figure /reffig:statics2 was used to

Table 2.1: Arm Strength in Pounds [NASA, 1995]



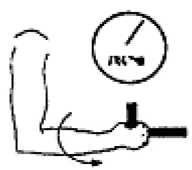
Elbow (1)	Pull (2)	Push (3)	Up (4)	Down (5)	In (6)	Out (7)
π	52	50	14	17	20	14
$\frac{5\pi}{6}$	56	42	18	20	20	15
$\frac{2\pi}{3}$	42	36	24	26	22	15
$\frac{\pi}{2}$	37	36	20	26	18	15
$\frac{\pi}{3}$	24	34	20	20	20	17

calculate moments about the bearing at point o (where point o represents the axis of rotation along the upper arm). That calculation provided a minimum spring strength (see Appendix B for complete details), while the data in table 2.1, provided a maximum.

Resting torques on the forearm are minimal. The data from table 2.2 was again considered to be the maximum, while the minimum was estimated.

Perhaps the most important consideration in regards to resistance is the use of weights in constraining the flexion and extension motion of the arm. If torsion springs had been used as per the original plans, the posing of the arm would not work nearly so well as it does. Using a spring would have meant that the arm would not stay where it was posed but would, because of the force of gravity, be pulled off the desired mark until the torquing of the spring had generated enough force to stop it. Instead, using

Table 2.2: Maximum Arm Torque Strengths [NASA, 1995]

Maximum Torque Type	Mean (in-lb)	Std. Dev. (in-lb)
	121.5	30.1
	153.9	45.0

the appropriate amount weight resting on the floor as a counterbalance means that the force of gravity alone cannot move the arm. This feature is ultimately what allowed the arm to be posed in a controllable manner.

Selection of the correct weight was also estimated by a simple statics calculation. The free-body diagram in figure 2.9 was used to calculate moments about the bearing at point a, where point a is the axis of rotation in the flexion/extension direction. The calculations (see Appendix B for complete details) dictated that the minimum weight to maintain the arm at horizontal extension (the worst case scenario) would have to be 28 lbs. However, this value did not perform as desired, so more weight was added, bringing the final weight to 35 lbs. The decision to hold the weights in a suspended container helped greatly, as it simplified the adjustment of resistance.

It should be noted, however, that the weight used in this project is far from final. The final dummy will (at a minimum) have different components in place of the elbow and hand, changing the required weight.

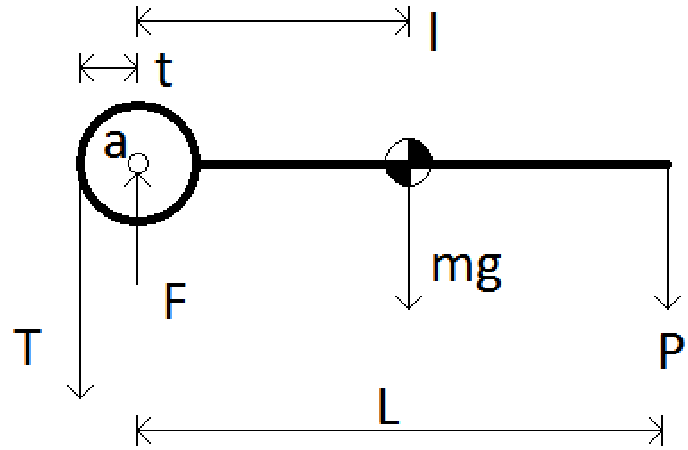


Figure 2.9: Simplified free-body diagram for horizontal arm position

2.5.4 Range of Motion

The forearm and upper arm rotation were designed with the limitations of the human body in mind. The pieces that hold the springs in place are designed to interfere with the tubes that hold the bearings, stopping motion at the correct points.

The elbow suffers from inaccuracies in the CAD drawings I obtained from the supplier. The first model elbow did not work as planned. The current model works slightly better; immediately after construction, it stopped at full extension (0 degrees) and full flexion (160 degrees) as planned. However, after some use and wear it began to slip past the stops and collapse upon flexion. Thankfully, this is not the final design for the elbow.

The first universal joint to be chosen proved to be inadequate to the task of mimicking a human shoulder. In certain cases, the u-joint could become locked in the wrong position, requiring a manual reset and interrupting the user's ability to practice. This would be even more problematic if the arm was actually covered in some sort of padding, obscuring the u-joint from view and making adjustments more difficult. The problem was solved by replacing the original part with an "extreme angle” universal joint that was designed to operate at much greater angles, giving it more freedom to bend.

2.6 Summary

A review of design goals (Table 2.3) shows that all of the specified targets were met by the final design. The next step was to build and test the prototype, to test the success of the design.

Table 2.3: Design goals met

Design Requirement	**Met/Not Met**
Minimize assembly	Met
50th percentile male dimensions	Met
Poseable, 3 positions	Met
Easily poseable	Met
Forearm rotates between wrist and elbow	Met
Forearm rotates 90 degrees int./ext.	Met
Forearm returns to neutral	Met
Wrists and hand are in vertical position	Met
Elbow 0 degree ext., 140 degree flex.	Met
Upper arm rotates close to shoulder	Met
Upper arm rotates 60 degrees int./ext.	Met
Upper arm to return to neutral	Met
Shoulder rotates to 180 degrees/-45 degrees	Met
Shoulder to return to posed position	Met

Chapter 3
THE PROTOTYPE

Following the completion of the final design, pieces that were not ordered off the shelf were manufactured. The following section details the pieces that were machined. A full bill of materials (BOM) can be found in table 3.1, on page 43. Detailed drawings of all manufactured parts can be found in Appendix A. All part numbers refer to McMaster-Carr and can be found on their website (www.mcmaster.com). Item numbers refer to table 3.1.

3.1 Manufacturing

All manufacturing was done in the University of Washington Integrated Learning Factory (ILF). Although the ILF has several computer-controlled lathes and mills, because of the relative simplicity of all the parts, most machining was done using standard mills and lathes or hand held tools.

3.1.1 The Mount Assembly

The mount assembly is the simplest of all the parts of the prototype. It requires only two identical machined pieces and several nuts and bolts.

Mounting Plates (Item 1.4)

The first step in machining the mounting plates (Figure 3.1, Page 30) was to cut a large piece of 1/4" aluminum plate into two similarly sized pieces using a band saw. The edges were then end-milled to be exactly the same size. The final step was to

Figure 3.1: Prototype mount assembly

drill 1/2” and 1/4” holes using the mill’s precise positioning. A detailed drawing can be found in Appendix A (Figure A.2, Page 64).

Assembling the Mount

See figure 3.2, page 31.

1. Choose one mounting plate and insert 5” bolts (Item 1.6) to outermost 1/2” holes and the stop pegs (1/4” screws in this case) into the appropirate 1/4” holes (Figure 3.2). Screw 1/2”-20 nuts (Item 1.1) down to lock in place.

2. Insert four 1/2” hex head screws (Item 1.3) into remaining 1/2” holes; insert through matching holes in 2x4 and then through second mounting plate. Screw four more 1/2”-20 nuts (Item 1.1) onto hex head screws to lock in place.

3.1.2 The Shoulder Assembly

The shoulder assembly is the focus of this project. It is comprised of several machined pieces and quite a few off-the-shelf parts as well.

(a) Step 1 (b) Step 2

Figure 3.2: Assembling the mount

Flexion/Extension Lock (Items 2.1, 2.9, and 2.6)

The flexion/extension lock (Figure 3.3, Page 32) is the mechanism that allows the arm to be posed. It is comprised of three pieces: the inner rod, the outer tube, and the pin. The inner rod (the piece with several radial holes) is mounted to an inner axle. The outer tube (the piece with the black square of velcro) is attached to an outer axle, allowing it to rotate around the inner rod. The peg (the piece with the knurled grip) locks the former two together.

Machining the inner rod was a matter of using a lathe to turn a rod to the correct diameter and to drill an end hole. A mill was then used to drill accurately positioned radial holes. Set screw holes and tapping were done with a hand held drill and tap.

The outer tube was cut from an aluminum tube of the appropriate size and a hole was drilled to accommodate the peg and line up with the inner rod's radial holes.

The peg was turned on a lathe and a die was used to cut threads for the knurled grip to be screwed on.

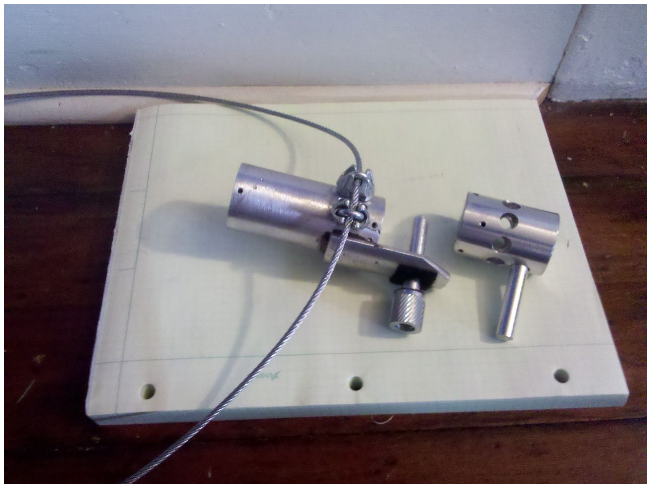


Figure 3.3: Prototype flexion/extension lock

Figure 3.4: Prototype shoulder axle

Shoulder Axle (Item 2.3)

The narrower section of the shoulder axle (Figure 3.4, Page 32) was turned on a lathe to allow it to fit through the smaller bearings in the shoulder. Two holes were later drilled to accommodate the U-bolt.

Shoulder Tube (Item 2.5)

The shoulder tube can be seen in figure 3.3, page 32. The shoulder tube was a simple matter of cutting a piece of aluminum tubing to size using a band saw and drilling six set screw holes using a hand held drill and tap.

Assembling the Shoulder

See figure 3.5, page 34.

1. Attach the outer flexion/extension tube (Item 2.9) to shoulder tube (Item 2.5) by welding or using epoxy (e.g. JB Weld) (cable attachments can also be added at this point using Crosby clamps).

2. Insert bearing (Item 2.4) into either side of shoulder tube and secure using three 1/4" set screws (Item 2.10) apiece.

3. Insert shoulder axle (Item 2.3) into bearings. Insert narrow end of shoulder axle into flexion/extension lock inner rod (Item 2.1). Secure using 6 1/3" set screws.

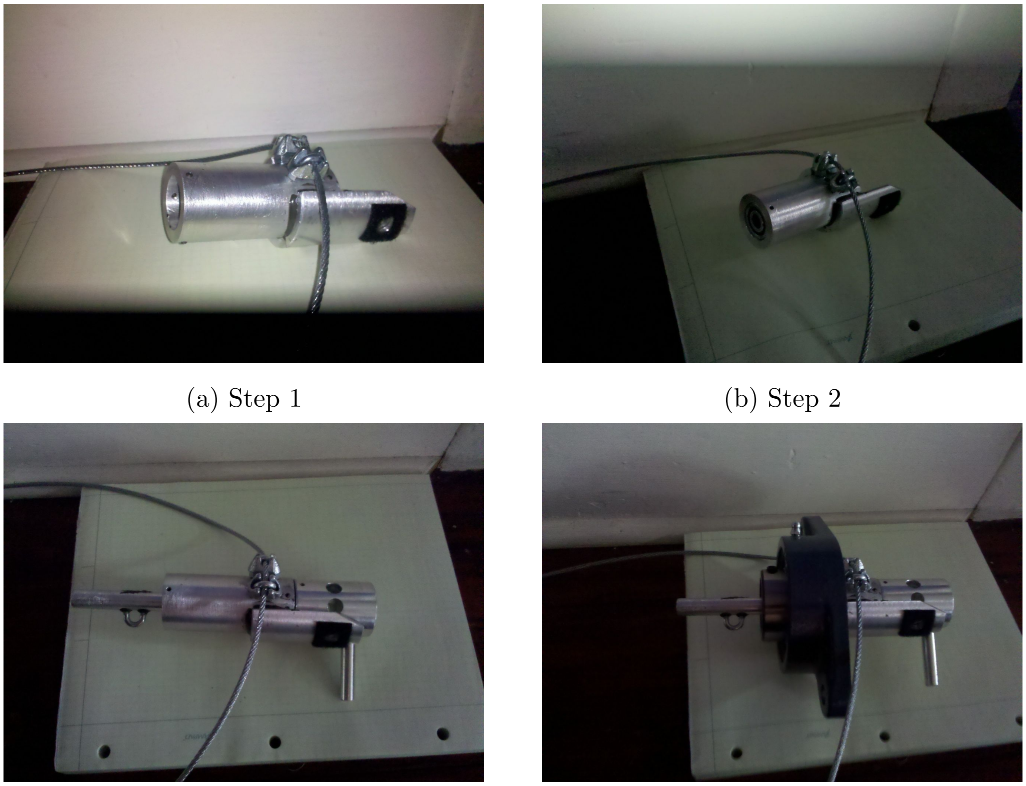
4. Insert shoulder tube into mounted bearing (Item 2.8), secure by tightening bearing set screws.

3.1.3 The Upper Arm Assembly

The upper arm also requires several machined pieces.

Bearing Lock (Item 3.4)

The bearing lock (Figure 3.6, Page 35) is one of the simplest pieces in the entire prototype. It is a 5/8"square of 1/4" aluminum plate, cut from the same stock as the mounting plates. A 3/8" hole was drilled through the center to accommodate the



(a) Step 1 (b) Step 2

(c) Step 3 (d) Step 4

Figure 3.5: Assembling the shoulder

narrow end of the arm bone and a set screw hole was drilled and tapped in the side to lock it into place. (NOTE: there is also an identical bearing lock in the forearm).

Torsion Spring Lock (Item 3.6)

The torsion spring lock (Figure 3.7, Page 35) is similar in function to the bearing lock, but it is designed to hold a torsion spring in place, rather than a bearing. A small block of aluminum was milled into an L-shape. A 1/2" hole was drilled to accommodate the arm bone and 3 set screws holes were drilled and tapped to ensure a firm lock. The shorter end of the L was then milled to accept one leg of the torsion spring. In figure 3.7 a glob of JB Weld can be seen; this is there to hold the spring in

Figure 3.6: Prototype bearing lock

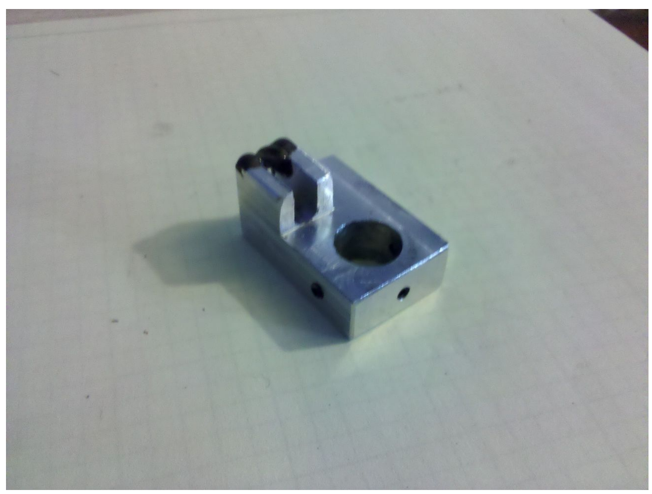


Figure 3.7: Prototype torsion spring lock

place. (NOTE: there is also an identical spring lock in the forearm).

Upper Arm Bone (Item 3.7)

The upper arm bone (Figure 3.8, Page 36) was a simple matter of cutting a piece of 1/2" diameter aluminum rod to length and lathing a small section of both ends down to 3/8". One end was threaded using a hand-held die.

Figure 3.8: Prototype upper arm bone

Upper Arm Tube (Item 3.9)

To machine the upper arm tube (Figure 3.9, Page 37), a piece of aluminum tubing was cut to the correct length. One end was bored out to accept the universal joint; the opposite end was milled to hold a torsion spring in place (much like the torsion spring lock). Set screw holes were drilled and tapped to secure the bearing and the universal joint. Two 1/4" holes were drilled to accommodate the U-bolt.

Assembling the Upper Arm

See figure 3.10, page 38.

1. Screw clevis (Item 4.1) onto threaded end of arm bone (Item 3.7) (NOTE: picture shows a nut that has been frozen to the clevis using JB Weld to prevent unscrewing).

2. Slide torsion spring (Item 3.5) and lock (Item 3.6) onto the arm bone. Do not tighten set screws on the lock until correctely positioned for elbow movement.

3. Slide on bearing (Item 3.8) and bearing lock (Item 3.4). Tighten set screw.

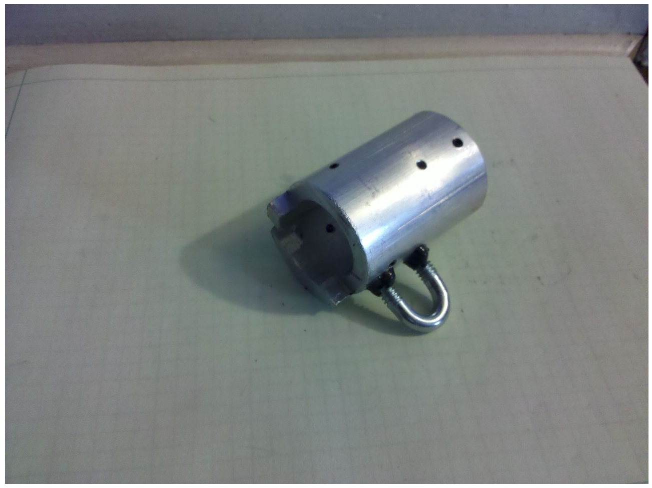


Figure 3.9: Prototype upper arm tube

4. Weld or epoxy U-bolt (Item 3.10) into upper arm tube (Item 3.9). Slide the tube over bearing, fitting the other leg of the torsion spring into the slot on the tube. Tighten set screws to secure bearing.

5. Slide universal joint (Item 3.1) into bored-out end of upper arm tube. Tighten set screws.

3.1.4 The Forearm Assembly

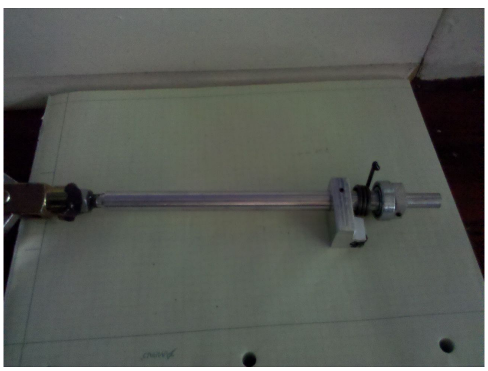
The forearm assembly is very similar to the upper arm, so identical parts have been omitted.

Clevis Connector (Item 5.1)

The clevis connector (Figure 3.11, Page 39) is an extremely simple piece. A short length of 1/2" aluminum rod, partially turned down to 3/8" and threaded to screw into one of the elbow clevises.

(a) Step 1

(b) Step 2



(c) Step 3

(d) Step 4

(e) Step 4

Figure 3.10: Assembling the upper arm

Figure 3.11: Prototype clevis connector

Forearm Tube (Item 5.2)

The forearm tube (Figure 3.12, Page 40) was turned and bored out of a solid rod of aluminum. The smaller end has an inner diameter of 1/2" to accept the clevis connector. The larger end has an inner diameter of 1" to accept the bearing and bearing lock. The larger end is milled in the same fashion as the upper arm tube to hold a torsion spring. Set screw holes are place to hold the connector and the bearing in place.

Forearm Bone (Item 5.4)

The forearm bone (Figure 3.13, Page 40) is effectively the same as the upper arm bone, but shorter.

Hand (Item 5.6)

This version of the hand (Figure 3.14, Page 41) is simply a piece of porous plastic cut to the approximate shape and dimensions of a human hand.

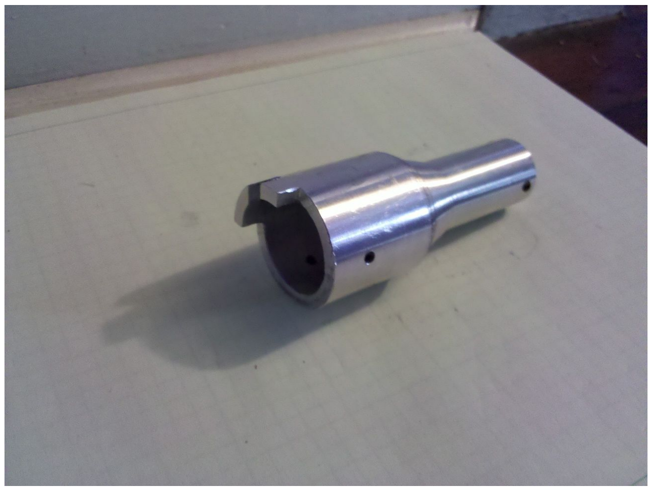


Figure 3.12: Prototype forearm tube

Figure 3.13: Prototype forearm bone

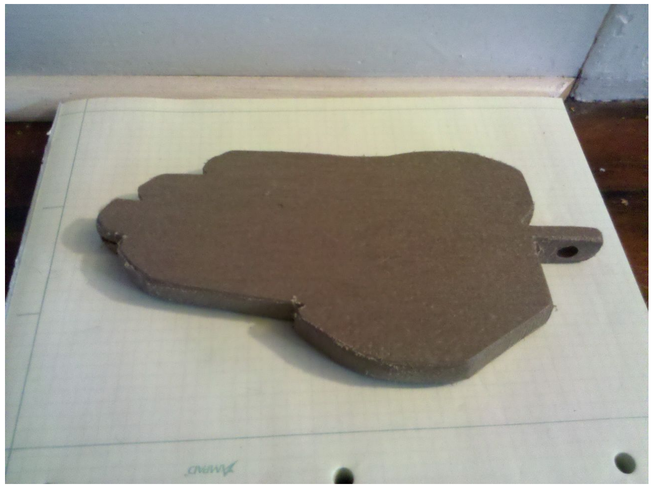


Figure 3.14: Prototype hand

Assembling the Forearm

See figure 3.15, page 42.

1. Screw clevis (Item 5.1) onto threaded end of arm bone (Item 5.4) (NOTE: picture shows a nut that has been frozen to the clevis using JB Weld to prevent unscrewing).

2. Slide torsion spring (Item 5.7) and lock (Item 5.8) onto the arm bone. Do not tighten set screws on the lock until correctely positioned for elbow movement.

3. Slide on bearing (Item 5.3) and bearing lock (Item 5.9). Tighten set screw.

4. Slide the forearm tube (Item 5.2) over bearing, fitting the other leg of the torsion spring into the slot on the tube. Tighten set screws to secure bearing.

5. Attach hand (Item 5.6) to clevis.

(a) Step 1

(b) Step 2

(c) Step 3

(d) Step 4

(e) Step 4

Figure 3.15: Assembling the forearm

Table 3.1: BOM for prototype

Item #	Part #	Description	Qty.
Mount Assembly			
1.1	91845A145	1/2”-20 Nut	12
1.2	-	1/4” Peg	2
1.3	91247A358	1/2”-20 Hex Head Screw, 2 1/2” length	4
1.4	-	Mounting plate (Figure A.2, Page 63)	2
1.5	-	2 x 4 board	1
1.6	92620A754	1/2”-20 Bolt, fully threaded, 5” length	2
Shoulder Assembly			
2.1	-	Flx/Ext lock, inner rod (Figure A.4, Page 67)	1
2.2	-	U-bolt	1
2.3	-	Shoulder axle (Figure A.5, Page 68)	1
2.4	6383K23	Roller bearing, ID = 3/8”, OD = 1”	2
2.5	-	Shoulder Tube (Figure A.6, Page 69)	1
2.6	65035K81	Knob	1
2.7	-	3/8” rod, 2” length	1
2.8	6665K26	Flange mounted bearing, ID = 1 1/2”	1
2.9	-	Flexion/Extension lock, outer tube (Figure A.7, Page 70)	1
2.10	92695A132	6-32 set screws, cone tip, 1/4” length	12
Upper Arm Assembly			
3.1	6444K16	Extreme angle universal joint	1
3.2	92695A130	6-32 set screws, cone tip, 1/8” length	6
3.3	92695A132	6-32 set screws, cone tip, 1/4” length	7
3.4	-	Bearing lock (Figure A.9, Page 73)	1
3.5	9271K113	Torsion spring	1
3.6	-	Torsion spring lock (Figure A.10, Page 74)	1
3.7	-	Upper arm bone, “humerus” (Figure A.11, Page 75)	1
3.8	6383K23	Roller bearing, ID = 3/8”, OD = 1”	1
3.9	-	Upper arm tube (Figure A.12, Page 76)	1
3.10	-	U-bolt	1
Elbow Assembly			
4.1	2447K17	Easy-Adapt clevis rod end	2
4.2	-	Elbow Linkage (Figure A.14, Page 73)	1
Forearm Assembly			
5.1	-	Clevis connector (Figure A.16, Page 82)	1
5.2	-	Forearm tube (Figure A.17, Page 83)	1
5.3	6383K23	Roller bearing, ID = 3/8”, OD = 1”	1
5.4	-	Forearm bone, (Figure A.18, Page 84)	1
5.5	2447K17	Easy-Adapt clevis rod end	1
5.6	-	Hand (Figure A.19, Page 85)	1
5.7	-	Torsion spring lock (Figure A.10, Page 74)	1
5.8	9271K113	Torsion spring	1
5.9	-	Bearing lock (Figure A.9, Page 73)	1
5.10	92695A132	6-32 set screws, cone tip, 1/4” length	2
5.11	92695A130	6-32 set screws, cone tip, 1/8” length	7

3.2 Cabling

After manufacturing was complete it was necessary to attach the cable for the suspended weights. The cabling was attached to the shoulder tube using two Crosby bolts (Figure 3.16a, Page 44): the wire rope was clamped into the bolts and then the ends of the bolts were set into holes on the tube. The ends of the cables were looped around thimbles and secured with two more Crosby bolts (Figure 3.16b, Page 44). Two oval threaded links were used to attach the looped ends to a container for the weights.

(a) Cable attachment at shoulder

(b) Cable loops

Figure 3.16: Cable attachments

3.3 Final Assembly

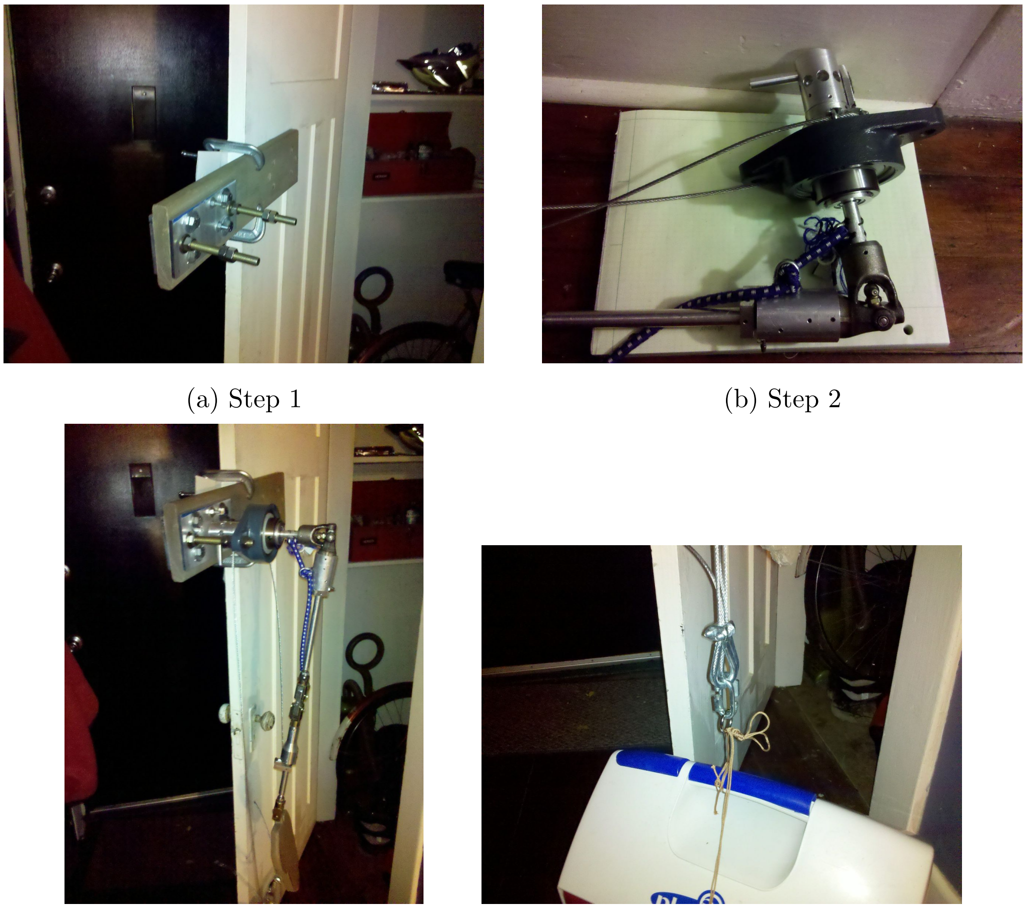
See figure 3.17.

1. Use clamps to attach mount assembly to door.

2. Attach forearm and upper arm assemblies using the elbow assembly. Slide universal joint on upper arm assembly onto shoulder axle.

3. Attach shoulder and arm assembly to mount using protruding bolts.

4. Connect cables to weighted container



(a) Step 1 (b) Step 2

(c) Step 3 (d) Step 4

Figure 3.17: Assembling the arm

3.4 Final Evaluation

After construction of the device was completed, a general overview and evaluation of the prototype was performed.

3.4.1 Resistance

It is difficult to quantitatively evaluate the accuracy of resistance of the different subsections. However, consulting table 2.1 on page 25 tells us that the average human arm can exert 15-20 pounds in medial and lateral rotation of the shoulder. This corresponds to a torque of approximately 200 in-lbs, requiring an extremely strong spring. However, this represents the maximum reasonable resistance and, depending how the data was gathered, may include the use of body weight. The spring chosen for resistance offers only a tenth of that (20 in-lbs) and provides resistance that is quite sufficient.

A similar pattern is seen in the forearm. Table 2.2 on page 2.2 shows that the supination and pronation movements of the forearm can exert an average maximum of 120-150 in-lbs. For simplicity's sake, the same 20 in-lb spring was chosen for use in the forearm, once again providing sufficient resistance.

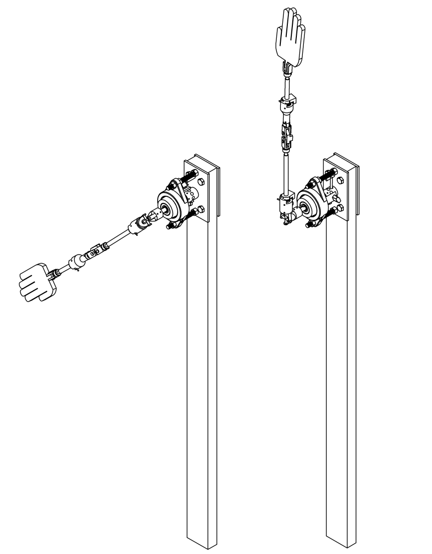
As for flexion and extension resistance, Hughes et al. [1999] tells us that the human arm can exert 400-700 in-lbs in this direction. Another statics calculation (Appendix B) reveals that the use of 35 lbs of weight offers approximately 15 in-lbs of resistance. While this would seem to be extremely low, using the device shows that this value may actually be slightly too high for comfortable usage. However, nothing can be done about it in this design.

Qualitatively, the resistance built into the arm works very well. Some joint locks work better than others, but most of them can be practiced. Exceptions include locks that require the opponent to bend at the waist or go to the ground, something that cannot be helped until this design has a waist of its own.

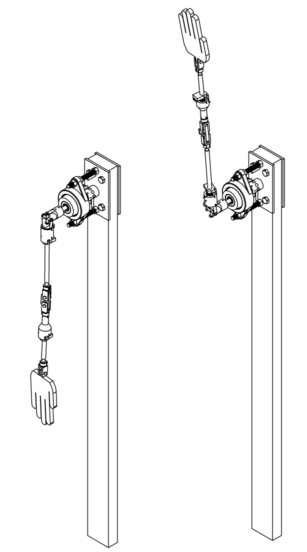
3.4.2 Range of Motion

The range of motion matches the sponsor's design specifications and the flexibility of a 50th percentile human male quite well. On a case-for-case basis, the arm can match each major joint movement of a human being (Figure 3.18, Page 48). However, in using the dummy arm as a whole, there are sometimes unwanted interferences (most notably in the universal joint, see discussion of improvements below).

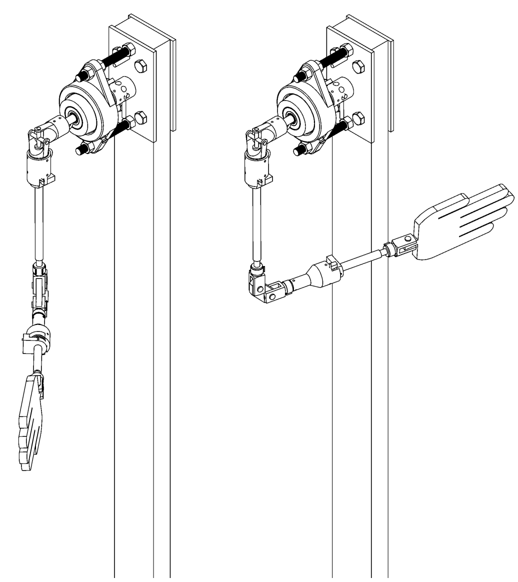
It should be noted, however, that the dummy arm acts differently than a human



(a) Shoulder flexion and extension range of motion

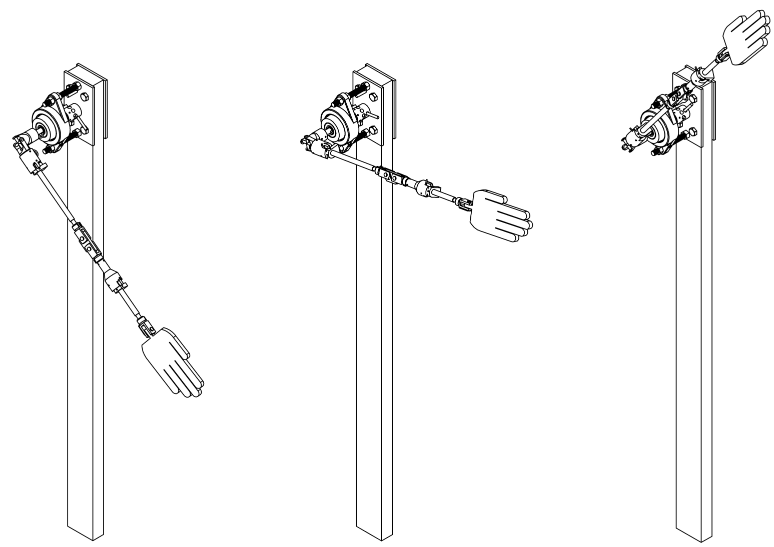


(b) Shoulder adduction and abduction range of motion



(c) Shoulder internal and external rotation range of motion

Figure 3.18: Shoulder range of motion



(a) Low position (b) Middle position (c) High position

Figure 3.19: Poseable arm positions

arm when it reaches the extreme range of motion. A human arm will slowly stop because of increasing resistance, or the rest of the body will move to compensate. The dummy arm simply ceases to move as it runs into a mechanical stop. See the improvements section for possible solutions.

3.4.3 Poseability

The prototype arm can be posed in four usable positions: at side (not pictured), low, middle, and high (Figure 3.19, Page 49). This feature works fairly well, but there are still some issues with slop in the placement of the arm. This may be unavoidable as the fully extended arm creates a very long lever arm. Overall, however, the arm *is* poseable and stays where it is put.

3.5 Summary

In the end, the prototype functioned as expected; it offered a wide range of motion, resistance to manipulation, and provides several poses. Some parts required more machine work than originally intended but most of the design decisions proved to be effective. The following chapter details possible improvements, future work to be done, and conclusions drawn.

Chapter 4

CONCLUSIONS

4.1 Future Design Improvements

While the prototype functions well, there are some areas where improvement is needed. This section details potential improvements for future models.

4.1.1 Fasteners and Modularity

Though extremely helpful in the prototyping phase, future designs should do away with much of the modularity in this design. In some cases, the set screws have been known to work themselves loose or prove insufficient to the task of holding pieces together under normal operating loads. They can and should be replaced with spring pins, bolts, welds, or other more permanent fasteners.

Also, the threaded clevis rod ends tend to (unsurprisingly) unscrew themselves when the arm is twisted in the proper direction. The problem was solved using JB Weld epoxy to freeze the rod ends in place, thus eliminating the usefulness of their threads.

4.1.2 The Mount Assembly

The mount assembly performs adequately. However, depending on how future models are marketed, this may need a redesign. One potential design is to sell standalone arms that can be mounted to a standing or suspended heavy bag, removing the need for designing an entire dummy. Furthermore, future models that incorporate the arm design into a full dummy may even do away with the need for mounting of this type.

4.1.3 The Shoulder Assembly

While the shoulder assembly functions quite well, in future designs it might be desirable to use a lighter mounted bearing. The one currently in use works flawlessly, but it is the heaviest part of shoulder by far. It could be replaced with something much lighter and less expensive with a fairly simple redesign.

Another area of concern is the suspended weight system. While it works very well, it is rather bulky and may be impractical in future designs. Possible solutions are to make the cables much shorter and rest the weights within the "body" of the final dummy. The weights may also cease to function as desired if the dummy is designed to bend at the waist; this would change the angle of the arm relative to the ground (changing the force due to gravity) and possibly change the length traveled by the cable. To solve this problem the weights could be replaced with springs. This would lead to more slop (lack of precision) in the positioning of the arms but eliminate the problems surrounding the weights. The use of a damper in the flexion/extension direction would help stability and should be considered for all joints using springs.

Alternatively, it may also be possible to route the cables *through* the waist joint. This would minimizing the change in distance during a waist bend because the distance traveled by the cable would remain the same. The angle of the arm would change, but the force exerted on the arm by gravity could never increase above the maximum calculated for posing purposes. So, assuming the cable length remained similar, a bend at the waist would have little-to-no effect on the positioning of the arm, though there might be some changes in apparent resistance for the user.

Finally, after replacement of the original universal joint, the arm as a whole works much better. However, there are still some issues with the functionality of the u-joint itself. While it no longer gets completely stuck in the wrong position, it does not move through all positions as smoothly as desired and sometimes inverts (returns to a position 90 or 180 degrees from where it began). The best option for future builds is most likely a custom-designed part that limits overall motion but retains the flexibility of a universal joint.

4.1.4 The Upper Arm Assembly

The upper arm assembly works very well, though in future models it could be easily modified to minimize the slop in rotation. This prototype was designed to accept springs of varying sizes and, as a result, lacks precision. Now that an appropriate spring has been chosen, the next model can use precision drilled holes instead of roughly milled slots, greatly reducing the freedom of the spring to move and turn without offering resistance.

Furthermore, in future designs it would be advisable to reinforce the stability of the bearings. Using a single narrow bearing, while inexpensive, means that the rotation motion is subject to a substantial amount of wobble and wear. One solution would be to use two bearings of this type and space them farther apart. Alternatively, a longer needle bearing might solve the problem as well. Either solution would require minimal redesign.

4.1.5 The Elbow Assembly

The current elbow design has very little to offer: it provides no resistance and its range of motion is not entirely correct. Future designs could offer quite a bit more in the way of accuracy and usefulness. A design operating on similar principles to the shoulder joint's flexion and extension poseablity would be extremely desirable. Such a design would provide resistance and allow posing of the forearm relative to the upper arm.

4.1.6 The Forearm Assembly

The forearm suffers from the same problem of slop as the upper arm and would benefit from the same solution. However, the wrist and hand are also in need of improvement. The wrist joint could be greatly improved through the use of a ball joint rod end. This would allow radial and ulnar deviation as well as flexion and extension. Furthermore, the wrist also needs resistance which can most likely be provided in the form of a torsion spring. A properly mounted torsion spring would provide resistance in flexion/extension and also for both deviation directions.

Finally, there is the matter of the hand. A simple piece of crudely milled plastic was used as a place holder. A biomimetic hand would be an extremely complex subsystem to design and create. A simple alternative might be to use the hand of a Hybrid III crash test dummy. This would provide a hand that meets the sponsor's specifications and do so without the need for more expensive research and development.

4.1.7 Resistance and Range of Motion

As previously mentioned, the stopping of the arm joints at the end of their range of motion is very unnatural. This might be mitigated by removing some of the stops and allowing the increasing resistance of a spring to prevent further motion of the arm, for a "soft" stop. Another option would be to add some kind of padding to the stops, making for a softer, more organic limit.

The addition of dampers to the various joints should also be incorporated into future designs. This would smooth the motion of the arm and prevent excessive vibrations after manipulation is complete.

4.2 Future Work

Aside from improvements to the working of the current design, there are several other paths of investigation that should be followed in the future.

4.2.1 Structural Analysis

One of the key requirements for a marketable dummy of this type will be its durability. A completed unit will have to withstand strikes from trained martial artists and continue to function perfectly. It will need to retain its range of motion and resistance despite rough treatment and continual use. Furthermore, one of the sponsor requirements (Appendix C) requires the dummy to last through at least one million cycles.

In light of these requirements, the final design of the dummy should undergo a complete structural analysis. It should be designed to maximize the number of cycles to failure.

Of particular concern are the cheap roller bearings in the upper arm and forearm. The amount of wobble they allow could lead to serious damage under continuous heavy use. It has already been suggested that they be replaced but whatever is chosen must also undergo analysis for durability and be able to withstand the various loads it will experience.

Furthermore, it may be desirable to use steel rather than aluminum for the final design, as steel can be designed for infinite life while aluminum cannot. For a device such as this, the main concern is most likely fatigue failure. Using narrow steel pipes might be the best choice for the arm bones, offering similar strength and weight to the aluminum rods currently in use. It's unlikely that the forces experienced during normal manipulation (or even during striking) would be enough to deform or fracture the arm bones (though this should be confirmed). Rather it is the continuous application of low-level force for a long period of time that is mostly likely to lead to failure in the bones. The same can be said of the arm tubes (spring and bearing holders) and shoulder axle and tube.

Any off-the-shelf parts should also be evaluated. Many parts can be found that are certified for a certain lifetime. Failing that, failure/fatigue calculations can be done to check out uncertified parts.

However, completing the required calculations will require gathering some of the following data: striking force, force of manipulation, what constitutes minimal/normal/heavy use, material properties, and part geometry. Material properties and part geometry are easily obtainable, but the others will require some experimentation and research all their own.

Striking force may be obtainable from literature but can also be measured in a lab. Obtaining accurate data that covers a wide range of user sizes and strengths would be ideal.

The forces applied during manipulation will have to be obtained via experiment. See the section on instrumentation below. Furthermore, this data could be used to confirm or refute the claim that the torsion springs in the upper arm and forearm will last even when torqued against the direction of winding.

4.2.2 Instrumentation

Adding instrumentation to the device has been discussed since the very beginning of the project. It was rejected as being too expensive and unnecessary for this design. However, some of the possibilities bear mentioning.

For research purposes, strain gages would be extremely useful for the aforementioned lifetime calculations. Capturing the real strain while the device is in use would be the best way to ensure a durable design. This would apply only to a development prototype and would be completely unnecessary in a production model.

A force transducer of some kind might also be used for measuring the force of a strike. Knowing the average force behind a kick or punch would also greatly aid in designing for durability. Furthermore, this could also be useful in a final product, giving feedback to a martial artist about his or her hitting power.

One other possibility would be to add sensors or electrical contacts to the joints of the arm. When triggered, they would activate a light or tone that would notify the user that pushing or pulling any farther might result in a dislocation or other serious injury in a human arm. This would be an extremely useful tool, especially for law enforcement where use of excessive force is often a problem.

4.2.3 Actuation

Using cables in the shoulder opens the door to actuation of the arm. Instead of weight, the cables could be pulled by linear actuators or pulleys to control the arm. This would most likely represent a dramatic increase in complexity and expense but might also produce substantial benefits. An actuated arm would be able to perform preprogrammed techniques (such as punches) and come even closer to replacing a human training partner. However, such a device would require an almost complete redesign of the resistance systems in the prototype.

4.2.4 Outer Covering

Whatever design is used in the end, its internal components must be covered, both for their own protection and that of the user; rotating parts and joints offer many pinch points for the unwary. Also, a correctly designed covering would increase the realism of the arm, making it match human size more accurately. Such a covering could be made of foam or rubber; it should be light (so as not to make the arm too heavy), strong (for durability), and pliable (to mimic human skin).

One possible method of attaching the "skin" would be to fasten a tube or pipe around the current design. It could be secured to the ends of the long bones. This would allow the rotation of the forearm and upper arm to continue without impediment while providing a solid surface to mount the skin.

4.2.5 Completing the Dummy

The arm design in this paper is only a subsystem. Aside from further work on the arm alone, there are several other pieces of the dummy that will need designing and testing. It has already been noted that integrating the arm into a dummy with a mobile torso may change the performance of the shoulder, and any such design should attempt to minimize such effects to avoid a complete redesign of the shoulder. The final dummy is also slated to include a head and flexing neck, as well as some sort of static legs. Full design specifications for the dummy can be found in Appendix C.

4.3 Other Applications

While the arm design is intended for empty hand martial arts applications, it may also have other uses. With modifications to the hand, the arms might also be useful for armed martial arts such as fencing or kendo. Putting a sword into the hand of the dummy would change the behavior of the arm, but would also open up another market.

An arm of a similar type could also be used to train physical therapists in shoulder- or elbow-specific techniques. In order for this to become reality, it is reasonable to assume that the shoulder design would need to emulate the more advanced design of the THOR (adding the scapular motions that were ignored for this project).

4.4 Summary

The project had it origins in attempting to replace a human training partner with a dummy. Research into similar devices found that there was space for a dummy that bridged the gap between striking and grappling dummies. For this thesis, the focus was the shoulder; the rest of the arm was built for the express purpose of testing the shoulder design. Previous work on humanoid shoulder devices revealed that most were robotic or actuated designs; joint replacements were ruled out because their intended application didn't lend itself to the design goals of this project.

The prototype design was chosen for development after several other possibilities proved to be either too complex or expensive. Inspiration for the prototype design was drawn from some of the similar designs. Every effort was made to use inexpensive and easy-to-assemble off-the-shelf parts. The design makes use of springs, elastic, and weights to provide resistance and accurately matches the range of motion of a human arm.

The prototype was constructed in a machine shop using lathes, mills, and other common tools. Parts were machined as necessary for use with the purchased items. Once assembled it became clear that several pieces, most notably the universal joint were in need of modification or replacement. By design, the prototype was intended to be easy to disassemble and reassemble so that changes and upgrades could easily be integrated.

One assembly and construction were completed, the device was tested to ensure that it's range of motion and resistance were appropriate for its intended purpose. The results of this testing are found in the previous section ("Future Design Improvements").

4.5 Conclusion

Despite flaws, this design represents a drastic improvement over the other products available on the market today. As a proof-of-concept design, the prototype has performed extremely well. It provides appropriate resistance for several types of joint locks and offers a modicum of poseablity. While the arm is not ready to replace a human training partner, it could be used to train certain techniques and to practice them at full speed. Furthermore, if the above improvements are made, it will be that much closer to being a marketable product. This project has successfully demonstrated that a product mimicking the human arm can be created and used for martial arts applications.

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Appendix A
DRAWINGS

All bill of material (BOM) part numbers are part numbers as specified by McMaster-Carr. Parts can be ordered at www.mcmaster.com.

A.1 The Mount Assembly

Table A.1: BOM for mount assembly

Item #	**Part #**	**Description**	**Qty.**
1.1	91845A145	1/2”-20 Nut	12
1.2	-	1/4” Peg	2
1.3	91247A358	1/2”-20 Hex Head Screw, 2 1/2” length	4
1.4	-	Mounting plate (Figure A.2, Page 63)	2
1.5	-	2 x 4 board	1
1.6	92620A754	1/2”-20 Bolt, fully threaded, 5” length	2

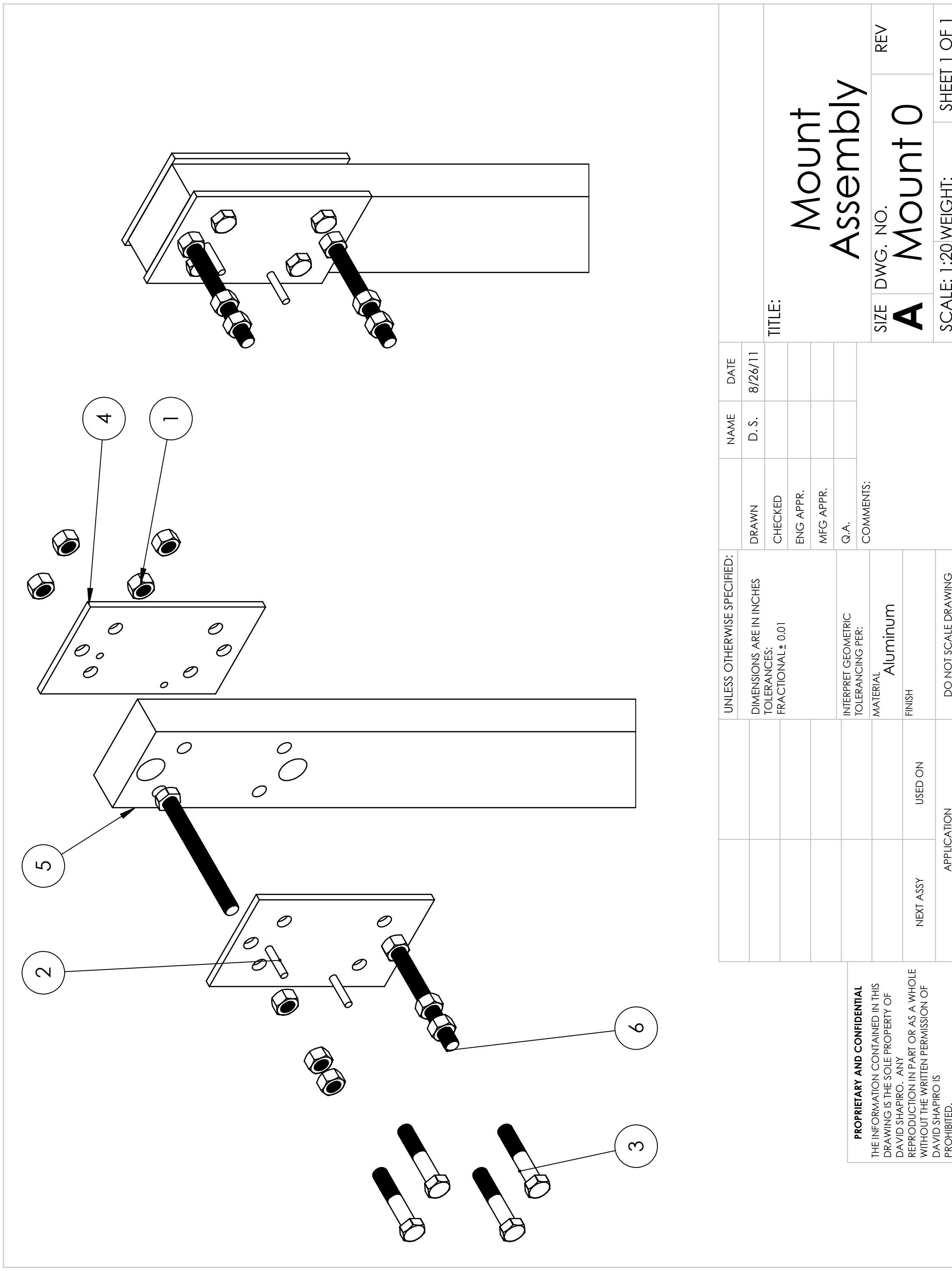

Figure A.1: Exploded view of mount assembly

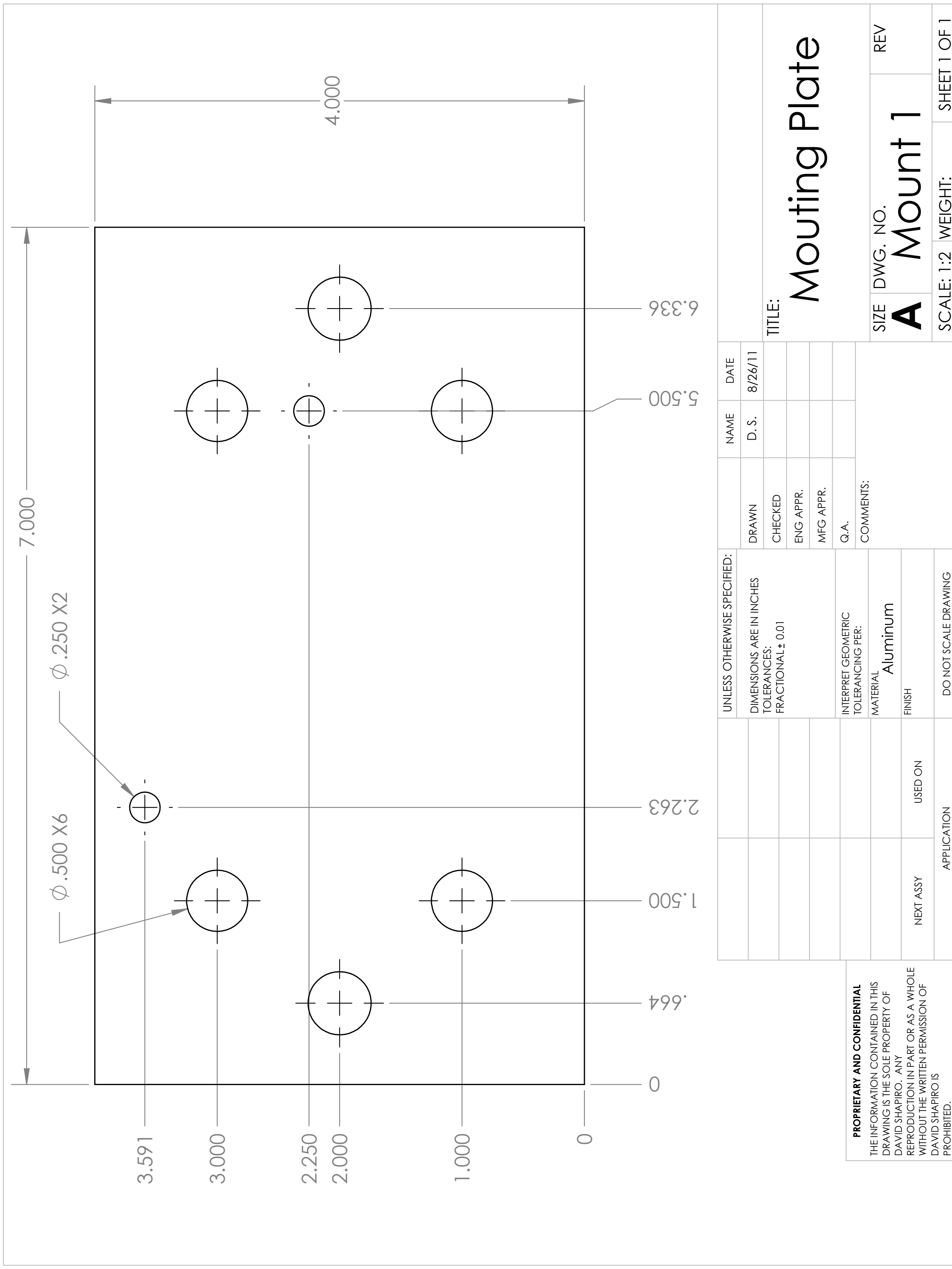

Figure A.2: Part drawing of mounting plate

A.2 The Shoulder Assembly

Table A.2: BOM for shoulder assembly

Item #	Part #	Description	Qty.
2.1	-	Flx/Ext lock, inner rod (Figure A.4, Page 67)	1
2.2	-	U-bolt	1
2.3	-	Shoulder axle (Figure A.5, Page 68)	1
2.4	6383K23	Roller bearing, ID = 3/8", OD = 1"	2
2.5	-	Shoulder Tube (Figure A.6, Page 69)	1
2.6	65035K81	Knob	1
2.7	-	3/8" rod, 2" length	1
2.8	6665K26	Flange mounted bearing, ID = 1 1/2"	1
2.9	-	Flx/Ext lock, outer tube (Figure A.7, Page 70)	1
2.10	92695A132	6-32 set screws, cone tip, 1/4" length	12

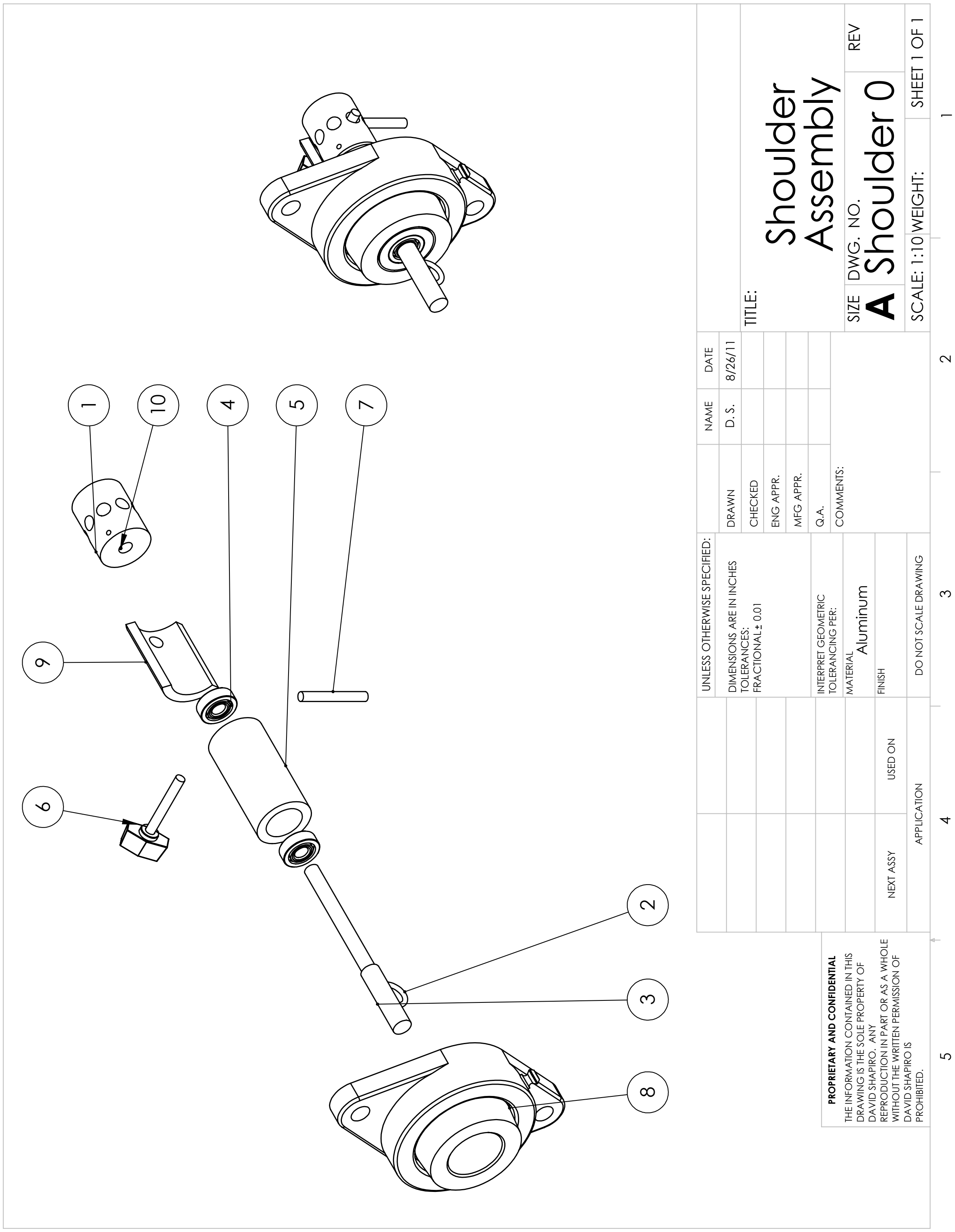

Figure A.3: Exploded view of shoulder assembly

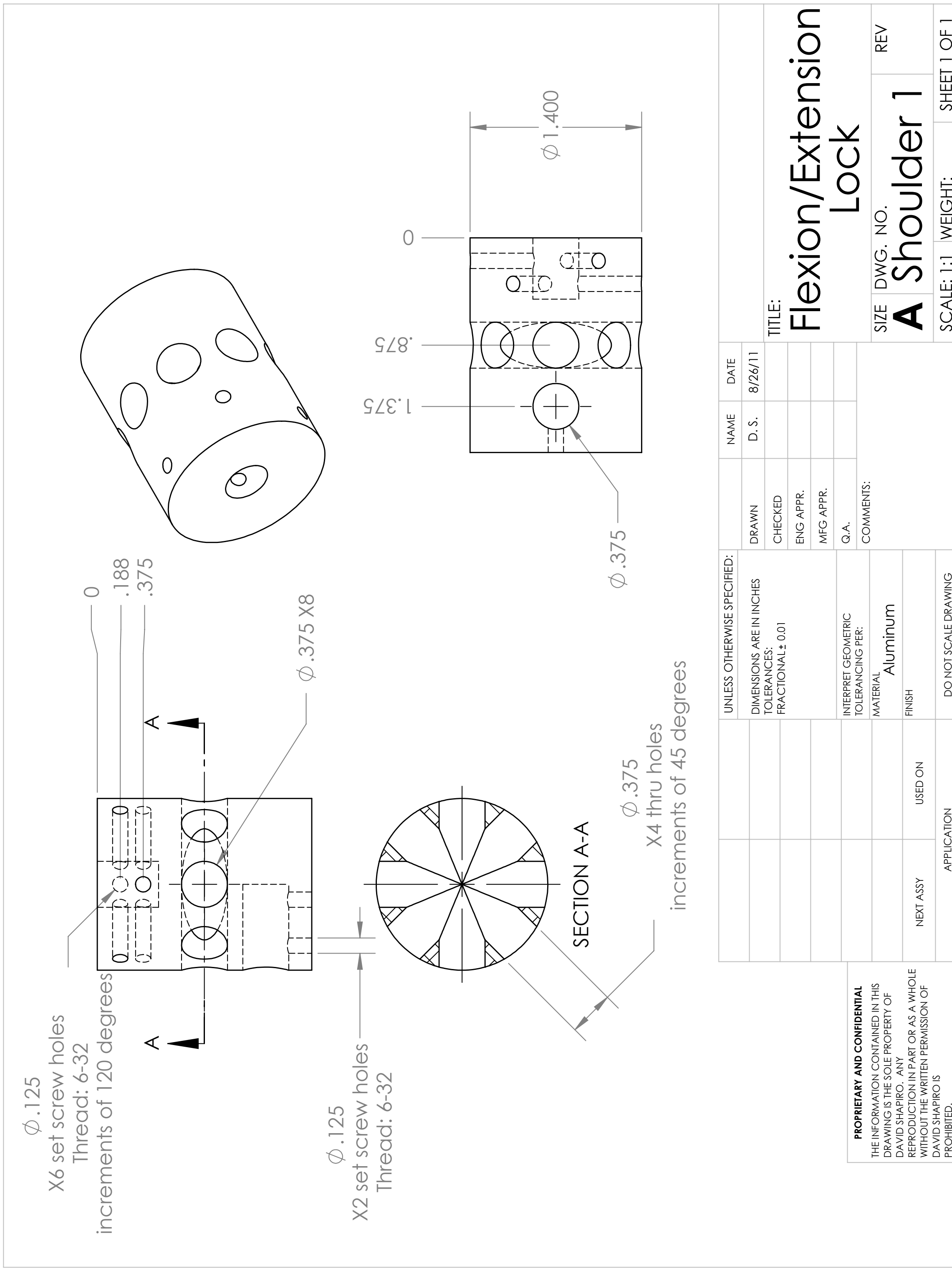

Figure A.4: Part drawing of flexion/extension lock rod

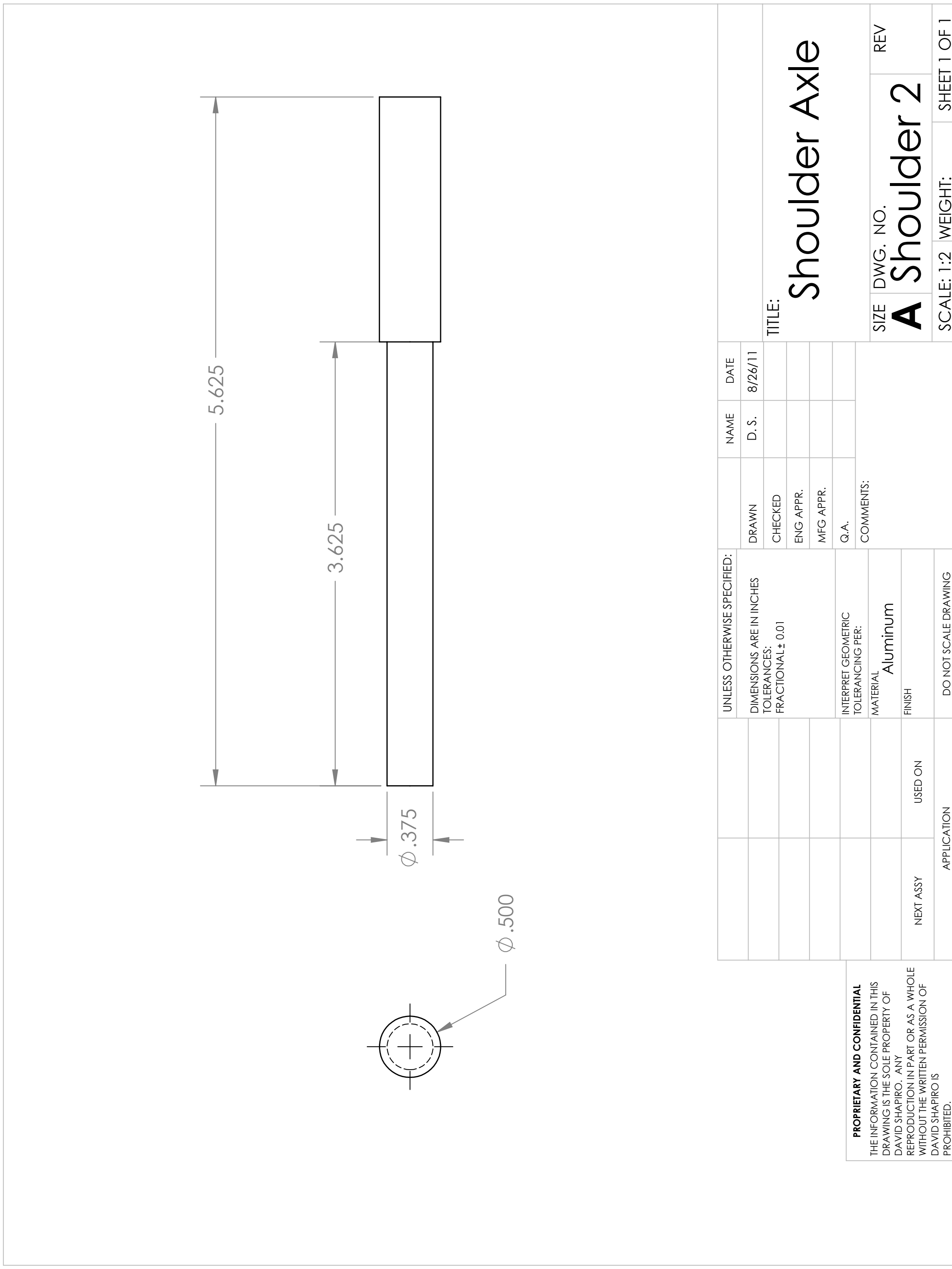

Figure A.5: Part drawing of shoulder axle

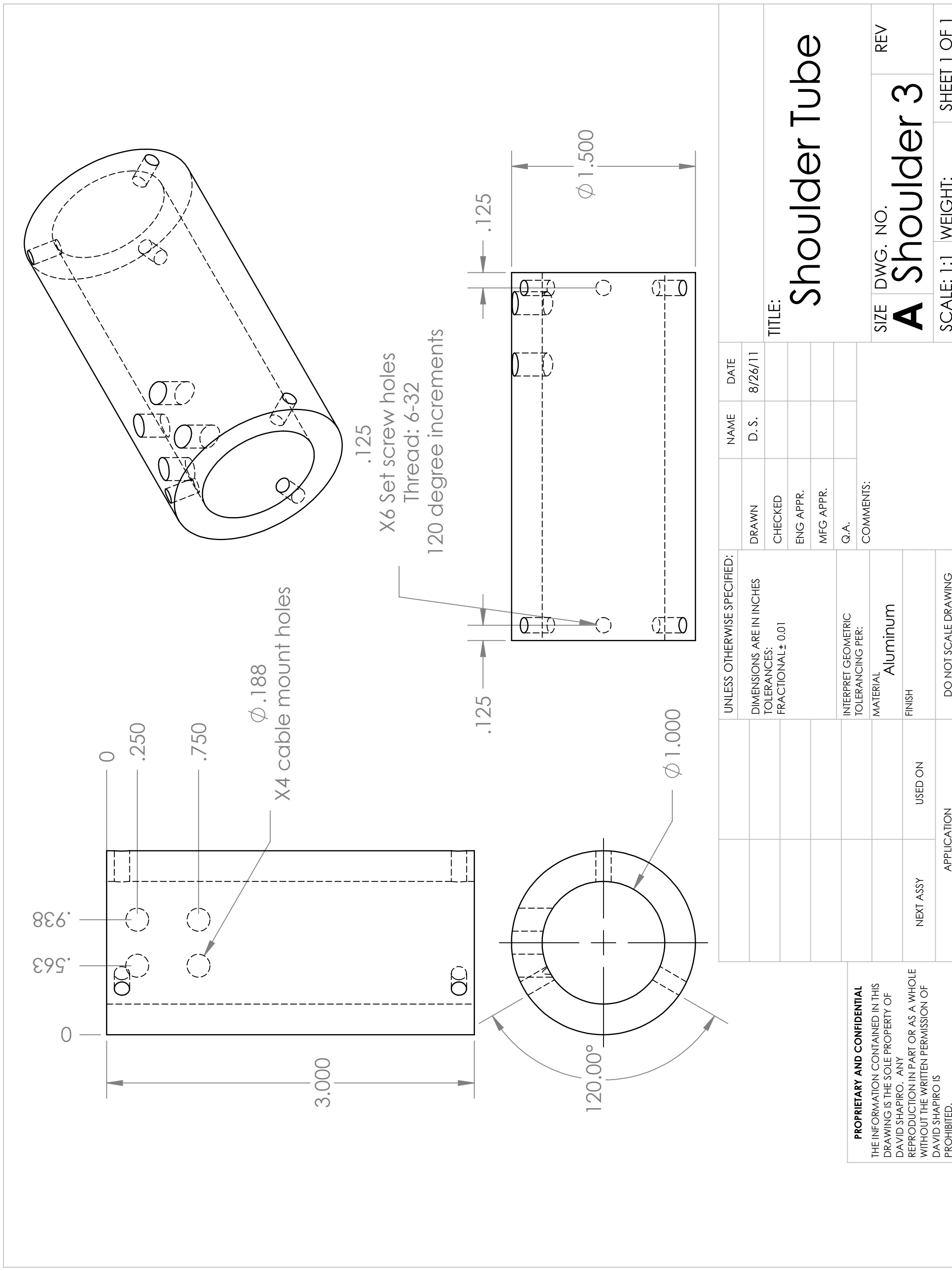

Figure A.6: Part drawing of shoulder tube

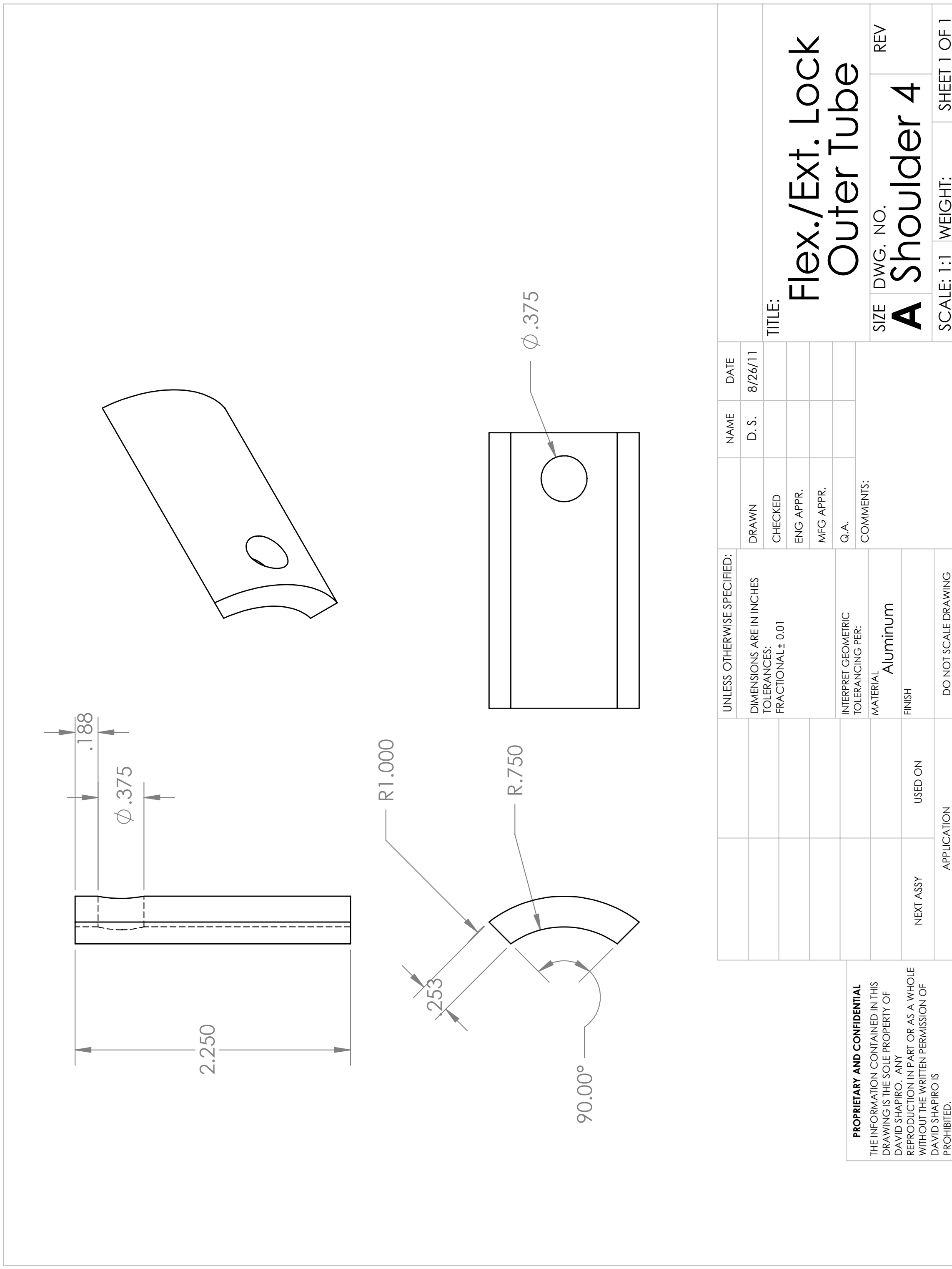

Figure A.7: Part drawing of flexion/extension lock tube

A.3 The Upper Arm Assembly

Table A.3: BOM for upper arm assembly

Item #	Part #	Description	Qty.
3.1	6444K16	Extreme angle universal joint	1
3.2	92695A130	6-32 set screws, cone tip, 1/8” length	6
3.3	92695A132	6-32 set screws, cone tip, 1/4” length	7
3.4	-	Bearing lock (Figure A.9, Page 73)	1
3.5	9271K113	Torsion spring	1
3.6	-	Torsion spring lock (Figure A.10, Page 74)	1
3.7	-	Upper arm bone (Figure A.11, Page 75)	1
3.8	6383K23	Roller bearing, ID = 3/8”, OD = 1”	1
3.9	-	Upper arm tube (Figure A.12, Page 76)	1
3.10	-	U-bolt	1

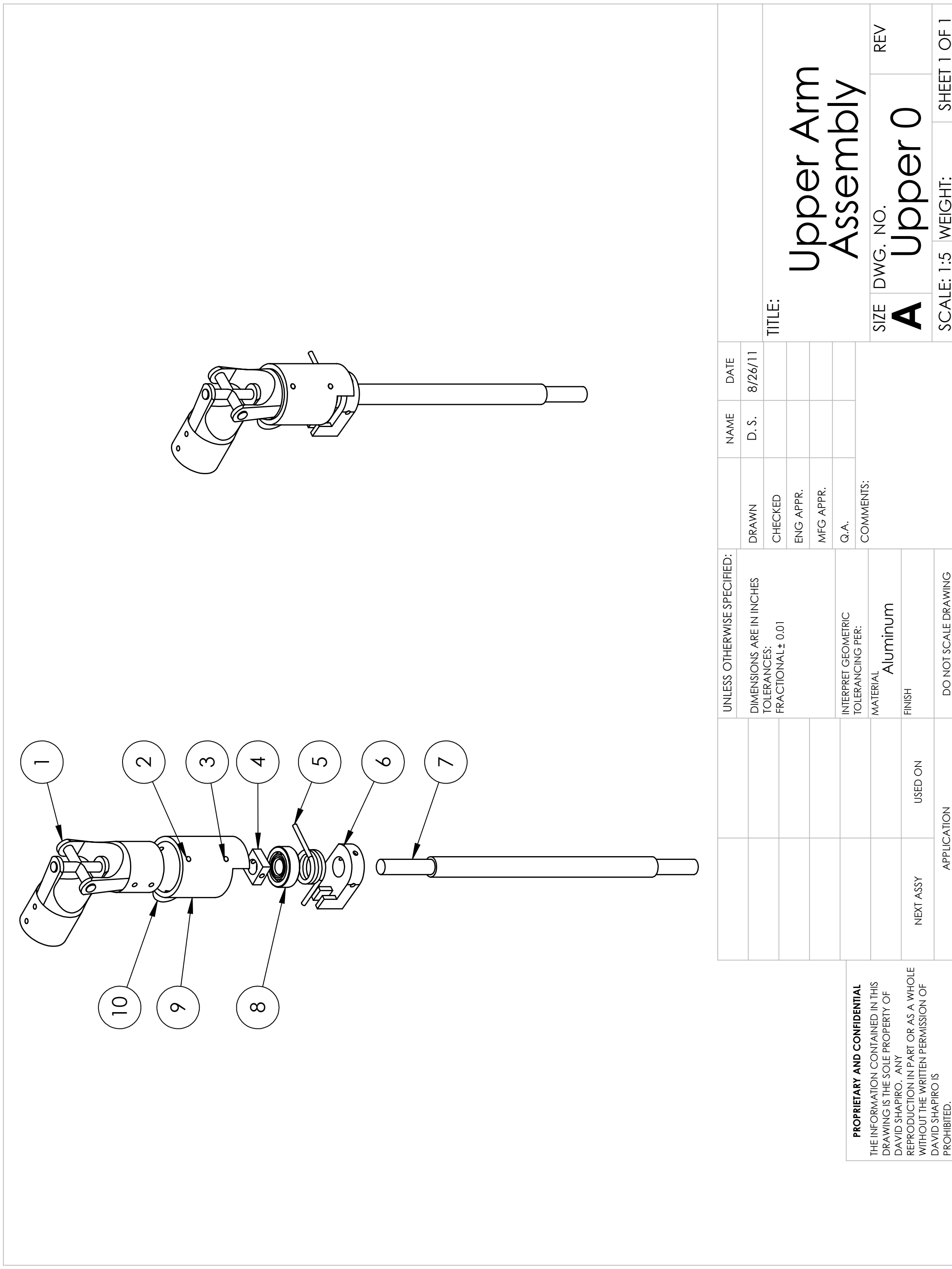

Figure A.8: Exploded view of upper arm assembly

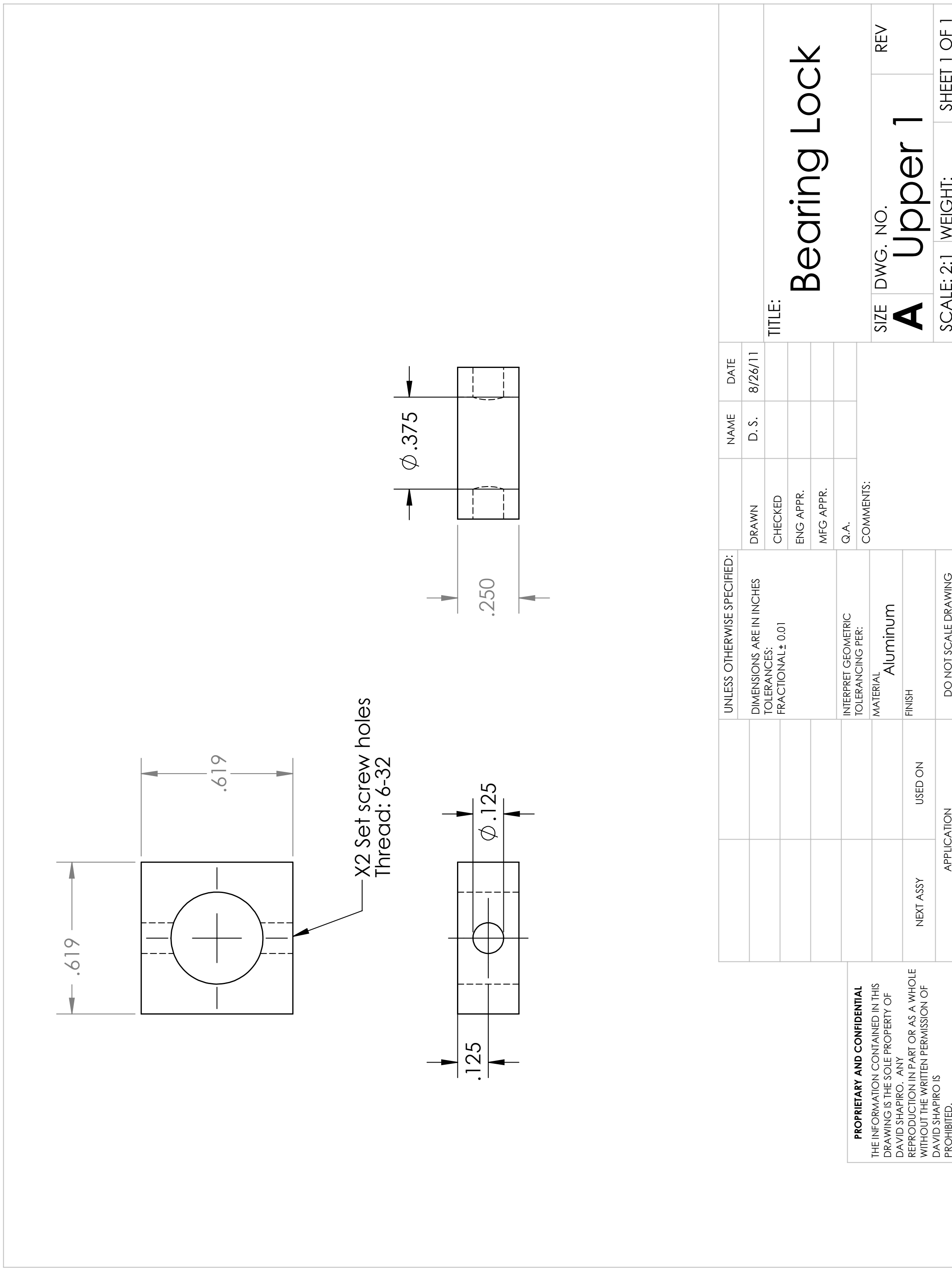

Figure A.9: Part drawing of bearing lock

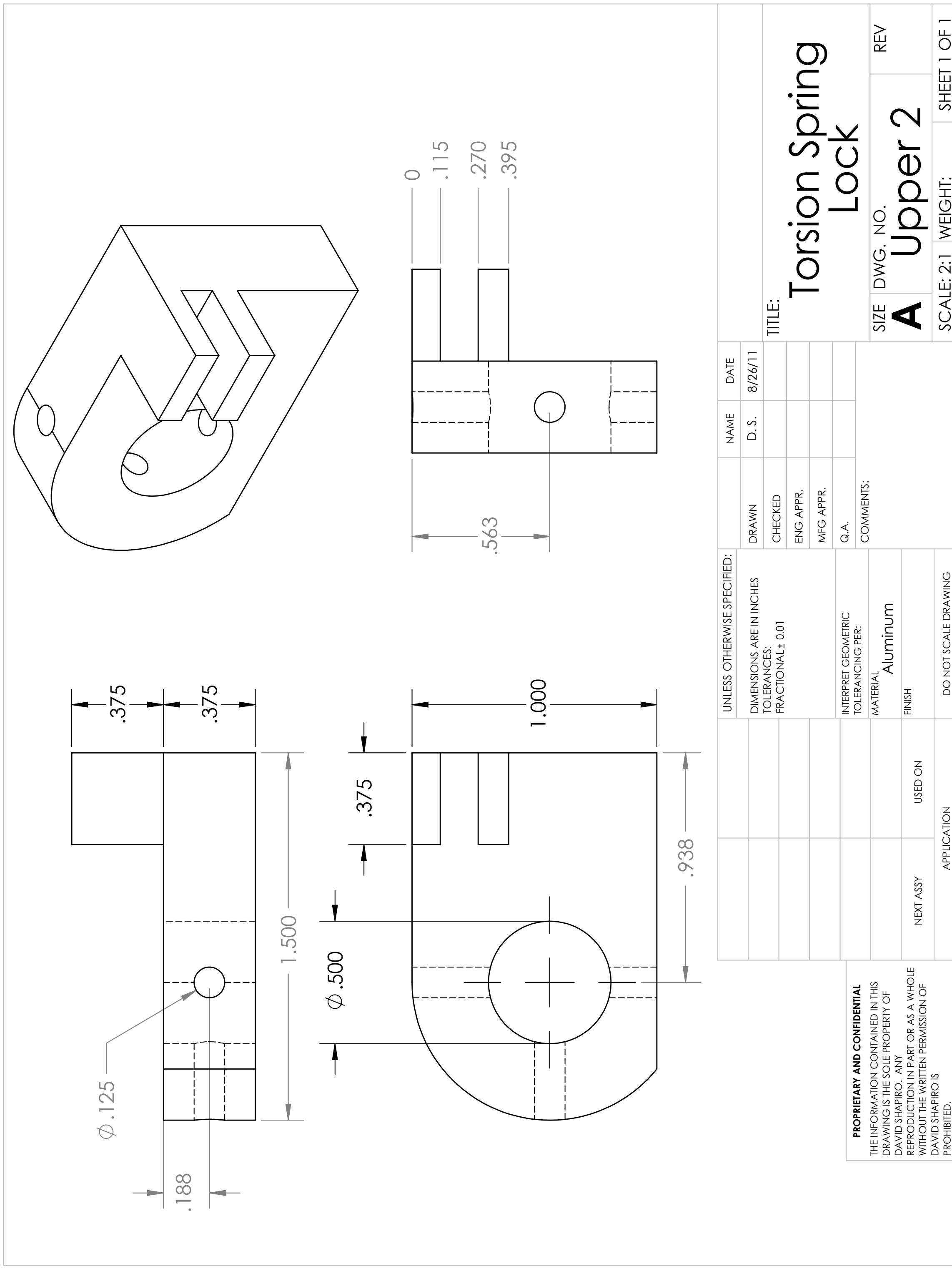

Figure A.10: Part drawing of torsion spring lock

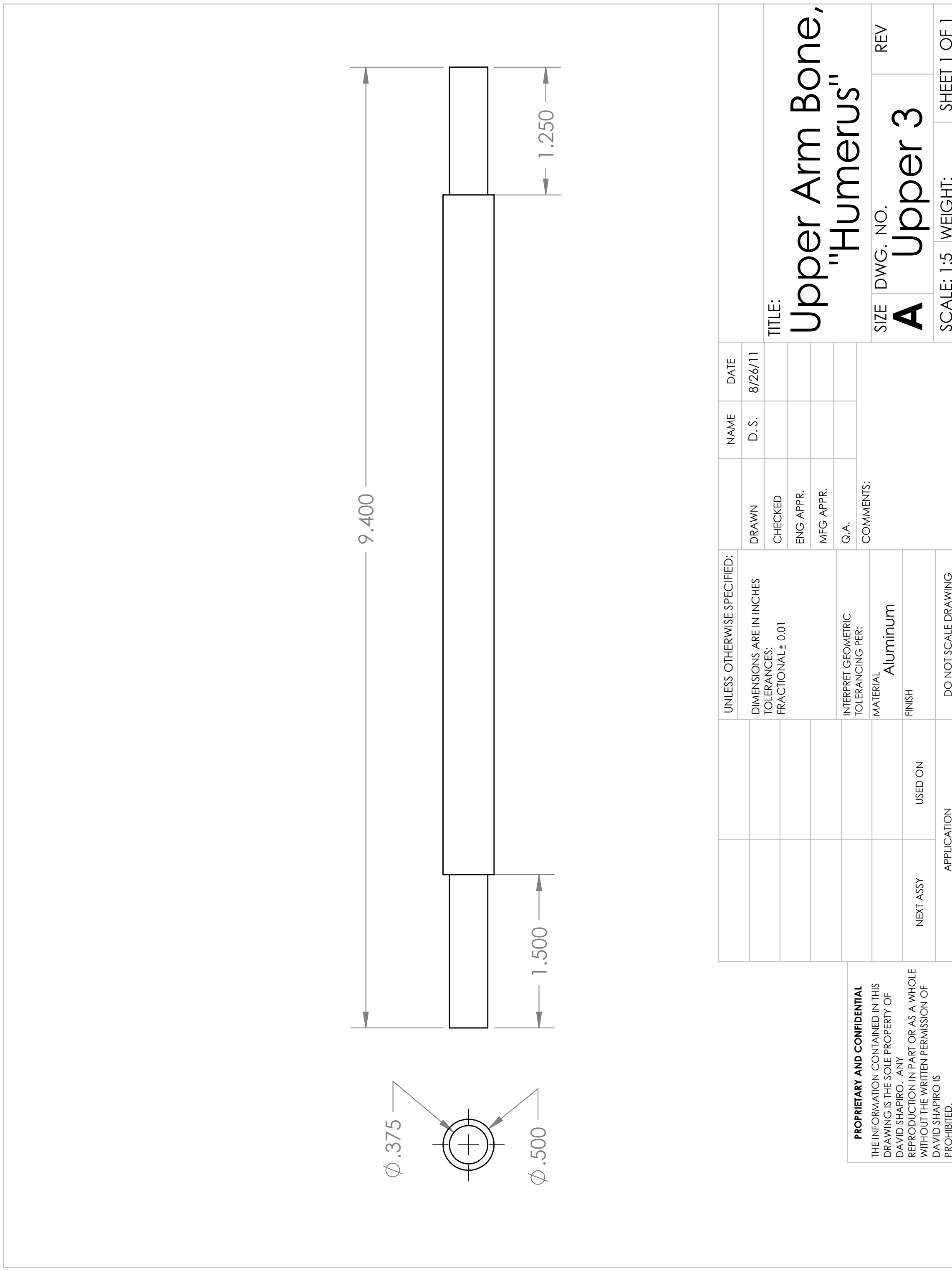

Figure A.11: Part drawing of upper arm bone

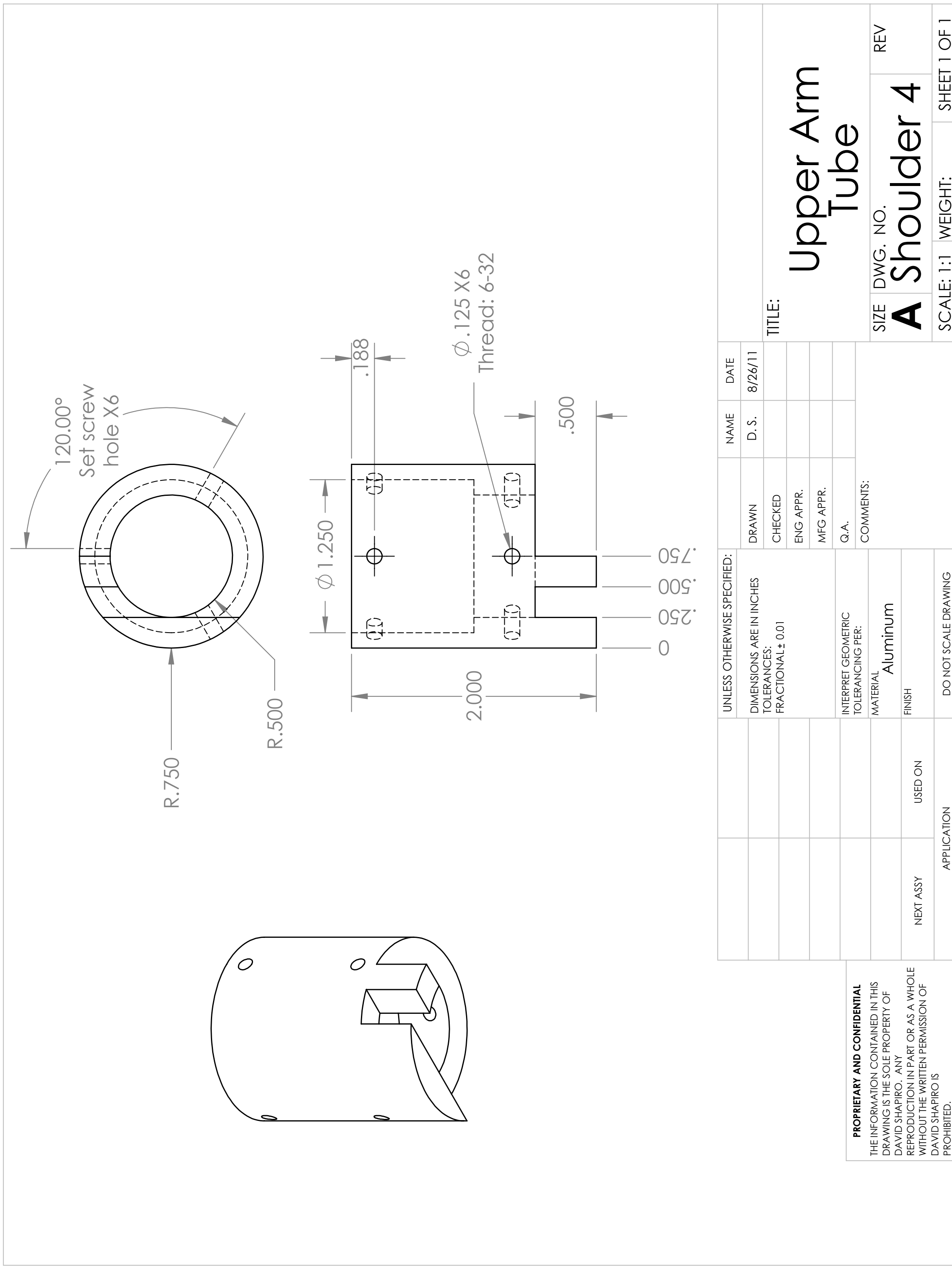

Figure A.12: Part drawing of upper arm tube

A.4 The Elbow Assembly

Table A.4: BOM for elbow assembly

Item #	Part #	Description	Qty.
4.1	2447K17	Easy-Adapt clevis rod end	2
4.2	-	Elbow Linkage (Figure A.14, Page 73)	1

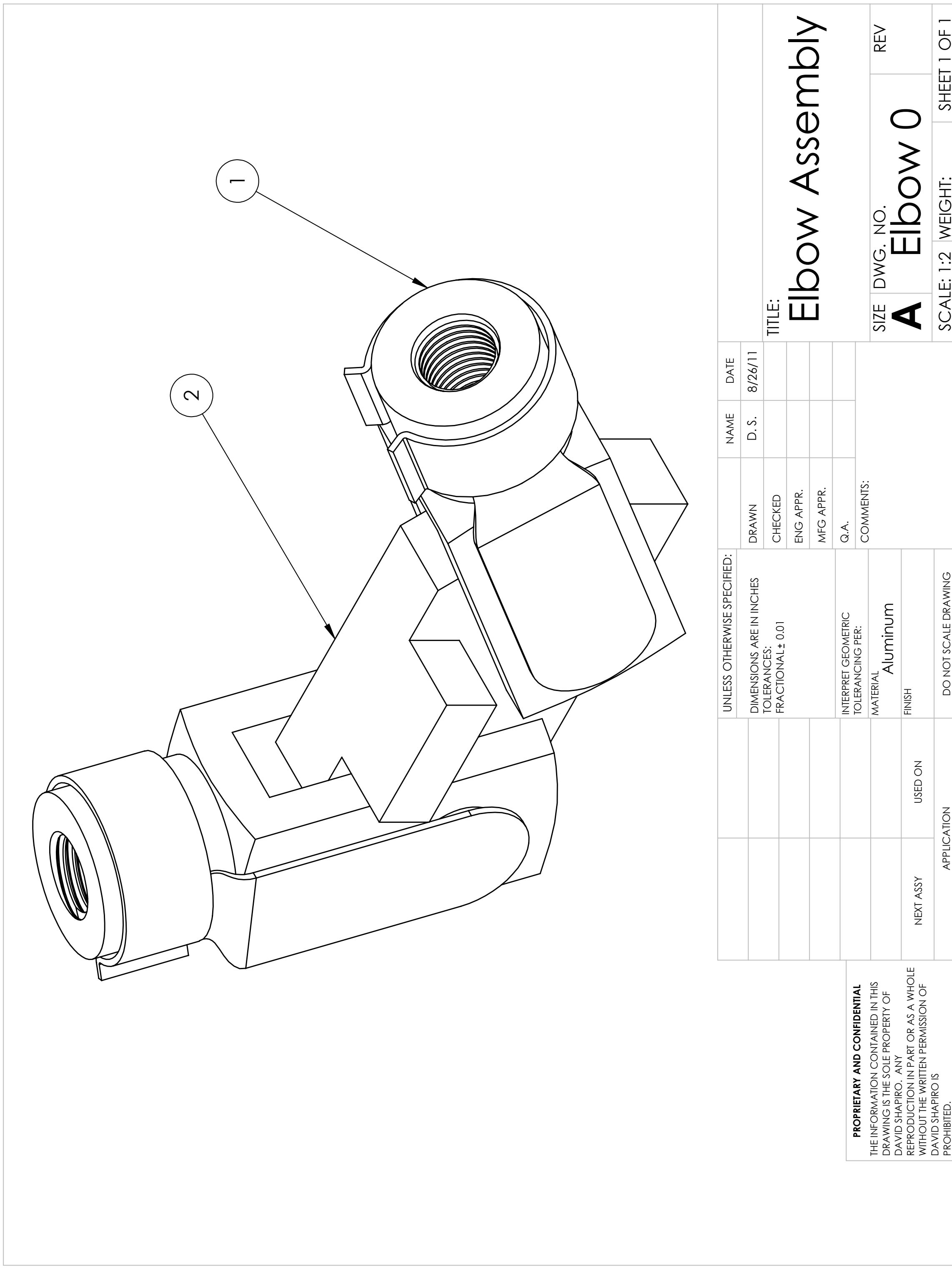

Figure A.13: Elbow assembly

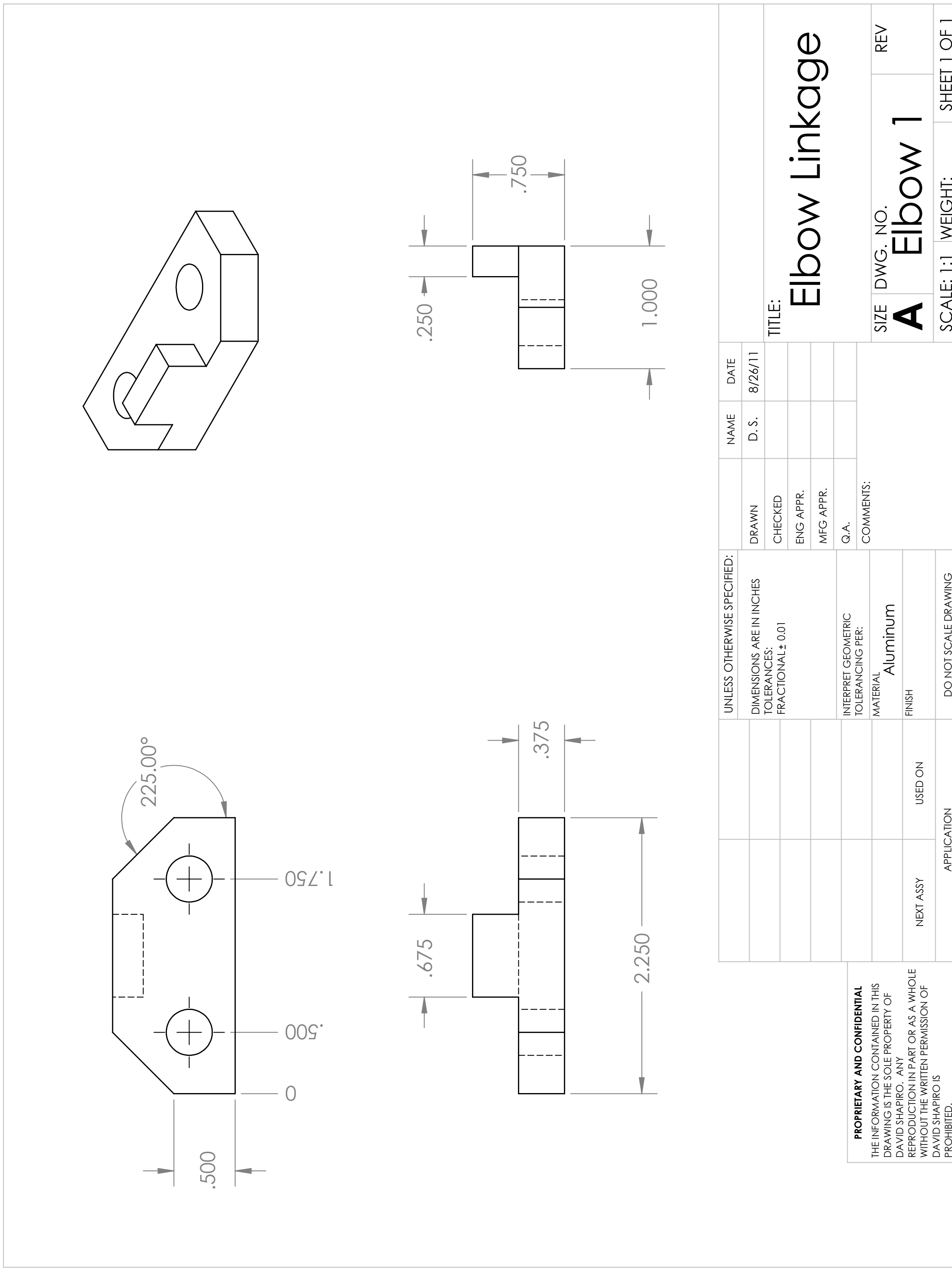

Figure A.14: Part drawing of elbow linkage

A.5 The Forearm Assembly

Table A.5: BOM for forearm assembly

Item #	**Part #**	**Description**	**Qty.**
5.1	-	Clevis connector (Figure A.16, Page 82)	1
5.2	-	Forearm tube (Figure A.17, Page 83)	1
5.3	6383K23	Roller bearing, ID = 3/8", OD = 1"	1
5.4	-	Forearm bone, (Figure A.18, Page 84)	1
5.5	2447K17	Easy-Adapt clevis rod end	1
5.6	-	Hand (Figure A.19, Page 85)	1
5.7	-	Torsion spring lock (Figure A.10, Page 74)	1
5.8	9271K113	Torsion spring	1
5.9	-	Bearing lock (Figure A.9, Page 73)	1
5.10	92695A132	6-32 set screws, cone tip, 1/4" length	2
5.11	92695A130	6-32 set screws, cone tip, 1/8" length	7

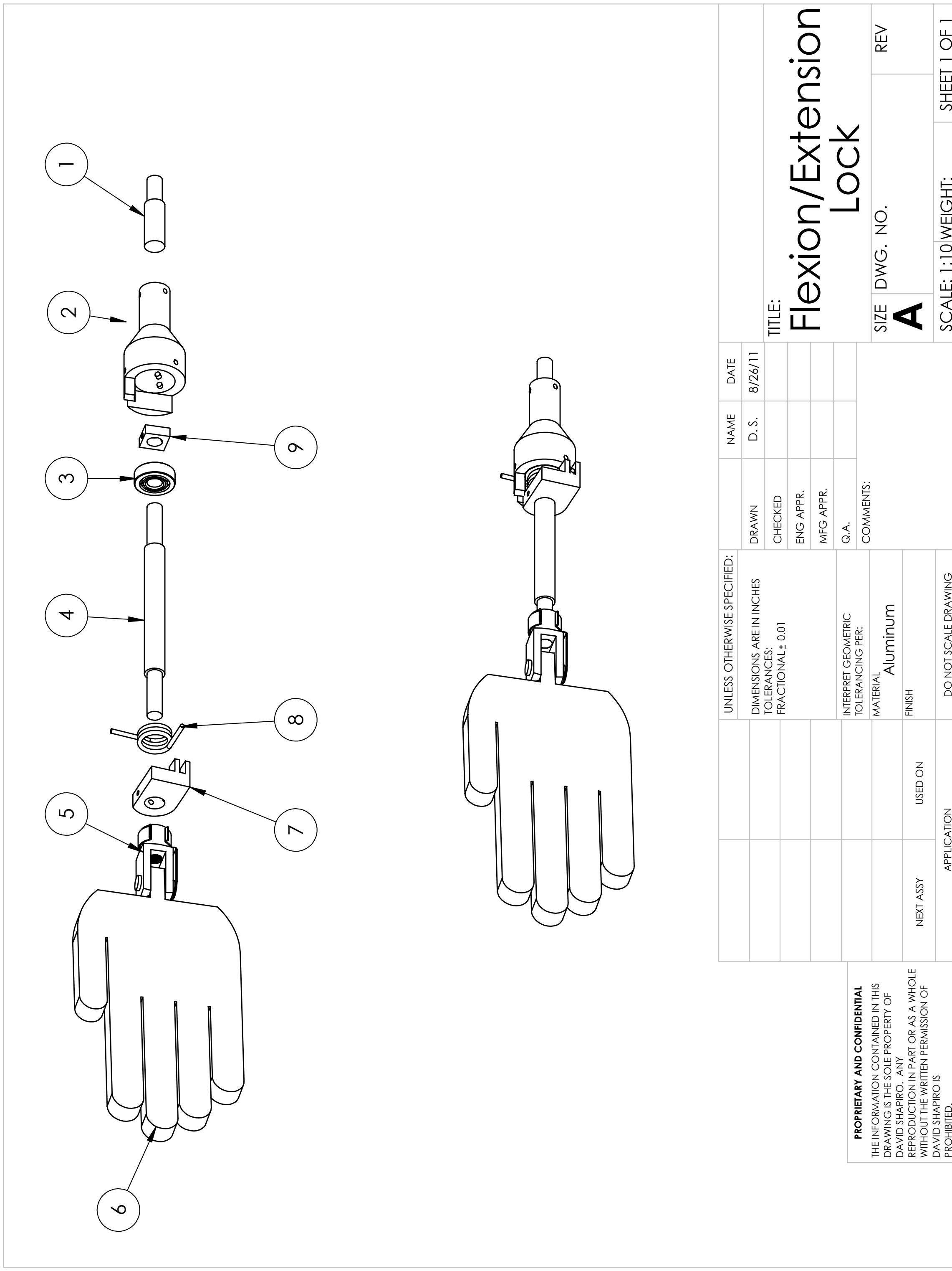

Figure A.15: Exploded view of forearm assembly

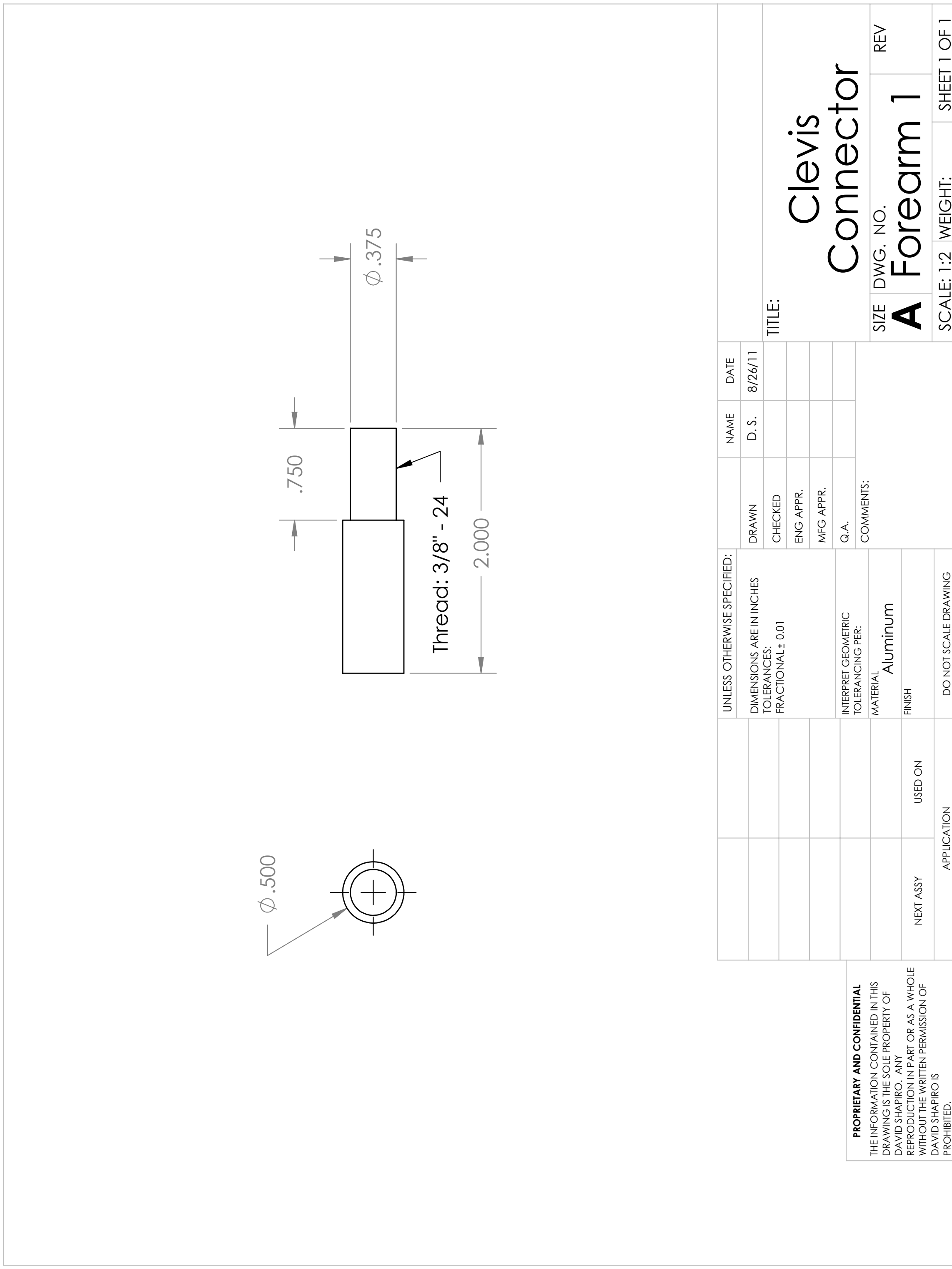

Figure A.16: Part drawing of clevis connector

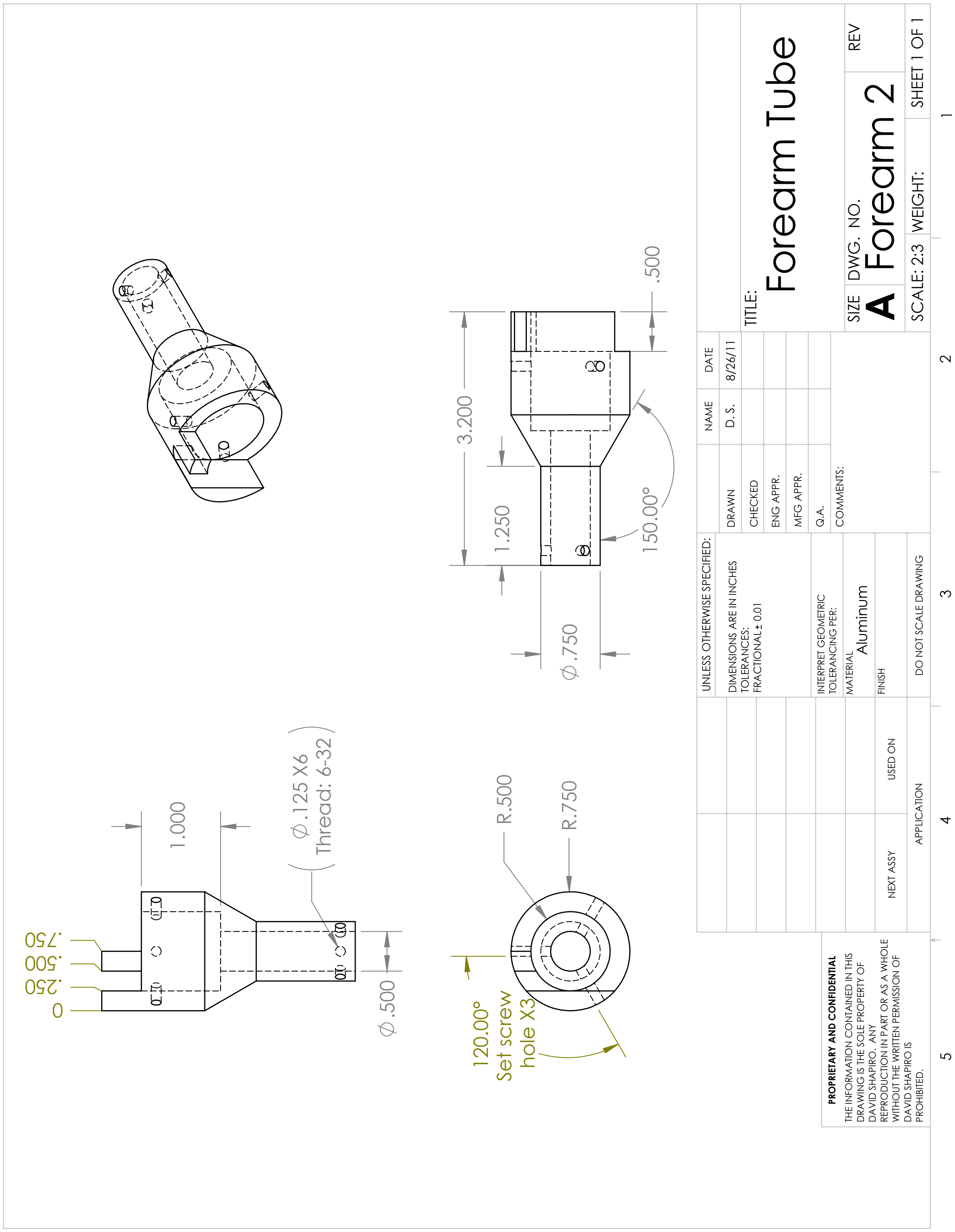

Figure A.17: Part drawing of forearm tube

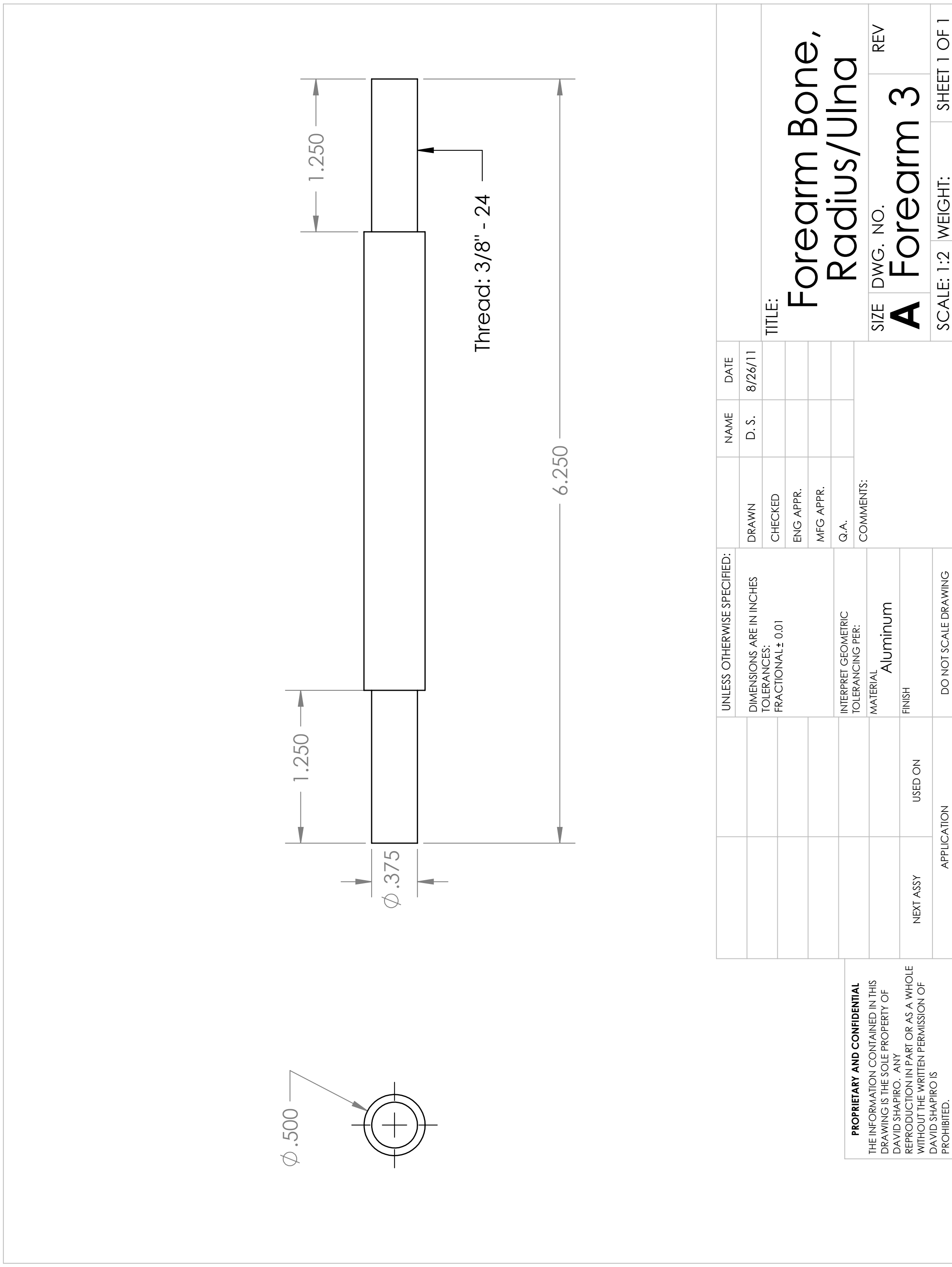

Figure A.18: Part drawing of forearm bone

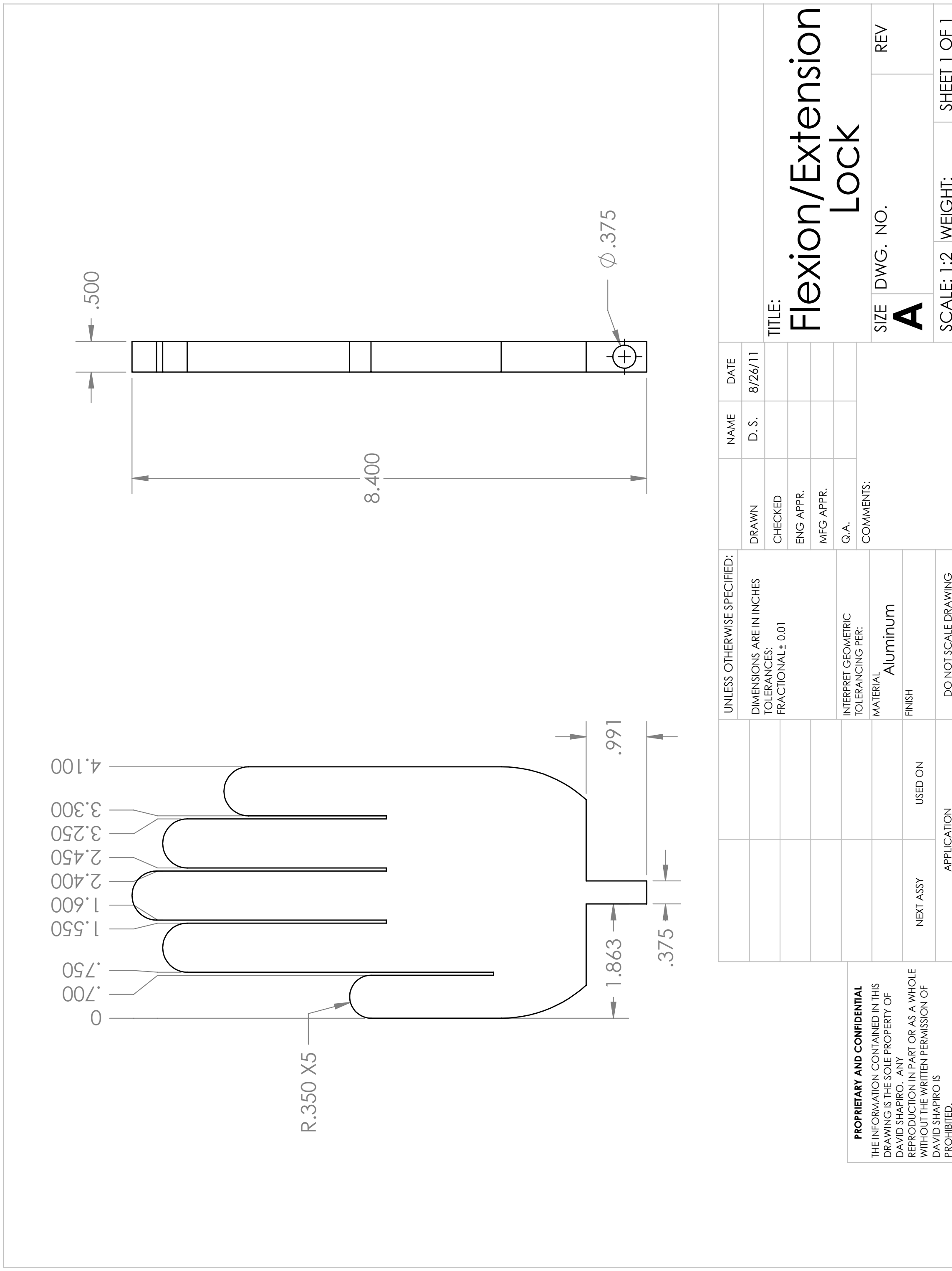

Figure A.19: Part drawing of hand

Appendix B
CALCULATIONS

B.1 Upper Arm Spring Calculation

This calculation was performed to obtain a lower limit on the required spring strength in the *upper arm* to prevent the weight of the forearm from causing undesired rotation.

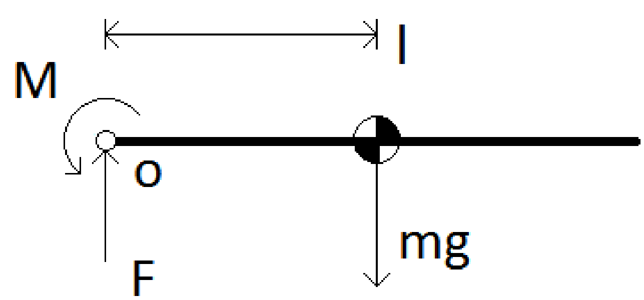

Figure B.1: Simplified free-body diagram for upper arm

Where:

- M = moment provided by spring
- mg = weight of gravity acting at the centroid of the arm
- l = lever arm of the force of gravity
- F = force of the bearing at point o

In this case:

- M = unknown variable
- $mg = 1$ lb
- $l = 5$ inches

$$\sum_{i=1}^{n} M_i = 0 \tag{B.1}$$

$$\sum_{i=1}^{n} F_i * d_i = 0 \tag{B.2}$$

$$F_1 * d_1 + F_2 * d_2 + \cdots + F_n * d_n = 0 \tag{B.3}$$

$$M - mg * l = 0 \tag{B.4}$$

$$M = mgl \tag{B.5}$$

$$M = 1 * 5 \tag{B.6}$$

$$M = 5 \tag{B.7}$$

The calculated spring strenght is 5 in-lbs.

B.2 Shoulder Flexion and Extension Weight Calculation

This calculation was performed to obtain a lower limit on the required weight to counterbalance the arm at 90 degrees of extension.

Where:

- T = tension in the cable
- t = lever arm of the cable
- mg = weight of gravity acting at the centroid of the arm

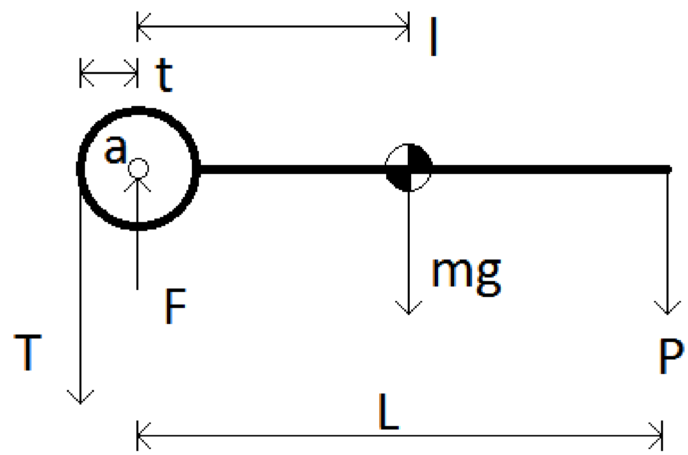

Figure B.2: Simplified free-body diagram of arm

- l = lever arm of the force of gravity
- F = force of the bearing at point a
- L = length of entire arm
- P = force acting at end of arm

In this case:

- T = unknown variable
- $t = 1$ inch
- $mg = 2$ lbs
- $l = 14$ inches

To calculate the force required to hold the arm level, T, we assume that $P = 0$

$$\sum_{i=1}^{n} M_i = 0 \tag{B.8}$$

$$\sum_{i=1}^{n} F_i * d_i = 0 \tag{B.9}$$

$$F_1 * d_1 + F_2 * d_2 + \cdots + F_n * d_n = 0 \tag{B.10}$$

$$T * t - mg * l = 0 \tag{B.11}$$

$$T * t = mgl \tag{B.12}$$

$$T = mgl/t \tag{B.13}$$

$$T = 2 * 14/1 \tag{B.14}$$

The calculated required suspended weight is 28 lbs.

B.3 Shoulder Flexion and Extension Force Calculation

This calculation was performed to obtain a lower limit on the required weight to move the arm at 135 degrees of flexion, when it was orginally posed at 90 degrees.

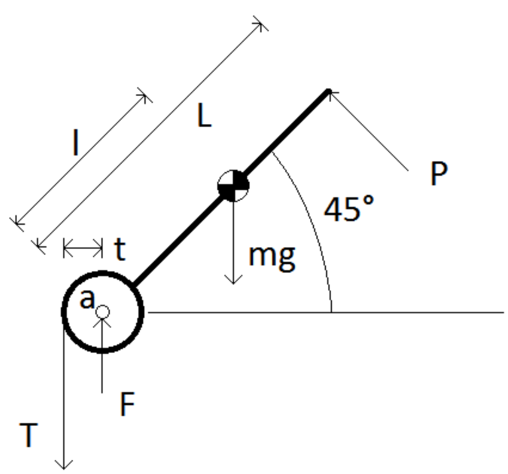

Figure B.3: Simplified free-body diagram of arm in 45 degree position

Where:

- T = tension in the cable
- t = lever arm of the cable
- mg = weight of gravity acting at the centroid of the arm
- l = lever arm of the force of gravity
- F = force of the bearing at point a
- L = length of entire arm
- P = force acting at end of arm

In this case:

- P = unknown variable
- $T = 35$ lbs
- $t = 1$ inch
- $mg = 2$ lbs
- $l = 14$ inches
- $L = 20$ inches

To calculate the torque required to move the arm from a level position to a 45 degree angle

$$\sum_{i=1}^{n} M_i = 0 \tag{B.15}$$

$$\sum_{i=1}^{n} F_i * d_i = 0 \tag{B.16}$$

$$F_1 * d_1 + F_2 * d_2 + \cdots + F_n * d_n = 0 \tag{B.17}$$

$$T * t - mg\cos(45) * l - P * L = 0 \tag{B.18}$$

$$PL = Tt - mgl\cos(45) \tag{B.19}$$

$$PL = 35 * 1 - 2 * 14 * \cos(45) \tag{B.20}$$

$$PL = 15.2 \tag{B.21}$$

The required torque to maintain an upward 45 degree angle is 15.2 in-lbs.

Appendix C

DESIGN REQUIREMENTS

1. Overall Specifications

    - Capable of being shipped while disassembled

      e.g. UPS max weight of 150 lbs, up to 165" length and girth combined

    - Capable of being transported by car when assembled
    - Assembly to require no more than two people using hand or power tools
    - Minimize assembly of full unit, no more than 5 actions
    - Base to have wheels for ease of movement
    - Base to have capability of being bolted to floor
    - Base to be weighted for stability
    - Overall dummy to match 50th percentile male (Figure C.1, Page 93)
    - Joints and surfaces must be durable to withstand approximately 1 million cycles
    - Must be able to withstand strikes of up to 1500 lbs
    - Joints and surfaces need to padded/protected to prevent injury
    - Only head and hand need to exactly mimic human appearance

2. Hand

    - Open hand position

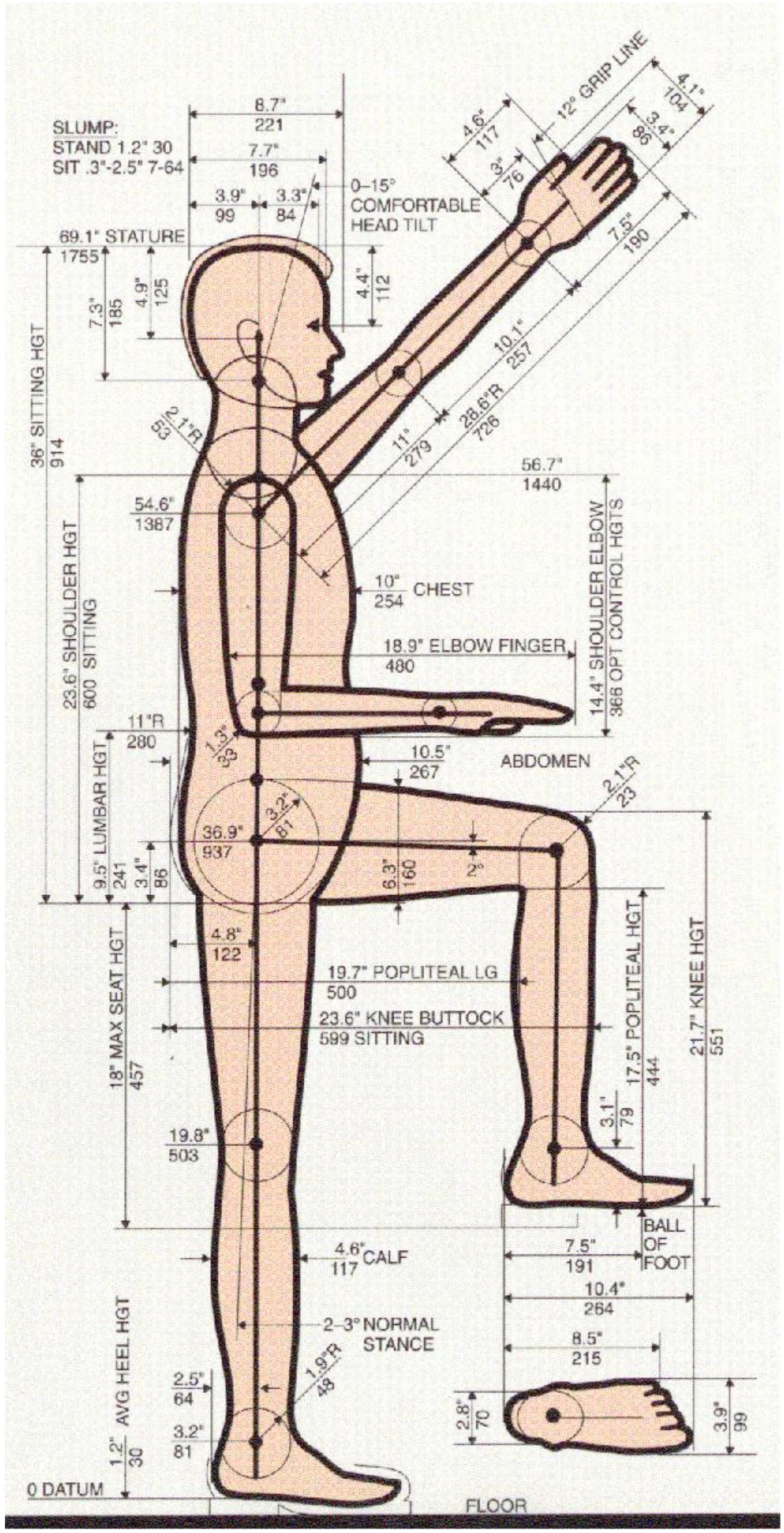

Figure C.1: The 50th percentile male

- Joints of hand do not need to move

  However, a big plus if fingers are flexible enough to grab and manipulate
- Anatomically correct in size
- Sold palm

3. Wrist
   - Neutral position: wrist stay flat, forearm to hand
   - Limited movement: 80 degrees extension, 50 flexion
   - Spring action to bring wrist back to neutral position
4. Forearm
   - Neutral postion: vertial, thumb up
   - Forearm rotation should take place in middle of forearm
   - Limited movement: 90 degrees supination, 90 degree pronation
   - Spring action to bring forearm back to neutral position
5. Elbow
   - Neutral position: relaxed arm, approximately straight
   - Limited motion: 15 degree extension, 90 degrees flexion
   - Spring action to bring elbow back to neutral position
6. Upper Arm
   - Neutral position: 20 degrees inward
   - Limited motion: 60 degrees medial and lateral rotation

- Spring action to bring elbow back to neutral position

7. Arm Unit

   - Each arm can be place in one of three positions

     Low: with arm straight, hand should be at solar plexus level

     Middle: with arm straight, hand should be at chin level

     High: with arm straight, hand should be at forehead level

   - User must be able to easily change from one position to another
   - Low position

     Elbow approximately 1 fist(4 in) from ribs

     Wrist and elbow in vertical position

     Inside of wrist in alignment with outside ofshoulder

8. Shoulder

   - Neutral position: low, middle, or high
   - Limited movement: flexion up to vertical, extension to 45 degrees behind
   - Spring action to bring shoulder back to chosen neutral position

9. Head and neck

   - Anthropomorphic head
   - Spring in neck to allow movement

10. Torso and waist

    - Spring in waist to allow movement
    - Limited movement: 15 degees back, 90 degrees forward
    - Pelvic bone represented for groin strikes