A.R.E.S
Assisted Robotic Exo-Skeleton

A thesis submitted to the
Faculty of the Mechanical Engineering Technology Program
of the University of Cincinnati
in partial fulfillment of the
requirements for the degree of

Bachelor of Science

in Mechanical Engineering Technology
at the College of Engineering & Applied Science

by

FRANK N. RICCIARDI

Bachelor of Science University of Cincinnati
May 2012

Faculty Advisor: Dr. Janet Dong
A.R.E.S. (Assisted Robotic Exo-Skeleton)  Frank Ricciardi (Upper Arm and Elbow)

ABSTRACT

This project is to develop a portion of an external skeletal structure in which to later mount armor to. This proof of concept design will focus on protecting the right arm of an operator in hostile environments by designing the support structure, not give the operator super strength. This military grade exoskeleton we call A.R.E.S. (Assisted Robotic Exo-Skeleton).

A powered exoskeleton is a skeleton like framework worn by a person and assisted by a power source that supplies the energy for limb movement. Exoskeletons can be regarded as wearable robots. This mechatronic system is designed around the shape and function of the human body, with joints corresponding to those of the person it is internally coupled with. Powered exoskeletons are primarily built to assist and protect the wearer. They could also be designed for police officers, work in rescue operations after disasters or working in toxic environments. The uses are limitless and an exoskeleton could provide benefits in nearly any field.

My team will focus on designing and fabricating a complete right arm that will have a near full range of basic motion. The arm will be fully movable and have two degrees of freedom, the elbow joint and shoulder joint, powered with an on-board power system. In addition, the operator will be contained inside of the structure. This report will focus on the shoulder and elbow configurations specifically.
ACKNOWLEDGMENTS

The A.R.E.S. build team would like to thank many individuals for the help they gave and the time they spared to help on this project. We couldn’t have done it without you. I want to personally thank my father, Anthony Ricciardi and The Work Force Development Agency for providing a very generous donation towards this project. The money provided a reassurance so we could focus on the project and not worry about the fundraising process while designing this project.

My grateful thanks also goes to Valerie Hill (Xavier University Occupational Therapy) for taking time from your busy schedule to educate us on the inner workings of the human arm. Without it, we wouldn’t have had the understanding to take this project to its fullest potential.

I want to thank Donald Hutson (Neuroscience Institute) for inviting us into his office and home to show us your robots and help us with our design problems. Your key insights led us to a great working design that we are proud to show off.
# TABLE OF CONTENTS

**ABSTRACT** ................................................................................................................................. I
**ACKNOWLEDGMENTS** .................................................................................................................. II
**TABLE OF CONTENTS** .................................................................................................................. III
**LIST OF FIGURES** ........................................................................................................................ V
**LIST OF TABLES** .......................................................................................................................... VIII
**BACKGROUND** ............................................................................................................................ 1
**CURRENT REHABILITATIVE AND MEDICAL GRADE EXO-SKELETONS** .................... 2
**CURRENT MILITARY GRADE EXO-SKELETONS** ................................................................. 7
**CUSTOMER FEED BACK, OBJECTIVES, AND CHARACTERISTICS** ..................... 11
  - **CUSTOMER FEEDBACK** .......................................................................................................... 11
  - **PRODUCT OBJECTIVES** ......................................................................................................... 12
  - **ENGINEERING CHARACTERISTICS** .................................................................................... 13
**DESIGN** ......................................................................................................................................... 14
  - **DESIGN RESEARCH** .............................................................................................................. 14
  - **DESIGN ALTERNATIVES AND SELECTION** ................................................................. 20
  - **SHOULDER DESIGN CONCEPTS** ......................................................................................... 21
  - **ROTATING RINGS DESIGN CONCEPTS** ............................................................................... 27
  - **RANGE OF MOTION** .............................................................................................................. 31
  - **LOADING CONDITIONS AND DESIGN ANALYSIS** .......................................................... 32
  - **FACTORS OF SAFETY** .......................................................................................................... 49
  - **MOTOR SELECTION** ............................................................................................................. 50
  - **MATERIALS** .......................................................................................................................... 52
  - **LUBRICATION** ....................................................................................................................... 52
  - **SURFACE TREATMENT** .......................................................................................................... 52
**MANUFACTURING** ....................................................................................................................... 54
**ASSEMBLY** .................................................................................................................................... 61
**WEARING THE PROTOTYPE** ......................................................................................................... 62
**TESTING** ......................................................................................................................................... 63
  - **RANGE OF MOTION** .............................................................................................................. 63
  - **LUBRICATION** ....................................................................................................................... 64
  - **DURABILITY** .......................................................................................................................... 64
  - **EASY TO REPAIR AND MAINTAIN** .................................................................................... 64
  - **EASY TO OPERATE** ............................................................................................................... 64
  - **LIGHTWEIGHT** ...................................................................................................................... 65
  - **ERGONOMIC FIT** ................................................................................................................... 65
  - **COMPACT DESIGN** ............................................................................................................... 65
  - **LOUDNESS** ........................................................................................................................... 65
  - **LOW COST** ............................................................................................................................. 65
**DESIGN CHANGES AND RECOMMENDATIONS** ................................................................. 66
  - **MOTORS, Mass production, Design changes** ....................................................................... 66
SCHEDULE AND BUDGET

SCHEDULE ................................................................. 67
BUDGET ................................................................. 68
FINAL PROJECT VIEW .................................................. 69
DRAWINGS ............................................................. 70

TECH EXPO ................................................................... 71

CONCLUSION .................................................................. 72

SPECIAL THANKS TO ..................................................... 73

REFERENCES ................................................................... 74

APPENDIX A - RESEARCH .................................................. 1
APPENDIX B - SURVEY ..................................................... 1
APPENDIX C – QUALITY FUNCTION DEVELOPMENT CHART ..... 1
APPENDIX D – PRODUCT OBJECTIVES ................................ 1
APPENDIX E - SCHEDULE .................................................. 1
APPENDIX F – BUDGET ..................................................... 1
APPENDIX G – MOTOR DATA SHEET ................................... 1
APPENDIX H - LUBRICATION .............................................. 1
APPENDIX I - BILL OF MATERIAL ........................................ 1
APPENDIX J – DRAWINGS .................................................. 1
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>MYOMO e100 NeuroRobotic System</td>
<td>2</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Mayo Clinic Elbow Brace P.N. 05E-R</td>
<td>3</td>
</tr>
<tr>
<td>Figure 3</td>
<td>eLEGS front and side view</td>
<td>4</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Luke Arm holding a light bulb</td>
<td>4</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Fully assembled H.A.L. suit</td>
<td>5</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Industrial manipulator picking up part.</td>
<td>6</td>
</tr>
<tr>
<td>Figure 7</td>
<td>HULC (Human Universal Load Carrier) carrying load on soldier</td>
<td>7</td>
</tr>
<tr>
<td>Figure 8</td>
<td>XOS-2 lifting an artillery round</td>
<td>8</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Troy Hurtubise in the Trojan Suit</td>
<td>9</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Shoulder elevation</td>
<td>14</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Shoulder depression</td>
<td>14</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Shoulder protraction</td>
<td>14</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Shoulder retraction</td>
<td>14</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Shoulder extension</td>
<td>15</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Shoulder flexion</td>
<td>15</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Shoulder internal rotation</td>
<td>15</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Shoulder external rotation</td>
<td>15</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Shoulder adduction</td>
<td>15</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Shoulder abduction</td>
<td>16</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Shoulder horizontal abduction</td>
<td>16</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Shoulder horizontal adduction</td>
<td>16</td>
</tr>
<tr>
<td>Figure 22</td>
<td>Elbow flexion and extension</td>
<td>16</td>
</tr>
<tr>
<td>Figure 23</td>
<td>Pitch, yaw, and roll degrees of freedom of a human arm</td>
<td>17</td>
</tr>
<tr>
<td>Figure 24</td>
<td>Axis of rotation and sliding</td>
<td>17</td>
</tr>
<tr>
<td>Figure 25</td>
<td>Axis of rotation on a coordinate system</td>
<td>17</td>
</tr>
<tr>
<td>Figure 26</td>
<td>Pitch, yaw and roll labeled on a coordinate system</td>
<td>17</td>
</tr>
<tr>
<td>Figure 27</td>
<td>Hip ball and socket joint with axes of rotation passing through the center</td>
<td>18</td>
</tr>
<tr>
<td>Figure 28</td>
<td>Complete arm degrees of freedom</td>
<td>20</td>
</tr>
<tr>
<td>Figure 29</td>
<td>Rotating Universal Joint</td>
<td>21</td>
</tr>
<tr>
<td>Figure 30</td>
<td>Armadillo Joint</td>
<td>22</td>
</tr>
<tr>
<td>Figure 31</td>
<td>Slotted Arc Joint</td>
<td>23</td>
</tr>
<tr>
<td>Figure 32</td>
<td>Rotating Track Joint</td>
<td>24</td>
</tr>
<tr>
<td>Figure 33</td>
<td>Rotating Track Shoulder</td>
<td>25</td>
</tr>
<tr>
<td>Figure 34</td>
<td>4D Track Shoulder</td>
<td>26</td>
</tr>
<tr>
<td>Figure 35</td>
<td>Locking ring exploded view</td>
<td>27</td>
</tr>
<tr>
<td>Figure 36</td>
<td>Locking ring assembly view</td>
<td>27</td>
</tr>
<tr>
<td>Figure 37</td>
<td>Clamping ring exploded view</td>
<td>28</td>
</tr>
<tr>
<td>Figure 38</td>
<td>Clamping ring assembly view</td>
<td>28</td>
</tr>
<tr>
<td>Figure 39</td>
<td>Load Case 1 load diagram</td>
<td>32</td>
</tr>
<tr>
<td>Figure 40</td>
<td>Maximum displacement for Load Case 1</td>
<td>33</td>
</tr>
<tr>
<td>Figure 41</td>
<td>Maximum stress for Load Case 1</td>
<td>33</td>
</tr>
<tr>
<td>Figure 42</td>
<td>Load Case 2 load diagram</td>
<td>34</td>
</tr>
<tr>
<td>Figure 43</td>
<td>Maximum displacement for Load Case 2</td>
<td>35</td>
</tr>
<tr>
<td>Figure 44</td>
<td>Maximum stress for Load Case 2</td>
<td>35</td>
</tr>
<tr>
<td>Figure 45</td>
<td>Load Case 3 load diagram</td>
<td>36</td>
</tr>
</tbody>
</table>
Figure 46 - Maximum displacement for Load Case 3 .................................................. 36
Figure 47 - Maximum stress for Load Case 3 .............................................................. 37
Figure 48 - Load Case 4 load diagram ................................................................. 38
Figure 49 - Maximum stress for Load Case 4 .......................................................... 38
Figure 50 - Maximum stress for Load Case 4 ......................................................... 39
Figure 51 - Load Case 5 load diagram ................................................................. 40
Figure 52 - Load Case 6.1-6.5 load diagram ...................................................... 41
Figure 53 - Double shear tear out ........................................................................ 41
Figure 54 - Cross sectional area of tear out ......................................................... 42
Figure 55 - Double shear tear out ........................................................................ 43
Figure 56 - Cross sectional area of tear out ......................................................... 43
Figure 57 - Double shear tear out ........................................................................ 44
Figure 58 - Cross sectional area of tear out ......................................................... 44
Figure 59 - Shear in shoulder bolt ...................................................................... 45
Figure 60 - Shear in shoulder bolt ...................................................................... 46
Figure 61 - Load Case 7 load diagram ................................................................. 47
Figure 62 - Max displacement for Load Case 7 ................................................... 48
Figure 63 - Max stress for Load Case 7 ............................................................... 48
Figure 64 - 1/3 Pulley system ............................................................................. 50
Figure 65 - Elbow actuating pulley system ......................................................... 51
Figure 66 - Shoulder actuating pulley system .................................................... 51
Figure 67 - Shoulder arc being machined in the HAAS ..................................... 54
Figure 68 - Blocks for the shoulder arcs being ground perfectly square .......... 54
Figure 69 - Raw 4140 Heat Treated Steel ............................................................ 55
Figure 70 - Round stock being turned down .................................................... 55
Figure 71 - Showing the step in the wrist rotating ring .................................. 55
Figure 72 - Tapping the holes in the elbow rotating ring ................................ 55
Figure 73 - Boring out the elbow rotating ring ................................................ 55
Figure 74 - Preparing to turn down the wrist rotating ring ............................ 55
Figure 75 - Clamping ring ................................................................................. 56
Figure 76 - Fitting a clasp to the clamping ring ............................................... 56
Figure 77 - Bending the locking wires in the jig ............................................. 56
Figure 78 - Machining the Shoulder Arc ............................................................ 57
Figure 79 - Fixturing the Shoulder Arc .............................................................. 57
Figure 80 - Shoulder "T" emboss ..................................................................... 57
Figure 81 - Shoulder "T" slot ............................................................................. 57
Figure 82 - Final shoulder arc slot .................................................................... 57
Figure 83 - Final shoulder arc hard stops ......................................................... 57
Figure 84 - Starting the outline cut .................................................................... 58
Figure 85 - Midway through the outline cut ....................................................... 58
Figure 86 - Final cut into the bottom plate ....................................................... 58
Figure 87 - Finished part ..................................................................................... 58
Figure 88 - Machining the Upper Arm Support ............................................. 59
Figure 89 - Machining the Upper Arm Support ............................................. 59
Figure 90 - Machining the Upper Arm Support ............................................. 59
Figure 91 - Final product .................................................................................... 59
Figure 92 - Measuring the shoulder side supports ................................................................. 60
Figure 93 - Measuring elbow flexion .................................................................................. 63
Figure 94 - Measuring elbow extension ............................................................................. 63
Figure 95 - Final Design ...................................................................................................... 69
Figure 96 - Complete assembly at Tech Expo .................................................................... 71
Figure 97 - A.R.E.S. Tech Expo poster ............................................................................. 71
Figure 98 - Operator wearing the prototype ....................................................................... 71
LIST OF TABLES
Table 1 - Team responsibilities................................................................................................. 1
Table 2 - Survey responses in order of importance................................................................. 11
Table 3 - Engineering characteristics and with units.............................................................. 13
Table 4 – Movement definition table.......................................................................................... 18
Table 5 - Weighted Rating Chart for the shoulder designs...................................................... 29
Table 6 - Weighted Rating Chart for the locking ring designs.................................................. 29
Table 7 - Recommended ranges of motion.................................................................................. 31
Table 8 - Actual range of motion.............................................................................................. 31
Table 9 - List of safety factors.................................................................................................. 49
Table 10 - Project schedule...................................................................................................... 67
Table 11 - Expected and final budget........................................................................................ 68
BACKGROUND

The idea of protecting the human body has existed for thousands of years. From layers of leather to high tech woven fabrics; each iteration of armor class provided different advantages and disadvantages. Some allowed the operator to move freely but offered little protection, whereas others offered maximum protection but little range of motion. The goal of this project was to merge high mobility with a high protection.

The term exo-skeleton is defined by Merriam-Webster as an artificial external supporting structure (1). Simply by designing to that definition, the arm has already separated itself from most of what is currently being researched. Currently, several exo-skeleton suits are being developed to fit within two different categories. One type is focusing on the rehabilitative and medical division and the other being the military division. The rehabilitative and medical division focuses on improving the quality of life for patients who have any number of physical or mental debilitations. They are used to rebuild muscle and strength, facilitate muscle re-education and maintain or increase range of motion. The military is focused on better protecting personal in hostile environments or increasing the payload an operator can carry without getting tired.

This project will be split up into two partitions. Although both team members will help each other and participate in each aspect of the build, the shoulder and upper arm design and construction will be grouped together. The lower arm and wrist design and construction will be grouped together. The elbow design and construction will be worked on by both group members. Group member’s names and responsibilities are expressed in Table 1 below.

Table 1 - Team responsibilities

<table>
<thead>
<tr>
<th>Name</th>
<th>Responsibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frank Ricciardi</td>
<td>Upper Arm and Elbow</td>
</tr>
<tr>
<td>Nick Plataniotis</td>
<td>Lower Arm and Elbow</td>
</tr>
</tbody>
</table>
CURRENT REHABILITATIVE AND MEDICAL GRADE EXO-SKELETONS

MYOMO

MYOMO is a rehabilitative devise designed for stroke patients. The device, seen below in Figure 1, has a sensor that can detect EMG (electromyography) waves sent from the user’s brain. The control software continuously monitors and senses, but does not stimulate, the affected muscles. The patient self-initiates and achieves natural movement patterns by their own muscular signals that indicate intention to move (2). With the device strapped to the patient’s arm it will in turn raise or lower the arm when the user has tried to send a signal from their brain for their arm to move.

Most importantly this system provides some insight on how an exoskeleton could be controlled. With EMG waves the system could provide fast reflexes needed in a hostile environment. The operator simply has to react as he or she normally would and the suit will follow each movement. This device also has a control dial that allows for the adjustment of the level of power assist based on the patient’s performance. Although the brace is not giving the user additional strength, it actually increases the reaction time. As soon at the user thinks about lifting their arm the brace immediately lifts the arm. Using an actual device obtained from an occupational therapist at Drake Hospital. The system was easy to use and moved with our arms without hesitation.

Figure 1 - MYOMO e100 NeuroRobotic System
Mayo Clinic Elbow Brace

Braces provide information on the overall design of a form fitting exo-skeleton. The Mayo Clinic Elbow Brace employs rigid axial rods to provide stability. The straps secure the brace to the arm and hold it securely in place. It is also fitted with aircells to hold the brace in place but also to add comfort to the user, avoid pressure points, and prevent injury to the user.

Located on the side in Figure 2 is a knob that, when turned, allows the brace to be locked in place or free floating. This would relate to a hard stop for an exo-skeleton. It is an important safety feature that limits the travel of a joint. Without it hyperextension may occur, causing injury to the operator. The knob can be converted so that the control knob is positioned either medially or laterally (3). This adds to the modularity of the device and it is now able to be used on either arm.

Figure 2 - Mayo Clinic Elbow Brace P.N. 05E-R
eLEGS

eLEGS, developed by Berkeley Bionics, is a full waist down system to help paralyzed users to be able to walk again. The system employs motors to power the legs instead of the user’s muscles. Although this appears to be a step towards an exo-skeleton, it is still designed for recovery and medical uses. This type of device won’t last very long in the harsh environment of a hostile area. The following figure shows just how fragile the system is. The system uses a bank of sensors to determine a user’s intentions and act accordingly (4). The batteries and control system is located on the back of the unit as seen in Figure 3. A control system like this may help the overall control of an exoskeleton.

Luke Arm

The Luke arm is a fully robotic prosthetic arm. It is controlled by EMG waves sent from the brain, foot pedal, or muscles to control each motor in the arm. Designed primarily to replace one’s lost limb, the Luke arm doesn’t fit around an existing arm making it exactly what it is, a prosthetic, not an exo-skeleton. The overall design will help with producing an exo-skeleton. This system was designed to be modular and fit nearly any amputee’s arm (5). Figure 4 shows all of the components combined for a person who needs a complete arm prosthesis. The modular design would help this project become easier to repair and assemble. In the figure below, it is set up for a person with an amputated arm from the shoulder down. As seen often in other robotic arms there are only two degrees of freedom represented in the shoulder. This has been a problem when designing a shoulder joint for an exo-skeleton.
H.A.L.

H.A.L., or Hybrid Assisted Limb, is a full body suit that can be worn by the operator. It uses a similar control system as the MYOMO in which the suit “listens” to weak signals that the brain sends to the limb for it to move. Cyberdyne, the creators of H.A.L., call this a voluntary control system that provides movement interpreting the wearer's intention from the biosignals in advance of the actual movement (6). They also use a robotic autonomous control system that provides human-like movement based on a robotic system which integrally works together with the autonomous control system. Making H.A.L. is the world's first cyborg-type robot controlled by this unique Hybrid System (6). Pictured in Figure 5 below, H.A.L. doesn’t fully surround the operator, but it does enhance the operator’s strength. This makes the operator stronger than without the suit. H.A.L. will be dispatched into various fields; including rehabilitation support, physical training, heavy labor or even disaster relief.

![Fully assembled H.A.L. suit.](image)

Figure 5 - Fully assembled H.A.L. suit.
Industrial Manipulator

An industrial manipulator is hardly a robot at all. They are utilized in factories, material handling or during the assembly of large components. As pictured below an operator uses an industrial manipulator to lift and move heavy parts. Figure 6 shows how the manipulators combine a pneumatic cylinder fed with compressed-air, with a transmission lever system that provides balance to the load weight applied (7). This takes the load of the part off of the operator, but still allows the part to be moved effortlessly. This is essentially at the most basic level how an exo-skeleton should be. They provide protection to the operator but do not limit the operator’s movements or weigh him or her down.

Figure 6 - Industrial manipulator picking up part.
CURRENT MILITARY GRADE EXO-SKELETONS

HULC

The HULC is a system designed for the military. As seen in Figure 7, this system allows the user to carry loads of up to 150 pounds with minimal physical effort, over any type of terrain for extended periods of time (8). The set of anthropomorphic legs are easy to strap on and take off the user. They are designed to carry the load applied to it without hindering the natural movements of the operator. The user can run, crouch and climb stairs with the HULC legs. From watching videos on the HULC legs, they seem to be an addition to the infantries gear in order for them to get traverse farther on their missions by foot. This implies that the system might need to be cheap in case it needs to be ditched in the middle of a mission also easy to get in and out at a moment’s notice. Having a modular design not only helps the operators load out the system differently on a mission by mission basis, but by being able to eject different parts of the system from damage during the mission. This will reduce maintenance cost and build costs. However this system offers almost no protection to the operator.

Figure 7 - HULC (Human Universal Load Carrier) carrying load on soldier.
XOS 2 Exo-skeleton

The EXO 2 exo-skeleton is a wearable robot developed by Raytheon Company. This suit is capable of extended use and heavy lifting without the operator even getting tired. This suit takes the entire load of the user and follows each of his/her movements without effort. The XOS 2 was used to lift 200 pounds repetitively for 500 repetitions before the user stopped; it should be noted that the reason for stopping was out of boredom and not due to fatigue (9). This is quite impressive, but the system is bulky and still offers little protection to the operator. With the way this suit is currently designed it would be difficult to mount armor to while still allowing all of the freedom the user has now. Pictured in Figure 8 below, the XOS-2 lifts up an artillery shell with one hand. This powerful and agile system is more suited to the rear lines helping out in rearming aircraft or loading supplies into a storage area.

Figure 8 – XOS-2 lifting an artillery round.
The Trojan Suit

The Trojan Suit, developed by Troy Hurtubise, is said to have 90% flexibility and 95% body coverage. The Trojan, shown below in Figure 9, allows the wearer to drive vehicles, run full-tilt, climb stairs and conduct dive roll maneuvers (10). His suit shown below suit isn’t powered, but it focuses on protecting the operator. The user still had to carry the weight of this suit with his “Shadow Armor” that he invented. Capable of stopping a 44 magnum round at point blank range, the armor is more than capable of protecting the user, but with having to physically carry the suit of armor would be detrimental to the physical endurance and longevity of the user. The armor seems to be held on by straps with the ability for it to shift during use. This could lead to uncomfortable situations or unnecessary distractions on the battlefield.

![Figure 9 - Troy Hurtubise in the Trojan Suit](image)

Interview

During an interview with First Lieutenant Brent Kreckman, he informed us of the possible uses and motions that a typical soldier would do.

A soldier needs to be mobile all the time and keep a low profile. On a long excursion a typical soldier would need to carry approximately 150 lbs. worth of guns, food, supplies, ammo. The armor typically weighs 20-40lbs by its self. In case of an emergency the suit could be drop it if needed. This would force us to design disposable and cheap suit.

Combat engineers are primarily responsible for mine clearing and building Forward Operating Base. This relates to lots of protection. These operations may be done while under
enemy attack. They would need to get up and down a lot and have an overall small size to get closer to disarm enemy mines. The elbows and knees will see the most ware and tare from getting up and down.

Bomb defusing workers needs a suit that will have fast motion, normal range of motion, easy and fast assembly of suit. He suggested that the suit doesn’t make the user excessively large and has the operators’ hands completely free to disarm a bomb.

Armor now is very restrictive and is hard to move or even throw a grenade. The soldier needs to be able to hold a standard M16 or M4 (collapsible but stock) rifle and to bring the rifle up to shoot or aim while keeping the butt stock against the armpit/shoulder. The operator may also have a three point sling holding their weapon up.

After compiling the research completed so far, only the Trojan Suit has fit the definition of a true exo-skeleton. Supporting and protecting the operator is the main goal of an exo-skeleton. The other researched topics will help when designing the prototype arm. The promising sections of each item will influence the design.

Through the research that has been done, The Trojan Suit, listed in Appendix A is the only suit that fits the definition of an exo-skeleton. Other companies twist the definition and have gotten the public to immediately think “exoskeleton means increased strength” when this is not the case. Protecting the operator is the goal of an exoskeleton, not to be able to lift 200 pounds 500 times (9). The purpose of this project is to design a prototype exo-skeleton support structure to protect a human in hostile environments. This structure will be used as a mounting structure for later use. The design will focus on the right arm as a proof of concept. The arm will have two degrees of freedom powered enough to hold its own weight so that the operator can move the suit effortlessly. It will not add strength to the operator or armor to the structure, even in the final design.
CUSTOMER FEED BACK, OBJECTIVES, AND CHARACTISTICS

CUSTOMER FEED BACK

Ten survey responses came back from Marines, Army, Army Reserves, veterans, and also retired police officials and firefighters. The survey included a general questioner about an exo-skeleton and what overall features the individual would like to see in the system. The survey requested that the potential customers ranked the criteria 1 – 5; one (1) being the least important and five (5) being the most important feature. The results will help during the design phase. Listed in Table 2, are the responses from the surveys. They have been sorted to show the most important feature first and the least important feature last.

Table 2 - Survey responses in order of importance.

<table>
<thead>
<tr>
<th>Feature</th>
<th>Customer Importance</th>
<th>Designer’s Multiplier</th>
<th>Modified Importance</th>
<th>Relative weight %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal Range of Motion</td>
<td>4.56</td>
<td>1.20</td>
<td>5.47</td>
<td>11.8%</td>
</tr>
<tr>
<td>Smooth Motion</td>
<td>4.20</td>
<td>1.20</td>
<td>5.04</td>
<td>10.9%</td>
</tr>
<tr>
<td>Safe for the operator/bystanders</td>
<td>4.80</td>
<td>1.00</td>
<td>4.80</td>
<td>10.3%</td>
</tr>
<tr>
<td>Be Durable</td>
<td>4.60</td>
<td>1.00</td>
<td>4.60</td>
<td>9.9%</td>
</tr>
<tr>
<td>Easy to Repair/ Maintain</td>
<td>4.50</td>
<td>1.00</td>
<td>4.50</td>
<td>9.7%</td>
</tr>
<tr>
<td>Easy to Operate</td>
<td>4.20</td>
<td>1.00</td>
<td>4.20</td>
<td>9.0%</td>
</tr>
<tr>
<td>Be Light Weight</td>
<td>3.70</td>
<td>1.10</td>
<td>4.07</td>
<td>8.8%</td>
</tr>
<tr>
<td>Have an ergonomic fit</td>
<td>3.90</td>
<td>1.00</td>
<td>3.90</td>
<td>8.4%</td>
</tr>
<tr>
<td>Have a Compact Design</td>
<td>3.44</td>
<td>1.00</td>
<td>3.44</td>
<td>7.4%</td>
</tr>
<tr>
<td>Loudness</td>
<td>3.40</td>
<td>1.00</td>
<td>3.40</td>
<td>7.3%</td>
</tr>
<tr>
<td>Low Cost</td>
<td>3.00</td>
<td>1.00</td>
<td>3.00</td>
<td>6.5%</td>
</tr>
</tbody>
</table>

The surveyed responded with the exo-skeleton having a normal range of motion to be the most important feature followed by: Smooth Motion, Safe for Operators and Bystanders, Being Durable and Easy to Repair and Maintain. The numbers were adjusted slightly for Normal Range of Motion, Smooth Motion and Being Light Weight. The designers decided that having a normal range of motion and have a smooth and fluid motion were the most important features. After speaking with First Lieutenant Brent Kreckman, he suggested that current armor systems hardly let the soldier throw a grenade due to the immobility induced by the armor. Those two characteristics were then adjusted by 20% each. Having structure be light weight was adjusted by 10%. Being lighter reduces the load on the power system, thus increasing operating times.

Should a problem arise during the design phase between conflicting features, this list would
be the deciding factor on which is more important. As expected, Low Cost was ranked last in importance. This is because the military generally will pay large amount of money for any system that would help protect soldiers in hostile environments.

**PRODUCT OBJECTIVES**

Listed below are the objectives of this project. They are listed in order of importance; with the most important feature on top and the least important feature on bottom. The importance level was decided on by the returned surveys. Under each objective is listed how the objective will be accomplished.

**Normal Range of Motion (11.8%)**
- Normal ranges of motion will be referenced from cited texts.

**Smooth Motion (10.9%)**
- Joints will be lubricated.
- Moving parts will not contact others causing them to bind.

**Safe for the operator/bystanders (10.3%)**
- Pinch points will be designed out or the operator will be guarded against them.
- An Emergency Stop will be included.
- Hard safety stops will be included into the joints to prevent hyperextension.

**Be Durable (9.9%)**
- Fasteners will be Grade 8 or equivalent.
- Correct materials will be chosen according to the design loads.
- Loctite will be applied to the fasteners to prevent them from backing out.
- A factor of safety agreeing with cited texts.
- All bolts will be tightened to the allowable torque in cited texts.
- Electrical connections will be soldered and then covered with heat wrap if needed.

**Easy to Repair/ Maintain (9.7%)**
- All fasteners will be bought and not made.
- Parts will not be welded.
- Sections will be modular.
- Quick connect electronic connectors will be used.

**Easy to Operate (9.0%)**
- Approximately 3 hours of training will be enough to qualify someone to be able to use it.
- No more than two people will be needed to assemble and put on the hardware.
- It will be easily controlled through sensors or switches.
Be Light Weight (8.8%)  
- The arm will weigh less than 50 pounds, excluding armor.

Have an Ergonomic Fit (8.4%)  
- The operator will be protected from coming in contact with the hardware.

Have a Compact Design (7.4%)  
- All drive and control systems will be contained in the skeleton.

Loudness (7.3%)  
- The arm will be no louder than an electric shaver.

Low Cost (6.5%)  
- Easily obtainable materials and fasteners such as steel or aluminum will be used for construction.

**ENGINEERING CHARACTERISTICS**

Engineering characteristics are terms that can be used to quantitatively evaluate each product objective. Listed in Table 3 are the characteristics that the design team decided to measure. Each characteristic has a corresponding “unit” that will be used to evaluate the design. This will determine, not only that the objective was looked at but, to what extent. Shown below in Table 3, each engineering characteristic is listed with an importance weight.

<table>
<thead>
<tr>
<th>Engineering Characteristics</th>
<th>Importance %</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force to change directions</td>
<td>8.55%</td>
<td>Torque (inch-pounds)</td>
<td>How responsive the system is to a users input.</td>
</tr>
<tr>
<td>Range of Motion</td>
<td>9.32%</td>
<td>Degrees (°)</td>
<td>From a neutral position, how far can each joint be extended.</td>
</tr>
<tr>
<td>Safety Factor</td>
<td>13.59%</td>
<td>Safety Factor (#)</td>
<td>How safe the system is under load.</td>
</tr>
<tr>
<td>Weight</td>
<td>11.57%</td>
<td>Pounds (lb)</td>
<td>Overall weight of the system.</td>
</tr>
<tr>
<td>Sensors or switches</td>
<td>6.24%</td>
<td>Yes/No</td>
<td>The system has input devices such as sensors or switches to control it.</td>
</tr>
<tr>
<td>Training Time</td>
<td>5.93%</td>
<td>Hours (hrs.)</td>
<td>How long it should take an operator to fully learn how to use the system.</td>
</tr>
<tr>
<td>Assembly/Maintenance</td>
<td>11.59%</td>
<td># of People (#)</td>
<td>How many people need to be present in order to assemble/maintain the system.</td>
</tr>
<tr>
<td>Modular Assembly</td>
<td>14.80%</td>
<td>Yes/No</td>
<td>the system can be assembled/disassembled in sections.</td>
</tr>
<tr>
<td>Drive system Contained</td>
<td>0.62%</td>
<td>Yes/No</td>
<td>the drive system is protected within the structure.</td>
</tr>
<tr>
<td>Cost</td>
<td>3.03%</td>
<td>Dollars ($)</td>
<td>Overall cost of the system.</td>
</tr>
<tr>
<td>Operator Protected</td>
<td>9.78%</td>
<td>Yes/No</td>
<td>If the operator is protected within the system.</td>
</tr>
<tr>
<td>Decible level</td>
<td>4.97%</td>
<td>Decibles (db)</td>
<td>Overall loudness of the system in use.</td>
</tr>
</tbody>
</table>

These characteristics have been decided upon by the design team and how important each one is to the overall system design.
The shoulder joint is one of the hardest joints to recreate with mechanical linkages. Most companies have reduced the shoulder degrees of freedom from its normal three to two; this is shown in the research section. A specialized two degree of freedom joint is capable of mimicking all three degrees of freedom; however, the motion becomes less fluid and requires the operator to possibly change the way they would normally move their arm in order to reach a position. This is called a “learned movement”. In order for the operator to move his/her arm into a position, the steps to get there may change due to how the combined degrees of freedom work together. They basically need to re-learn how to move their arm into a certain position in some instances. The movements represented in the Figures below will be considered when designing the range of motion for the shoulder and elbow. Originally, the extra degrees of freedom and range of motion gained from the scapula (shoulder blade) and clavicle (collar bone) bones were to be excluded, Figures 10-13. After researching possible designs, they were included to provide a more fluid arm motions and range of motion. The movements include Shoulder elevation/depression, shoulder abduction/adduction, shoulder rotation and shoulder flexion/extension. Combining those movements described will be the basis of a proper shoulder and elbow joint. Listed in Table 4, below the figures, is a brief explanation of each movement. (11) (12)
Figure 14 - Shoulder extension.

Figure 15 - Shoulder flexion.

Figure 16 - Shoulder internal rotation.

Figure 17 - Shoulder external rotation.

Figure 18 - Shoulder adduction.
Figure 19 - Shoulder abduction.

Figure 20 - Shoulder horizontal abduction.

Figure 21 - Shoulder horizontal adduction.

Figure 22 - Elbow flexion and extension.
Figure 23 - Pitch, yaw, and roll degrees of freedom of a human arm

Figure 24 - Axis of rotation and sliding

Figure 25 - Axis of rotation on a coordinate system

Figure 26 - Pitch, yaw and roll labeled on a coordinate system
A.R.E.S. (Assisted Robotic Exo-Skeleton)  Frank Ricciardi (Upper Arm and Elbow)

Table 4 – Movement definition table

<table>
<thead>
<tr>
<th>Figure #</th>
<th>Movement</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 10</td>
<td>Shoulder Depression</td>
<td>To move the scapula upward, as in lowering your shoulder away from the skull.</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Shoulder Elevation</td>
<td>To move the scapula upward, as in raising your shoulder closer to the skull.</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Shoulder Protraction</td>
<td>Used when spreading the lats, as in pulling your shoulder infront of the body.</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Shoulder Retraction</td>
<td>Performed when you squeeze the shoulder blades together.</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Shoulder Extension</td>
<td>To move the shoulder joint straight backwards. Similar to a hammering motion.</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Shoulder Flexion</td>
<td>Used when lifting your arm straight up in front.</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Shoulder Internal Rotation</td>
<td>Rotating the shoulder joint medially or toward the midline of the body.</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Shoulder External Rotation</td>
<td>Rotating the shoulder joint medially or toward the midline of the body.</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Shoulder Adduction</td>
<td>Adduction means to bring a body part closer to the midline or center of the body.</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Shoulder Abduction</td>
<td>Abduction means to take a body part away from the midline or center of the body.</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Shoulder Horizontal Abduction</td>
<td>This is abduction in a horizontal or transverse plane, as in moving your arms toward your back.</td>
</tr>
<tr>
<td>Figure 21</td>
<td>Shoulder Horizontal Adduction</td>
<td>This is abduction in a horizontal or transverse plane, as in moving your arms toward your front.</td>
</tr>
<tr>
<td>Figure 22</td>
<td>Elbow Flexion and Extension</td>
<td>Such as using a hammer to hammer a nail.</td>
</tr>
</tbody>
</table>

Each of these Figures, Figures 10-22, has a corresponding mechanical joint that can simulate the correct movement. The complicated part is combining all of the movement together to create a seamless moving experience.

Each of these movements has an axis of rotation that passes through the center of the joint normally on a human arm. Where all three axes intersect is the ideal location for the joint to be. In the case of the shoulder, the ball joint allows three degrees of freedom. Below, Figure 27 shows a similar ball and socket joint to the shoulder, the hip joint, with the three degrees of freedom and their respective axis of rotation passing through the center. (13)

Figure 27 - Hip ball and socket joint with axes of rotation passing through the center.
This project tries to mimic these axes of rotation. In order for this to work, the axis of rotation must pass through the manufactured pivot and continue to pass through the center of the joint inside of the body.

The shoulder has twelve different movements as seen in Figures 10-21. These moments are comprised of three degrees of freedom, pitch, roll, yaw, and sliding up, down, forward, backward. This gives us a total of five degrees of freedom in the shoulder. Using Figures 23-26, each movement can be classified and be put into more basic and understandable terms (14) (15). The pitch corresponds with shoulder extension and flexion, Figure 14 and Figure 15. Roll corresponds with shoulder internal and external rotation, Figure 16 and Figure 17. Yaw corresponds with shoulder abduction and adduction, Figure 18 and Figure 19. The shoulder can then slide up and down, otherwise known as elevation and depression, as seen in Figure 10 and Figure 11. It can also slide forwards and backward, otherwise known as protraction and retraction, as seen in Figure 12 and Figure 13. Figure 20 and Figure 21, shoulder horizontal abduction and adduction, do not get classified as an additional degree of freedom. They show a combination of moment brought on by two different degrees of freedom working together, pitch and yaw. With each degree of freedom relating to a mechanical axis of rotation different design concepts could now be generated. The elbow only has one degree of freedom comprised of two movements, elbow flexion and extension. An example of this can be seen in Figure 22.
Design Alternatives and Selection

The shoulder, being the most complex joint in the human body, took several different design concepts before a match between range of motion, ease of moment and what could actually be manufactured could be achieved. Brainstorming was a very useful tool when designing each component. To simplify the project more, the design team spit the degrees of freedom up into three groups aptly named “Shoulder”, “Elbow”, and “Wrist”. These three areas, shown in Figure 28, divided the arm degrees of freedom up into distinct groups. The three groups better defined which area or which component was being discussed. Figure 28 shows all of the degrees of freedom obtained with this project. The “Shoulder” and “Elbow” areas will only be discussed in this section of the report.

![Figure 28 - Complete arm degrees of freedom](image)
SHOULDER DESIGN CONCEPTS

The design team developed six shoulder designs. They can be seen below in Figures 29 - 34. Each design incorporated a different idea or built upon the previous model. Some added degrees of freedom while others simplified the movement with only two degrees of freedom, but were easier to manufacture. Each joint is also listed with a unique identifier code to help classify which pivot is in question.

Rotating Universal Joint

The first design called the Rotating Universal Joint, Figure 29, allows for three degrees of freedom. Pitch, yaw, and roll arrows are shown to explain the movement. Figure 25 and Figure 26 show which directions these are in relation to the rest of the arm.

This design was ruled out for several reasons. This joint design was very large and would prohibit the operator lowering the arm completely down alongside the body. It would also interfere with the armpit of the operator, creating a pinch point. The offset in pivot RUJ-1, was thought to help in rotating the arm in front of the body. After modeling the joint, the movement of this joint would cause the structure to extend as the arm was rotated from the extended out position to wrapping it across the chest. This system also included a threaded locking ring feature. The high tolerances on the threads and rotating features made this design very difficult to manufacture.
Armadillo Joint

The second design was the Armadillo Joint, Figure 30. The design team developed this idea from the armored plates on an armadillo’s back. The idea was to include many degrees of freedom that would work together to allow for the correct movement. In total, there would be five degrees of freedom.

The Armadillo Joint, once modeled, showed obvious flaws. The design had too many degrees of freedom. The model would often bind on its self, preventing any other movement. However this design did lead the design team in an interesting direction. It was noticed that all of these components were on the top back quadrant of the shoulder. This area of the shoulder does not see as much movement or conflicting bodies as the side, front and top of the shoulder does.
Slotted Arc Joint

The third design shown below in Figure 31 used several concepts learned from the past designs and research, such as the physical location of the joint on the top back quadrant of the shoulder. With this concept, the axes of rotation intersect in the center of the shoulder, just like the ball joint in Figure 27 does. This joint allows for three degrees of freedom. It also allows for near identical movement of a ball joint, which the shoulder is. As stated in the design research, the axes of rotation need to pass through the center of the joint to ensure proper fluid motion. With this design, they do.

However, this joint design has some limiting problems. The slot and capturing feature on pivot SAJ-2 would be very difficult to manufacture. This would increase cost and machine time. Also as the arcs rotated past each other additional clearance was needed so no pinch points were introduced, making the joint larger. Finally, as the modeled joint was moved around it would get to a certain position and either bind or allow the motion to come back to the original location but the links would be in a different orientation. This would then not allow the proper movement the next time that position would need to be reached.
Rotating Track Joint

This design, Rotating Track Joint in Figure 32, was created to improve the manufacturability of the Slotted Arc Joint. The semicircle feature has a “T” slot cut into it cordially. The mount on the shoulder has a matching “T” emboss that allows the semicircle track rotate along that feature. This is a much stronger design and can be manufactured in less time and cost substantially less. This design does have three degrees of freedom.

Figure 32 - Rotating Track Joint

Despite the improvements, this design still had some limitations. Again the clearance issue between the arced links forced the overall size to be much larger that the team wanted. The design team also experienced the same binding problem as before in the Slotted Arc Joint, Figure 31.
Rotating Track Shoulder

In the fifth redesign, the “T” slotted track was reused because of the rigidity and reduced manufacturing time and cost. The shorter arc attached to the “T” slotted semicircle has been removed. This reduced the design to only two degrees of freedom. The axes of rotation still pass through the center of the operators shoulder joint. Even though this design only has two degrees of freedom, all of the movement obtained by three degrees of freedom can be achieved with only two. The operator would have a “learned movement” in order to move the arm a certain way to achieve certain movements.

![Rotating Track Shoulder](image)

Figure 33 - Rotating Track Shoulder

This design allowed the team to achieve some of the desired movements with proper range of motion. With it we can have Shoulder flexion and extension, adduction and abduction, horizontal adduction and abduction. These movements are listed in Figure 14, Figure 15, Figure 18, and Figure 19. A learned movement is needed to achieve the movements shown in Figure 20, and Figure 21.
4D Track Shoulder

This final shoulder design incorporates a series of extending cylinders, faux collar bone, and a small ball joint. The cylinders can work together or separate in order for the shoulder to raise, lower or move forward or backward. These motions are represented in 4DTS-1 and 2. When both cylinders extend or contract, they will push the entire shoulder up or pull it down, as seen in Figure 34, slide 4DTS-1. If one cylinder extends and the other retracts, the shoulder will move forward and backward, as seen in Figure 34, slide 4DTS-2. The cylinders mimic the sliding of the scapula. Two cylinders had to be used in order to counter the effects of the other one. In effect, it maintains a static equilibrium in the system by counteracting the forces brought on by the other cylinder extending or contracting. In this build, these cylinders will simply be tubes and rods. Later builds will have pneumatic or hydraulic pistons to power these movements.

Figure 34 - 4D Track Shoulder

This is the final design and the one that provided the most efficient use of pivots. The shoulder design has four degrees of freedom and can imitate the natural five degrees of freedom the human shoulder has.
ROTATING RINGS DESIGN CONCEPTS

Locking Ring

The rotating rings are an integral part of this project. The initial idea came from the locking nuts that hold the bearings and their shafts in place on jet engines. Although the design has changed from that idea, the use of a large diameter threaded nut stayed. The assembly can be seen below in Figure 36. One of the rings is attached to the upper arm and the other to the lower arm. The Outer Ring fits inside of the Inner Ring. Then a threaded locking ring threads into the inner ring and holds the other two rings together. This can be seen in Figure 35.

This idea was abandoned for several reasons. The large diameter threads would have been very difficult and time consuming to manufacture. This would lead to a lot of waste and money spent. This idea also required a special spanner wrench to tighten down. The team would have had to design and build this special tool that few, if any others, would have. Another reason was assembly issues and maintainability. The assembly time would have increased due to aligning the rest of the arm and threading the nut on. Maintaining the threads would also be a challenge. If the threads were damaged in the field, the part might need to be scrapped.
Clamping Ring

To avoid some of the problems that the Locking Ring presented, the design was changed to a more modular and simple design. The Clamping Ring uses two nearly identical rotating rings that are held together with a clamping feature. Having the rings very similar will reduce machine setup time. The clamping features simply hold the flanges on either ring together. The clamps are held together at the bottom with a pin and allowed to rotate about it. After the clamping rings are around the flanges, a small lever lock gets pressed down and locks them together. The exploded view is seen in Figure 37, showing each part.

Figure 37 - Clamping ring exploded view

Figure 38 - Clamping ring assembly view

In Figure 38, the assembly view shows how simple this idea is. The clamps can be put on much faster than the locking ring and it requires no extra tools to assemble. They are also low tolerance parts that are easy to machine, thus reducing costs. If for some reason these parts need to be scraped, their low costs don’t hinder the manufacturing of a new one.
Shoulder Design Weighted Rating of Concepts

A weighted rating chart was also used to evaluate the designs against each other. Listed below in Table 5 - Weighted Rating Chart for the shoulder designs. Table 5 and Table 6 are the Weighted Rating charts for the shoulder design and locking ring design.

Table 5 - Weighted Rating Chart for the shoulder designs

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Rating</th>
<th>Weighted Rating</th>
<th>Rating</th>
<th>Weighted Rating</th>
<th>Rating</th>
<th>Weighted Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>10%</td>
<td>1</td>
<td>0.1</td>
<td>2</td>
<td>0.2</td>
<td>3</td>
<td>0.3</td>
</tr>
<tr>
<td>Maintainability</td>
<td>15%</td>
<td>2</td>
<td>0.3</td>
<td>4</td>
<td>0.6</td>
<td>3</td>
<td>0.45</td>
</tr>
<tr>
<td>Assembly</td>
<td>12%</td>
<td>2</td>
<td>0.24</td>
<td>4</td>
<td>0.48</td>
<td>2</td>
<td>0.24</td>
</tr>
<tr>
<td>Range of Motion</td>
<td>20%</td>
<td>2</td>
<td>0.4</td>
<td>3</td>
<td>0.6</td>
<td>2</td>
<td>0.4</td>
</tr>
<tr>
<td>Weight</td>
<td>8%</td>
<td>1</td>
<td>0.08</td>
<td>3</td>
<td>0.24</td>
<td>2</td>
<td>0.16</td>
</tr>
<tr>
<td>Degree of Freedom</td>
<td>15%</td>
<td>1</td>
<td>0.15</td>
<td>2</td>
<td>0.3</td>
<td>1</td>
<td>0.15</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>20%</td>
<td>1</td>
<td>0.2</td>
<td>1</td>
<td>0.2</td>
<td>3</td>
<td>0.6</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>2.60</td>
<td>2.62</td>
<td>2.30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6 - Weighted Rating Chart for the locking ring designs

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Weight</th>
<th>Rating</th>
<th>Weighted Rating</th>
<th>Rating</th>
<th>Weighted Rating</th>
<th>Rating</th>
<th>Weighted Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>10%</td>
<td>1</td>
<td>0.1</td>
<td>3</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maintainability</td>
<td>15%</td>
<td>2</td>
<td>0.3</td>
<td>4</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assembly</td>
<td>12%</td>
<td>2</td>
<td>0.24</td>
<td>4</td>
<td>0.48</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range of Motion</td>
<td>20%</td>
<td>4</td>
<td>0.8</td>
<td>4</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weight</td>
<td>8%</td>
<td>2</td>
<td>0.16</td>
<td>2</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degree of Freedom</td>
<td>15%</td>
<td>4</td>
<td>0.6</td>
<td>4</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manufacturability</td>
<td>20%</td>
<td>2</td>
<td>0.4</td>
<td>4</td>
<td>0.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
<td>2.60</td>
<td>3.74</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The Weighted Rating Chart is a way to quantify the designs and determine mathematically which one is superior. The initial weights of each criterion were chosen by the design team. The total weight for criteria equals 100%. This is needed to the equation can be balanced. For each design, and individual rating was given for each criteria. This rating is then multiplied by the criterion weight to get a weighted rating. This is repeated for each criterion then summed up. The final answer is a value that displays how well that concept did overall. Each design concept is then compared; the highest total rating gives the best design. Table 5 shows that the 4D Track Shoulder is the best design out of the six generated concepts. Table 6 shows the weighted rating for the locking ring designs. The Clamping Ring design scored the highest rating. The Clamping Ring won because it is far easier to maintain, assemble, and manufacture. It is also much cheaper to produce. Because of this, the design team chose to incorporate this concept into the final design.
A.R.E.S. (Assisted Robotic Exo-Skeleton)  Frank Ricciardi (Upper Arm and Elbow)

**Range of Motion**

Listed below in Table 7 are the recommended ranges of motion for the human upper arm (16). These ranges of motion correlate with the degrees of freedom listed in Table 4. The listed Internal and External alternate measuring methods does not apply to this project.

<table>
<thead>
<tr>
<th>Movement</th>
<th>From Natural Plane to End Point (deg)</th>
<th>Designed Total Motion (deg)</th>
<th>Cited Total Motion (deg)</th>
<th>% Reduction in Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shoulder Flexion</td>
<td>0-115</td>
<td>126</td>
<td>240</td>
<td>-47.5%</td>
</tr>
<tr>
<td>Shoulder Extension</td>
<td>0-11</td>
<td>116</td>
<td>180</td>
<td>-35.6%</td>
</tr>
<tr>
<td>Shoulder Abduction</td>
<td>0-116</td>
<td>0</td>
<td>110</td>
<td>-33.3%</td>
</tr>
<tr>
<td>Shoulder Horizontal Abduction</td>
<td>0-90</td>
<td>90</td>
<td>135</td>
<td>-33.3%</td>
</tr>
<tr>
<td>Shoulder Horizontal Adduction</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.0%</td>
</tr>
<tr>
<td>Shoulder Internal Rotation</td>
<td>0-70</td>
<td>110</td>
<td>110</td>
<td>0.0%</td>
</tr>
<tr>
<td>Shoulder External Rotation</td>
<td>0-90</td>
<td>140</td>
<td>150</td>
<td>-6.7%</td>
</tr>
</tbody>
</table>

Due to limitations of materials and size requirements, the design team was unable to fully replicate the ranges of motion recommended for a healthy human arm. Listed in below in Table 8, the actual obtained ranges of motion are listed. Internal Rotation, according to the reference book, starts measuring at 90 degrees and goes down to 70, giving an actual range of motion of 20 degrees. This project obtains that movement.

As the table shows the shoulder was the most difficult aspect of this project. The ranges of motion were significantly reduced. This may impede the operator from carrying out his/her normal tasks. The elbow seemed to be the easiest. There was ample room for the materials and only two degrees of freedom, as opposed to the shoulders five degrees of freedom.
LOADING CONDITIONS AND DESIGN ANALYSIS

Several loading conditions were considered in this design project. It proved difficult to quantify exactly how the arm would operate under actual loading conditions because there are so many degrees of freedom. The design team tested the safety hard stops to ensure that they were strong enough to withstand the load. If these passed then the structure would be able to withstand most loading conditions in the field. The loading scenarios that were tested were Load Case 1 and Load Case 2; these are both extremes that will contact the shoulder safety hard stops. Load Case 3 and Load Case 4 test the safety hard stops on the elbow. Load Case 5 is a torquing or twisting force, against the safety hard stop pins in the elbow rotating ring. Load Case 6 tests the bolts and shear tear out in case the system is pulled down its axis. Load Case 7 verifies the structure can withstand a side load. Although a low force is applied in these stress calculations, the safety factors were very large in some cases. This means that the force applied can be multiplied by the safety factor in order to get the maximum stress the area of concern could withstand. In the following stress calculations the force has already been divided in half if necessary, half of the force on each side of the structure. In double shear tear out, the stress theoretically must tear the entire piece of material out. Therefore the stress calculations multiply the area by two for each area in shear tear out. Some of the parts under review have the exact same geometric dimensions as other parts in the system. Therefore there is no need to review them again; the safety factor would be exactly the same. If these parts pass, then they will too.

Load Case 1

![Load Case 1 load diagram](image)

Figure 39 - Load Case 1 load diagram

\[ F = 150\text{lb} \]
Load Case 1
Maximum Displacement = 0.007in

Figure 40 - Maximum displacement for Load Case 1

Maximum Stress = 53,609psi

Figure 41 - Maximum stress for Load Case 1

Safety Factor

\[ SF = \frac{\sigma_s}{\sigma} = \frac{251600\text{psi}}{53609\text{psi}} = 4.7 \]
Load Case 2

Load Case 2 has a smaller force because at this position the structure would hit your body before the hard stop. It will be tested in a worst case scenario.

The forces used in FEA to test the shoulder were derived from the following equation set:

\[ M = F \times d \]
\[ F = 75\text{lbf} \]
\[ d = 22.5\text{in} \]

\[ M = 75\text{lbf} \times 22.5\text{in} \]
\[ M = 1688\text{inlbf} \]

\[ T = \frac{M}{h} \]
\[ M = 1688\text{inlbf} \]
\[ h = 11.1\text{in} \]

\[ T = \frac{3375\text{inlbf}}{11.1\text{in}} \]

\[ T = 153\text{lbf} \]
Load Case 2 FEA
Maximum Displacement = 0.009in

Figure 43 - Maximum displacement for Load Case 2

Maximum Stress = 71,100psi

Figure 44 - Maximum stress for Load Case 2

Safety Factor

\[ SF = \frac{\sigma_s}{\sigma} \]
\[ SF = \frac{251600psi}{71100psi} \]
\[ SF = 3.5 \]
Load Case 3

The load is applied to the elbow safety hard stop.

Figure 45 - Load Case 3 load diagram

Load Case 3 FEA
Maximum Displacement = 0.000006in

Figure 46 - Maximum displacement for Load Case 3
Maximum Stress = 934psi

Figure 47 - Maximum stress for Load Case 3

Safety Factor

\[
SF = \frac{\sigma_s}{\sigma} \\
SF = \frac{251600\text{psi}}{934\text{psi}} \\
SF = 269
\]
Load Case 4

The load is applied to the elbow safety hard stop.

\[ F = 150\text{ lbf} \]

Load Case 4 FEA
Maximum Displacement = 0.000009in

Figure 48 - Load Case 4 load diagram

Figure 49 - Maximum stress for Load Case 4
Maximum Stress = 1,290psi

Figure 50 - Maximum stress for Load Case 4

Safety Factor

\[ SF = \frac{\sigma_s}{\sigma} \]

\[ SF = \frac{251600\text{psi}}{1290\text{psi}} \]

\[ SF = 195 \]
Load Case 5

This force is applied to shear the pins. The pins are rated at 2700lbf in double shear. The pins in the design are in single shear, but there are two pins total seeing the load in single shear. The double shear value can then be used. A straight force can be used because the side supports that would produce the torque are nearly in line with the pins. The force doesn’t travel perpendicular to the axis.

![Load Case 5 load diagram](Figure 51 - Load Case 5 load diagram)

\[ R = 150\text{lbf} \]
\[ Dss = 2700\text{lbf} \]
\[ SF = \frac{Dss}{R} \]
\[ SF = 18 \]
Load Case 6

Force pulls along the axis.

Figure 52 - Load Case 6.1-6.5 load diagram

Load Case 6.1

Double shear tear out through one location (2 areas).

Figure 53 - Double shear tear out
Figure 54 - Cross sectional area of tear out

\[ a = 0.3\text{in} \times 0.125\text{in} + 0.125\text{in} \times 0.125\text{in} \]
\[ a = 0.053125\text{in}^2 \]

\[ F = 75\text{lb}f \]
\[ \sigma = \frac{F}{2 \times a} \]

\[ \sigma = \frac{75\text{lb}f}{2 \times (0.053125\text{in}^2)} \]
\[ \sigma = 706\text{psi} \]

\[ SF = \frac{\sigma}{\sigma_s} \]
\[ SF = \frac{251600\text{psi}}{706\text{psi}} \]
\[ SF = 357 \]
Load Case 6.2

Double shear tear out through one location (2 areas).

![Diagram of A.R.E.S. (Assisted Robotic Exo-Skeleton) Frank Ricciardi (Upper Arm and Elbow)](image)

**Figure 55 - Double shear tear out**

**Figure 56 - Cross sectional area of tear out**

\[
\begin{align*}
\alpha &= 0.12\text{in} \times 0.187\text{in} \\
\alpha &= 0.02244\text{in}^2 \\
F &= 75\text{lbf} \\
\sigma &= \frac{F}{2 \times \alpha} \\
\sigma &= \frac{75\text{lbf}}{2 \times (0.02244\text{in}^2)} \\
\sigma &= 1672\text{psi} \\
SF &= \frac{\sigma_s}{\sigma} \\
SF &= \frac{251600\text{psi}}{1672\text{psi}} \\
SF &= 150
\end{align*}
\]
Load Case 6.3

Double shear tear out through two locations (4 areas).

Figure 57 - Double shear tear out

$a = 0.0695\, \text{in} \times 0.2815\, \text{in}$
$a = 0.01956\, \text{in}^2$

$F = 75\, \text{lbf}$
$\sigma = \frac{F}{4 \times a}$

$\sigma = \frac{75\, \text{lbf}}{4 \times (0.02244\, \text{in}^2)}$
$\sigma = 959\, \text{psi}$

$SF = \frac{\sigma_s}{\sigma}$
$SF = \frac{251600\, \text{psi}}{959\, \text{psi}}$
$SF = 262$
Load Case 6.4

Single shear through the bolt (1 area)

\[ F = 75 \text{lbf} \]
\[ r = 0.074 \text{in} \]

\[ a = \pi r^2 \]
\[ a = \pi (0.074)^2 \]
\[ a = 0.0172 \text{in}^2 \]

\[ \sigma = \frac{F}{2 \times a} \]

\[ \sigma = \frac{75 \text{lbf}}{2 \times (0.0172 \text{in}^2)} \]
\[ \sigma = 2179 \text{psi} \]

\[ SF = \frac{\sigma_{bolt}}{\sigma} \]
\[ SF = \frac{82080 \text{psi}}{2179 \text{psi}} \]
\[ SF = 37 \]
Load Case 6.5

Single shear through two bolts at the same time (2 areas).

![Figure 60 - Shear in shoulder bolt](image)

\[
\sigma_{bolt} = 144000 \text{psi} \times 57%
\]

\[
\sigma_{bolt} = 82080 \text{psi}
\]

\[F = 75 \text{lbf}\]

\[r = 0.064 \text{in}\]

\[a = \pi r^2\]

\[a = \pi (0.064^2)\]

\[a = 0.0129 \text{in}^2\]

\[
\sigma = \frac{F}{2 \times a}
\]

\[
\sigma = \frac{75 \text{lbf}}{2 \times (0.0129 \text{in}^2)}
\]

\[\sigma = 2914 \text{psi}\]

\[SF = \frac{\sigma_{bolt}}{\sigma}\]

\[SF = \frac{82080 \text{psi}}{2914 \text{psi}}\]

\[SF = 28\]
Load Case 7

Side load

Figure 61 - Load Case 7 load diagram

\[ M = F \times d \]
\[ F = 150\text{lbf} \]
\[ d = 22.5\text{in} \]

\[ M = 150\text{lbf} \times 10.7\text{in} \]
\[ M = 1605\text{inlbf} \]
A.R.E.S. (Assisted Robotic Exo-Skeleton)  Frank Ricciardi (Upper Arm and Elbow)

Load Case 7 FEA
Maximum Displacement = 0.001 in

Figure 62 - Max displacement for Load Case 7
Maximum Stress = 59,195psi

Figure 63 - Max stress for Load Case 7
Safety Factor

\[ SF = \frac{\sigma_s}{\sigma} \]
\[ SF = \frac{251600psi}{59195psi} \]
\[ SF = 4.25 \]
FACTORS OF SAFETY

Safety factors are a major concern for this project. Possibly being implemented in the battle field, the operator needs to know that the suit can withstand the harsh environment. For this project the design team shoes a goal safety factor of 4. A safety factor of 4 is recommended for assemblies under a repeated load (17). The team felt that this would be satisfactory. A list of all the safety factors is listed below in Table 9.

Table 9 - List of safety factors

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Safety Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load Case 1</td>
<td>4.7</td>
</tr>
<tr>
<td>Load Case 2</td>
<td>3.5</td>
</tr>
<tr>
<td>Load Case 3</td>
<td>269</td>
</tr>
<tr>
<td>Load Case 4</td>
<td>195</td>
</tr>
<tr>
<td>Load Case 5</td>
<td>18</td>
</tr>
<tr>
<td>Load Case 6.1</td>
<td>357</td>
</tr>
<tr>
<td>Load Case 6.2</td>
<td>150</td>
</tr>
<tr>
<td>Load Case 6.3</td>
<td>262</td>
</tr>
<tr>
<td>Load Case 6.4</td>
<td>37</td>
</tr>
<tr>
<td>Load Case 6.5</td>
<td>28</td>
</tr>
<tr>
<td>Load Case 7</td>
<td>4.25</td>
</tr>
</tbody>
</table>

Although Load Case 2 had a safety factor of 3.5, it was deemed acceptable because the addition of armor at a later point would dramatically increase the rigidity and strength of the system. Also the human arm can move in many different ways and this system was design to mimic that as much as possible. The human body tends to move and contort in order to prevent bodily damage. Those two factors will greatly increase the listed safety factors and provide a more robust system.
**MOTOR SELECTION**

A motor is needed to actuate at least two of the degrees of freedom. Shoulder abduction and adduction and elbow flexion and extension were selected. These movements can be seen in Figure 18, Figure 19, and Figure 22 respectfully.

$$M = 14.5\text{lb}f \times 10.7\text{in}$$
$$M = 156\text{in}lb$$

Most small DC motors are rated in inch ounces. Therefore the moment needs to be converted

$$\text{convert to inoz} = 156\text{in}lb \times .16\text{inoz}$$
$$M = 2482\text{inoz}$$

This is a very high value and no small motor can achieve this within the budget limits. A pulley system was devised to help lower the lifting load. This can be seen below in Figure 64. The total weight of the system is divided by three (18).
The new value is much lower and more reasonable. After researching several motors the Dynamixel RX-64, Appendix G, motor was selected. This motor has a torque value of 888 in oz at 18 volts. This exceeds the design 828 in oz. The pulley system will reduce the torquing requirements by 2/3.

\[
M = \frac{14.5 \text{lbf}}{3} \times 10.7 \text{in} \\
M = 52 \text{in lbf}
\]

\[
\text{convert to in oz} = 156 \text{in lbf} \times 16 \text{in oz} \\
M = 828 \text{ in oz}
\]

Figure 65 - Elbow actuating pulley system

Figure 66 - Shoulder actuating pulley system
Materials

Since the inception of the project idea, the original material has changed. During the initial brainstorming sessions it was decided that any components that would experience wear, such as the rotating rings, would be made out of wear resistant steel and the structural components, such as the side supports, would be made out of aluminum. The aluminum would reduce the overall weight of the system. As the design analysis and FEA was started. The design loads applied were simply too much for the aluminum and some of the steal components. After each test the material was changed for a stronger one.

The final material for all parts was set to AISI 4140 Steel. It will also have heat treating performed on it. It will be normalized at 870°C, reheated to 845°C (1550°F), oil quenched, and tempered at 205°C (19).

The complete Bill of Materials can be found in Appendix I

Lubrication

The rotating contacting parts will be lubricated with Lucas Oil 8 oz. White Lithium Grease. This grease is recommended for several all-purpose jobs. Some of them include all weather, all temperature, home, farm, auto and marine lubricating needs. It also protects against rust. Additional details can be found in Appendix H.

Surface Treatment

The entire assembly will be black-oxidized. The design team is doing this because of the following reasons (20):

- **No dimensional changes:** The as-formed dimensions do not change (as they do when plated or painted). Black oxide is a coloring of the base metal, no metal is removed or deposited.
- **The finish will not chip, peel, flake, or rub off:** Black oxide can only be removed by mechanically or chemically removing the finish itself.
- **Reduces light glare (reflection):** Black oxide makes an excellent finished surface for moving parts such as hand tools and machine parts. The reduction in reflectivity reduces eye fatigue and is less distracting.
- **Can be coated for additional protection:** Black oxide finishes with supplementary treatments ("after-finishes") improve the appearance, abrasion resistance, and corrosion resistance of the part to which they are applied. The normal after-finishes are Oil, Wax, Lacquer, and Chromic Seals. The part configuration and the end-use will help to determine which after-finish to specify.
- **Improved lubrication characteristics:** Black oxidized parts have improved lubricity and anti-galling characteristics due to the after-finish (oil or wax) resulting in smoother running, mating parts.
- **Color change resistant to temperature:** Black oxide finishes can be exposed to a temperature of 900 degrees F. (482 degrees C.) before the color begins to change.
- **No hydrogen embrittlement:** The black oxide process does not require an acid activation nor is it an electro-process; therefore, hydrogen embrittlement is not a factor. If the parts are scaled or rusty and an acid pickle is required, any hydrogen that may have evolved will quickly dissipate in the black oxide tank (running temp. 285 degrees F). Any remaining hydrogen will be completely dissipated within 48 hours after processing.

- **No white corrosion:** The finished part does not have a "white-corrosion" state as some electro-plated parts exhibit over time. This makes black oxide an excellent finish for parts used internally on electronic components. The small white corrosive flecks are conductive and may cause an electrical short.
MANUFACTURING

A major portion of this project was the manufacturing of it. Several different machines were used. They are: HAAS VF2 Vertical Mill, Mori Seiki Lathe (with live tooling), Water-Jet Cutting Machine, Disk Grinder, assorted manual milling and lathe machines from the OCAS North Lab.

The team followed a general process for each part. A stock piece of metal was started with and then cut and ground to size with a band saw and a disk grinder. This cut the raw stock down to a more manageable size and then the grinder “trued” each piece up and provided perfectly flat sides to be later held in a vice and machined. Figure 68 shows this process with the raw stock for the shoulder arcs. These steps are actually very critical to the machining process. Having all of the sides parallel and flat to within 0.001 of an inch increases the chances for the tolerances to be maintained later, when they were fixtured in a milling or lathe machine and further machined to the correct dimensions.
Here is raw 4140 Heat Treated round stock.5 being cut to size. This piece will become all of the rotating and clamping rings. In is a piece of raw round stock being turned down in a lathe to produce one of the rings.

Figure 69 - Raw 4140 Heat Treated Steel

Figure 70 - Round stock being turned down

Figure 71 - showing the step in the wrist rotating ring

Figure 72 - Tapping the holes in the elbow rotating ring

Figure 73 - Boring out the elbow rotating ring

Figure 74 - Preparing to turn down the wrist rotating ring
The rings used the more sophisticated machines to cut them down to size. They had high tolerances and complicated machining processes that wouldn’t have been as accurate if a manual machine had performed the same process. The clamping rings were very difficult to machine. An example is shown below in Figure 75. The inner channel had to be very precise to allow the rotating rings to rotate freely.

![Clamping ring](image1)

Figure 75 - Clamping ring

Shown below in Figure 76, a clasp is being fitted up to a clamping ring to ensure that it was machined properly. In Figure 77, a locking wire is being formed into shape. A jig was used to ensure that the lengths were correct.

![Fitting a clasp to the clamping ring](image2)

Figure 76 - Fitting a clasp to the clamping ring

![Bending the locking wires in the jig](image3)

Figure 77 - Bending the locking wires in the jig

The shoulder arc was the hardest part to machine. In the figures below, the general process is shown. Total machining time was about 10 hours with 9 separate operations. The raw bar stock was first ground smooth to help with fixturing as shown in Figure 68. Figure 78 and Figure 79 show just some of the machining and fixturing steps. A series of vices and tow clamps were used to insure that the part was firmly fixed down but was still able to be machined. The part was slowly machined down enough to allow the “T” slot cutter to cut the
slot. The slot allows for the shoulder mount, Figure 80, to slide freely and rotate the shoulder arc. Figure 82 and Figure 83 show the final product. The “T” slot follows the arc nearly all of the way around it. The hard stops allow correct movement, but doesn’t permit the operator to injure them self.

Figure 78 - Machining the Shoulder Arc

Figure 79 - Fixturing the Shoulder Arc

Figure 80 - Shoulder "T" emboss

Figure 81 - Shoulder "T" slot

Figure 82 - Final shoulder arc slot

Figure 83 - Final shoulder arc hard stops
The upper arm supports are the core structure pieces in the prototype. Shown in the figures below is Lower Arm Elbow Support being machined. The raw stock was first ground smooth for fixturing. The next process involved taking the raw stock and drilling and tapping the holes for the brackets, lower arm, and elbow rotating ring. The holes were then used to bolt this plate to another one with the same bolt pattern. The outline of the part was then machined. On the last cycle, the bit cut into the bottom plate and made a final pass. This cut the part completely out of the plate.

The Upper Arm Left/Right Supports were machined in a different fashion. The raw stock was again ground square for fixturing, but the part itself was not bolted to another plate. It was machined down while in a vice clamp. Simple machine cutting process reviled most of the geometric shapes. The Prototrak was used for the more complex radiiuses. The machining process can be seen below in Figure 88 through Figure 91.
Once a part was complete, they were polished and de-burred with a file. This process helped protect the operator from cuts and also improve the fit ups of the other parts.
After each step the parts were measures to insure that they are the correct size. There was little room for error. The design required lots of moving parts that must be correct for everything to work properly together. If a dimension was off by more than a few thousands then parts would out of alignment and cause additional friction. This would ultimately cause binding of the system, restricting movement of the operator. The measuring process can be seen below in Figure 92.

The entire project was able to be kept within the tolerances assigned. Each part tolerances varied depending on the role it played. The side supports had slightly lowered tolerances witch enabled a little more leniency when manufacturing. The rotating rings required higher tolerances. The rings rotated within the clamping rings. If the tolerances were too lax, then the rings would not rotate freely due to too much friction against the walls.
ASSEMBLY

Assembling the Shoulder

1. Attach the Shoulder Mount bracket to the ball joints located on the shoulder pads

NOTE: APPLY LUCAS OIL WHITE LITHIUM GREASE TO THE “T” SLOT BEFORE ASSEMBLING.

2. Slide the Shoulder Track Arc “T” slot around the “T” emboss on the Shoulder Mount making sure that the cut out portion of the arc is pointing down.

NOTE: APPLY LUCAS OIL WHITE LITHIUM GREASE TO THE CONTACT POINTS OF THE UPPER ARM SUPPORTS BEFORE ASSEMBLING.

3. Use two (2) 10-32 Dia.0.25” by 0.125” Lg shoulder bolts attach the Upper Arm Left Support and the Upper Arm Right Support to the Shoulder Track Arc making sure that the embosses are pointed inward, towards the center of the arm.

4. Using four (4) 8-36 Dia.0.165” by 1.25”Lg flat head screws, attach the Elbow Upper Arm Rotating Ring to the ends of each Upper Arm Support.

5. Insert two (2) Wrist Clamp Lever Pins onto the two (2) holes 180 degrees apart on the Elbow Forearm Rotating Ring.

6. Using four (4) 8-36 Dia.0.165” by 0.5” Lg flat head screws, attach the Lower Arm Elbow Left Support and Lower Arm Elbow Right Support to the Elbow Forearm Rotating Ring making sure that the Lower Arm Elbow Supports counter bore is facing away from the center of the arm.

7. Attach the Lower Arm Left Support and Lower Arm Right Support to the Lower Arm Elbow Left Support and Lower Arm Elbow Right Support with two (2) 10-32 Dia.0.25 by 0.3125” Lg shoulder bolts making sure the safety hard stop emboss is facing away from the center of the arm.

8. Position the arm so that all of the upper arm and lower arm side supports are parallel with each other and the Lower Arm Elbow Left/Right Support 0.75” radius’s are pointing upwards from the table.

9. Attach two (2) PK32KD3B2100-051 Planetary Gear Brushed Motors using eight (8) M3 bolts and washers bolting through the Motor Mount and into the motors.

10. Attach the two (2) pulleys to the motors and tighten the set screw.

11. Attach the Motor Mount to the Shoulder Support Bracket Top with three (3) 8-32 Dia.0.164” 0.5” Lg button head cap screws.

NOTE: IT IS ADVISABLE TO INSTALL THE WRIST ROTATING JOINT UPPER ARM RING OR WRIST ASSEMBLY AT THIS POINT. WITHOUT IT, ASSEMBLY OF THE BRACKETS MAY BE DIFFICULT.

12. Assuming the arm is in the same orientation, install the Shoulder Support Bracket Top to the top of the Upper Arm Left/Right Supports with eight (8) 8-32 Dia.0.164” 0.5” Lg button head cap screws making sure that the two motors are on the right side of the arm.
13. Attach the Shoulder Support Bracket Bottom to the bottom of the Upper Arm Left/Right Supports in the four (4) remaining holes with four (4) 8-32 Dia. 0.164” 0.5” Lg button head cap screws.

14. Attach the Bicep Support Bracket Top to the top of the Lower Arm Elbow Left/right Support in the four (4) holes closest to the Elbow Forearm Rotating Ring with four (4) 8-32 Dia. 0.164” 0.5” Lg button head cap screws.

15. Attach the Shoulder Support Bracket Bottom to the bottom of the Upper Arm Left/Right Supports in the eight (8) remaining holes with eight (8) 8-32 Dia. 0.164” 0.5” Lg button head cap screws.

16. Attach the Forearm Support Bracket to the bottom of the Lower Arm Left/Right Supports with twelve (12) 8-32 Dia. 0.164” 0.5” Lg button head cap screws.

17. Attach the Forearm Support Bracket to the top of the Lower Arm Left/Right Support in the eight (8) remaining holes in the Lower Arm Left/Right Supports with four (4) 8-32 Dia. 0.164” 0.5” Lg button head cap screws.

18. Install the Wrist Clamp Wire Loop into the Wrist Clamp Lever by inserting the ends of the wires into the two holes the farthest away from the radius.

19. Insert a 0.0625” pin into the holes closest to the radius of the Wrist Clamp Lever and through the Elbow Clamp Left making sure that when the Wrist Clamp Lever is flat against the Elbow Clamp Left it is not protruding over the end of the Elbow Clamp Left.

20. Install the Elbow Wrist Clamp Pin into the mating holes in the Elbow Clamp Right and Elbow Clamp Left.

NOTE: APPLY LUCAS OIL WHITE LITHIUM GREASE TO THE CONTACTING SURFACES OF THE ELBOW ROTATING RINGS. ALSO APPLY LUBRICATION TO THE INSIDE CHANNEL ON BOTH CLAMPING RINGS BEFORE ASSEMBLING.

21. Mate the Elbow Upper Arm Rotating Ring and the Elbow Forearm Rotating Ring
22. Using the Elbow clamp, join the two rings together and lock in place with the Elbow Clamp making sure that the Wrist Clamp Lever is on top of the rings.
23. Proceed to the Wrist Assembly instruction on completing the assembly.

WEARING THE PROTOTYPE

1. To wear the prototype, put on protective clothing to prevent injury.
2. Slide right arm through the shoulder zone and place the shoulder pads on the torso of the operator.
3. Tighten the straps to secure the shoulder pads.
4. Slide arm through the elbow zone while holding your hand palm up.
5. Mate the Elbow Upper Arm Rotating Ring and the Elbow Forearm Rotating Ring
6. Using the Elbow clamp, join the two rings together and lock in place with the Elbow Clamp making sure that the Wrist Clamp Lever is on top of the rings.
7. Slide hand through the wrist.
8. Proceed to the Wrist Assembly instruction on completing the instillation.
TESTING

Testing was a major concern for this project. The Customer Feed Back, Objectives, and Characteristics section outlines the objective for this project. Correct degrees of freedom and range of motion were the key goals that this project was designed to achieve.

Several criteria will be used to test this proof of design. These are selected in a way that covers the most important factors of this project. They test for proper degrees of freedom, proper ranges of motion, and ease of assembly amongst others. If these are achieved within reason, then the overall design was a success and agrees with the questionnaire that was sent to the possible customers.

RANGE OF MOTION

Table 8 above shows that every degree of freedom was obtained. Not all of the range of motion was achieved though. Some joints had almost 50% reduction in movement. The design team still thinks that this is acceptable because at least some motion was able to be translated in that direction; that was the goal of this project. With more time and possibly a larger design team, these ranges could be improved to near identical to the human body. The shoulder was the area seeing the large reduction of movement. There are a lot of complicated parts that mush work in unison to obtain these movements. If they don’t work together it causes the system to bind or injure the operator. Having the system fully powered would help with this. The operator wouldn’t have to physically move the system around. Each motor could detect the movement that the operator wants and move each component into the right position in order to obtain certain positions. The system ranges of motions were by actuating each degree of freedom and following it with a protractor. Shown below in Figure 93 and Figure 94 is just an example of the measuring process. This process was done for each joint and the measurements were double checked against the 3D model as well. A member of the design team tried the prototype on and preformed some basic range of motion exercises; movements such as raising the arm in any direction. Also, a small baseball sized box was thrown to show that it was possible.
**LUBRICATION**

Each joint was lubricated to ensure smooth motion. Lucas Oil White Lithium Grease was used for this. The lithium grease was a thick compound that stuck to the parts and only came off while cleaning them. The semi viscous liquid smoothed the rotation of the parts out. There was no binding and the joints rotated smoothly. The joints were very easy to control with just the motion of the operators arm in the prototype. The thickness also ensured that the grease would stay on the parts for an extended period of time to prevent wear. If these parts wore down they would create a very fine metal dust that could build up and cause the parts to bind. This is unacceptable for a system such as this that could be used in the battlefield when lives are at stake.

**DURABILITY**

The system is very durable. Almost all of the components were made out of 4140 Heat Treated Steel with a very high Yield Strength. Also, 4120 Heat Treated Steel is still classified as ductile steel. This allows the structure to absorb inputted energy, such as an impact from a bullet, and disperse it in lateral movement by flexing slightly before returning to its original state. The lubrication also helps here. The lubrication prevents wear on both the parts themselves and improves the longevity of the powering system. Each bolt in the system was torqued to the correct value and Loctited into place to prevent unwanted backing out of the bolts.

**EASY TO REPAIR AND MAINTAIN**

This system is fully modular. It was designed and built in three distinct and separate zones. As shown in Figure 28, these zones are connected to each other with the Clamping Rings. Each zone can be quickly and easily added or removed if needed. The system also contains no welds. Each part is bolted on and can be easily replaced if it gets damaged. All of the fasteners used were commercially bought and not made. This allows for even faster and easier repairs.

**EASY TO OPERATE**

The system was very easy to operate. The only pre-requisite of the use of this system is to learn one “learned movement”. That movement is only seen when the operator lift his/her arm out to the right and then wants to rotate it out in front. The operator first must lower the arm; rotate it up and in front and then out to the right of the operator. Other than that, the movements follow close to the natural normal body movements, making it very easy to operate. A third party member was allowed to try the system on to determine how long it took to understand and use it. The user figured it out nearly instantly due to the correct degrees of freedom and close to correct ranges of motion.
**LIGHTWEIGHT**

During the design phase, Solidworks was used to determine the total weight of the system. Solidworks determined that it would weigh less than 15 pounds. Once the fabrication was completed it was weighed on a scale. The indicator pointed to just under 15 pounds like Solidworks had said. The design team had a goal to shoot for less than 40 pounds. 15 pounds is obviously much lower than that.

**ERGONOMIC FIT**

The system had a very good fit to the human arm. There were a few spots that rubbed against the operator but the padding prevented injury. Simple design changes could alleviate nearly all of these issues. The use of the shoulder pads provided a great mounting surface that conformed to the operator’s body.

**COMPACT DESIGN**

The system was very streamlined and followed the operators arm. The only protruding parts were the motors. In future designs they would be relocated or a new smaller motor would be chosen.

**LOUDNESS**

The system was tested for how loud it was. It was compared to an electric razor. With both motors running it was still quieter that the electric razor.

**LOW COST**

Cost was the last feature that customers deemed important. With the military as the most likely customer, cost is second to operator safety. As seen in the budget in Table 11 the prototype cost far less than originally budgeted. This is mostly due to less expensive controls and motors, and material and machine time being donated.
DESIGN CHANGES AND RECOMMENDATIONS

*MOTORS, MASS PRODUCTION, DESIGN CHANGES*

After researching further a different motor was chosen to power the system. The original motors Dynamixel RX-64 required extensive coding knowledge. This proved un-feasible due to the time constraints. In future builds these motors, or similar, would be very promising. They could be individually programmed to operate the different joints. The high customizability and output torque would be favorable when powering the entire system. The PK32KD3B2100-051 Planetary Gear Brushed Motors were chosen for their high torque output and relatively small size. The new motors were tried out during testing and performed flawlessly. They worked better than expected. The team was planning on having to add a pulley system to help the motors lift the arm. These motors were strong enough to do it without a pulley system. They were so strong that they snapped one of the cables during testing. Still an even small motor is recommended in future builds with an actual control system to actuate them.

In order for this prototype to be mass produced only a few changes would be needed. The main concern is the material. This project was fabricated out of already heat treated 4140 Steel. This lead to long machining times due to the time it took to cut the hardened material. If the parts were machined and then heat treated, the system could be built faster. Another area of concern was the rotating rings, especially the wrist clamping rings. The clamps were machined on a lathe and then cut in half to create each side of the clamp. When the ring was cut in half, the internal stresses of the already hardened material caused the clamping rings to bend, ultimately giving it a smaller radius. When it came time to assemble the project, then clamping rings were now too small to fit around the rotating rings. The channels in each clamping ring had to be ground down by hand and custom fit to the wrist rotating rings. This process took a very long time. If the parts were machined before heat treating, then the internal stresses would not have been so high, causing this error.

As stated before, one of the major design changes would be to heat treat the material after machining the parts out. This would decrease machine time, reduce costs, reduce the amount of internal stresses the parts had, and speed up production. Another design change would be to redesign the brackets. As they are now, some of them were required to be very thick to help disperse the stresses when loaded. Because they were thick, it became hard to bend the pieces with the break press in the OCAS North Lab and one piece had to be sent to Spring Grove Sheet Metal to have the bends completed. Also, it was very hard to bend the brackets to exactly 45 degrees. The break was designed to bend to 90 degrees. The brackets had to be taken out of the break to be measured with a protractor. If the angle was off, it was bent the rest of the way by hand in a vice. This added machine time and caused problems later when assembling the entire system. Using a bigger break would yield better brackets. A different design might alleviate some of these problems.

A new design for the Shoulder Mount is needed. The current design for the “collar bone” seemed to impede movement contrary to the 3D model. It is believed to have just been too short causing it to rub against the shoulder pads.
SCHEDULE AND BUDGET

SCHEDULE

The timeline for this project is shown below in Table 10. For a more detailed schedule refer to Appendix E. The Design Freeze signals the time where no major design changes will be permitted.

<table>
<thead>
<tr>
<th>Important Milestone Dates</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design Freeze</td>
<td>February 4, 2012</td>
</tr>
<tr>
<td>Final Modeling</td>
<td>February 4, 2012 - February 14, 2012</td>
</tr>
<tr>
<td>Purchasing</td>
<td>February 18, 2012 – March 27, 2012</td>
</tr>
<tr>
<td>Fabrication</td>
<td>March 10, 2012 – April 10, 2012</td>
</tr>
<tr>
<td>Assembly</td>
<td>March 31, 2012 – April 24, 2012</td>
</tr>
<tr>
<td>Testing</td>
<td>April 14, 2012 – May 1, 2012</td>
</tr>
</tbody>
</table>

Table 10 - Project schedule

As this project progressed, the approximate dates were updated to show completion times of each sub-project. This updated schedule can be found in Appendix E.
BUDGET

Listed below, Table 11 is a general list of supplies needed to complete this project. The total cost of the project is expected to be just under $11,250.00. After design changes, purchasing supplies and receiving donations from companies, the final system only cost $3,119.38. This is far less than was originally for casted. A major deduction in cost was the machine time. Some of it was donated, but most of it was done by the design team. Another significant reduction was in the motor selection. A comparable motor was found for far less than was budgeted.

Table 11 - Expected and final budget

<table>
<thead>
<tr>
<th>Item</th>
<th>Forecasted Cost</th>
<th>Actual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Trip</td>
<td>$1,500.00</td>
<td>$1,500.00</td>
</tr>
<tr>
<td>Batteries</td>
<td>$400.00</td>
<td>$307.28</td>
</tr>
<tr>
<td>Control Electronics</td>
<td>$1,500.00</td>
<td>$538.48</td>
</tr>
<tr>
<td>Mounting Brackets</td>
<td>$200.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Wires</td>
<td>$200.00</td>
<td>$66.18</td>
</tr>
<tr>
<td>Motors (2)</td>
<td>$1,600.00</td>
<td>$107.98</td>
</tr>
<tr>
<td><strong>Controls Sub Total</strong></td>
<td><strong>$5,400.00</strong></td>
<td><strong>$2,519.92</strong></td>
</tr>
<tr>
<td>Aluminum Plate</td>
<td>$1,000.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Steel Round and Plate</td>
<td>$800.00</td>
<td>$333.96</td>
</tr>
<tr>
<td>Bolts and Fasteners</td>
<td>$400.00</td>
<td>$159.84</td>
</tr>
<tr>
<td>Consumable Tooling</td>
<td>$500.00</td>
<td>$64.03</td>
</tr>
<tr>
<td>Machine Time</td>
<td>$2,500.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Heat Treating</td>
<td>$400.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Mounting Apparatus</td>
<td>$250.00</td>
<td>$41.63</td>
</tr>
<tr>
<td><strong>Material Sub Total</strong></td>
<td><strong>$5,850.00</strong></td>
<td><strong>$599.46</strong></td>
</tr>
<tr>
<td><strong>GRAND TOTAL</strong></td>
<td><strong>$11,250.00</strong></td>
<td><strong>$3,119.38</strong></td>
</tr>
</tbody>
</table>

The schedule outlines a general guide for this project. Important dates have been marked to keep the design team on schedule. The design team will source materials while keeping a close eye on the budget as not to go over the estimated cost.
**Final Project View**

This assembly view, Figure 95, depicts the right arm extended out from the side of the body with the palm of the hand facing up.

![Final Project View](image)

Figure 95 - Final Design
DRAWINGS

The two dimensional drawings and assembly drawings for manufacturing this project are located in Appendix J.
TECH EXPO

The project was completed on time to display at the University of Cincinnati Tech Expo. Shown in Figure 96, Figure 97, and Figure 98 below, are some pictures displaying the project and the outcome.

Figure 96 - Complete assembly at Tech Expo

Figure 97 - A.R.E.S. Tech Expo poster

Figure 98 - Operator wearing the prototype
CONCLUSION

The exo-skeleton is the future of warfare. The ultimate soldier on the battlefield would be unstoppable while wearing an exo-skeleton. This prototype is just a step in the long road to developing a full encompassing protective suit. The development of this prototype carries the ambition to help protect people in hostile environments in the future. Safety should be and is the most important right our soldiers should be guaranteed when facing danger. This project is viewed as a success by fulfilling the customers’ requirements. This was accomplished by protecting the operator, allowing normal range of motion, being durable, modular, amongst others. These were then implemented into the design. The fabrication of the project brought the ideas to life. Testing proved that this concept is possible and effective. This idea must be continued to be worked on to make the battlefield a little safer for those who fight in it. soldiers.
SPECIAL THANKS TO

The design team would like to thank the many people and companies that help with this project. They provided valuable insight, donations, ideas, and professional knowledge. Without them, this project would have been far less fruitful.

A Special Thanks To:

- Curtiss Myers (HAAS)
- Spring Grove Sheet Metal
- The Work Force Development Agency
- Anthony Ricciardi (University of Cincinnati)
- JF Berns Company
- Kevin Bevan (GBI Cincinnati)
- Valerie Hill (Xavier University - Occupational Therapy)
- Donald Hutson (Neuroscience Institute)
REFERENCES

http://matweb.com/search/DataSheet.aspx?MatGUID=8e87bc1cf20343b985b1a46a1f1eb1c3.
This impressive breakthrough in robotics technology is being developed by Steve Jacobsen and the engineers at Sarcos; a robotics company that he founded in 1983 and was purchased by Raytheon. The engineers at Sarcos realized that this exoskeleton would require the ability to mimic the soldier’s movements perfectly in order for it to be successful. Therefore, they created flexible joints so that it can adapt to the versatile movements of the human wearing it; and made it capable of performing fluid, precise tasks. The major benefits for the soldier wearing the suit is that it will make the subject faster, stronger and more resistant to fatigue. In some tests the XOS was used to lift 200 pounds repetitively for 500 repetitions before the user stopped; it should be noted that the reason for stopping was out of boredom and not due to fatigue.

The major hurdle for Sarcos is that they need to develop a continuous power source that will allow the XOS to function for 4 to 24 hours. Sarcos predicts that the first versions will be used for heavy work rather than combat until a solution to this problem can be negotiated. This type of technology makes the sci-fi world of Robocop more realistic than we previously imagined.
Specific stats on the Trojan are as follows: 90% flexibility, 95% body coverage. The Trojan allows the wearer to drive vehicles, run full-tilt, climb stairs and conduct dive roll maneuvers. The Trojan weighs a mere 30 pounds without the Trojan shield. The Trojan incorporates 16 different electronic functions and prototypes impregnated into its exoskeleton. Some of the Trojans key features are a laser tracking system, 5 L.E.D. light spectrums, a voice recorder, a voice activated pedometer, a digital electronic compass, built in compartments for salt tablets and morphine pills, a digital thermometer, a built in intake cooling fan which runs on solar power, a throwing and knife, a medical emergency light transponder and much more.

http://christianburns.wordpress.com/2007/02/19/trojan-suit-full-body-armor-failed-to-sell-on-ebay/

7/15/11 Trojan Suit Armor made by Troy Hurtlebis

http://www.metacafe.com/watch/528600/the_trojan_suit/

Never been tested in the field
Too many gizmos
Cheap to produce
Light weight
Not powered
Covers most of the body
Near full range of motion
Durable
Not low profile
Somewhat streamlined
One man assembly
No hard limit
"Robot Suit HAL" is a cyborg-type robot that can expand and improve physical capability.

When a person attempts to move, nerve signals are sent from the brain to the muscles via motor neurons, moving the musculoskeletal system as a consequence. At this moment, very weak biosignals can be detected on the surface of the skin. "HAL" catches these signals through a sensor attached on the skin of the wearer. Based on the signals obtained, the power unit is controlled to move the joint unitedly with the wearer’s muscle movement, enabling to support the wearer’s daily activities. This is what we call a ‘voluntary control system’ that provides movement interpreting the wearer’s intention from the biosignals in advance of the actual movement. Not only a ‘voluntary control system” “HAL” has, but also a ‘robotic autonomous control system’ that provides human-like movement based on a robotic system which integrally work together with the ‘autonomous control system’. “HAL” is the world’s first cyborg-type robot controlled by this unique Hybrid System.

“HAL” is expected to be applied in various fields such as rehabilitation support and physical training support in medical field, ADL support for disabled people, heavy labour support at factories, and rescue support at disaster sites, as well as in the entertainment field.

<table>
<thead>
<tr>
<th>HAL-5 Type-5 Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
</tr>
<tr>
<td>wearable robot</td>
</tr>
<tr>
<td>Height 1,600mm</td>
</tr>
<tr>
<td>Weight</td>
</tr>
<tr>
<td>Full Body Type approx. 23kg</td>
</tr>
<tr>
<td>(Lower body approx. 15kg)</td>
</tr>
<tr>
<td>Power</td>
</tr>
<tr>
<td>Battery Drive</td>
</tr>
<tr>
<td>Charged battery( AC100V)</td>
</tr>
<tr>
<td>Continuous operating time</td>
</tr>
<tr>
<td>Approximately 2 hours 40 minutes</td>
</tr>
<tr>
<td>Motions</td>
</tr>
<tr>
<td>Daily Activities( standing up from a chair, walking, climbing up and down stairs)</td>
</tr>
<tr>
<td>Hold and lift heavy objects and more...</td>
</tr>
<tr>
<td>Operation</td>
</tr>
<tr>
<td>Hybrid Control System</td>
</tr>
<tr>
<td>Working Environment</td>
</tr>
</tbody>
</table>

- Light weight
- Near full range of motion
- Overly powered
- Expensive
- Little operator protection
- Not designed for combat
- Designed For rehab
- Easy operation
- Operating life: mediocre
- Fluid motion
- Ergonomic
- Streamline designed
- Takes load from operator

http://www.cyberdyne.jp/english/robotsuithal/ 7/15/11
HAL Suit Cyberdyne
Berkeley Bionics, a designer and manufacturer of exoskeletons for augment human strength and endurance, has introduced a device that increases its wearer’s strength while at the same time decreasing the “metabolic cost of walking.” The demonstrated exoskeleton is comprised of two powered anthropomorphic legs, a power unit, small on-board microcomputer, and a backpack-like frame on which a variety of heavy loads can be mounted. Such a system allows the user to carry loads of up to 150 pounds with minimal physical effort, over any type of terrain for extended periods of time. According to the company, the wearer simply doesn’t feel the backpack’s weight, as the exoskeleton moves in accordance with the user movements, minimizing interaction force between the two.

http://thefutureofthings.com/video/6647/artificial-strength.html 7/15/11
Berkeley Bionics,

<table>
<thead>
<tr>
<th>Light weight</th>
<th>Near full range of walking motion</th>
<th>Overly powered</th>
<th>Expensive</th>
<th>Almost no operator protection</th>
<th>Designed for combat</th>
<th>Easy operation</th>
<th>Operating life: mediocre</th>
<th>Fluid motion</th>
<th>Ergonomic</th>
<th>Streamline designed</th>
<th>Get in and out of it fast</th>
<th>Durable</th>
<th>Takes load from operator</th>
</tr>
</thead>
</table>

Appendix A4
Eythor Bender of Berkeley Bionics brings onstage two amazing exoskeletons, HULC and eLEGS -- robotic add-ons that could one day allow a human to carry 200 pounds without tiring, or allow a wheelchair user to stand and walk. It's a powerful onstage demo, with implications for human potential of all kinds.
Dean Kamen’s "Luke arm"—a prosthesis named for the remarkably lifelike prosthetic worn by Luke Skywalker in Star Wars—came to the end of its two-year funding last month. Its fate now rests in the hands of the Defense Advanced Research Projects Agency (DARPA), which funded the project. If DARPA gives the project the green light—and some greenbacks—the state-of-the-art bionic arm will go into clinical trials. If all goes well, and the U.S. Food and Drug Administration gives its approval, returning veterans could be wearing the new artificial limb by next year.

The Luke arm grew out of DARPA’s Revolutionizing Prosthetics program, which was created in 2005 to fund the development of two arms. The first initiative, the four-year, US $30.4 million Revolutionizing Prosthetics contract, to be completed in 2009, led by Johns Hopkins Applied Physics Laboratory in Laurel, Md., seeks a fully functioning, neurally controlled prosthetic arm using technology that is still experimental. The latter, awarded to Deka Research and Development Corp., Kamen’s New Hampshire–based medical products company (perhaps best known for the Segway), is a two-year $18.1 million 2007 effort to give amputees an advanced prosthesis that could be available immediately "for people who want to literally strap it on and go.” Kamen’s team designed the Deka arm to be controlled with noninvasive measures, using an interface a bit like a joystick.
A pneumatic cylinder fed with compressed-air, combined with a transmission lever system, provides balance to the load weight applied.
The cylinder force is controlled through two pneumatic circuits purposely arranged: the first one always keeps the weight system balanced; the second one provides to always keep the weight load balanced.
The operator can change the load level applying a minimum force on the gripping tool or directly on the load.

**Technical characteristics of pneumatic Manipulators**

**Partner PS**

- Max weight capacity 250 Kg
- Max working radius: 3400 mm
- Max vertical lifting speed: 0,5 meters/second
- Constant 360° rotation on the column and tooling axis
- Vertical lift: 1900 mm
- Control system: solely pneumatic
- Supply: filtrated compressed-air (40 µm), not lubricated
- Working pressure: 0.7 ÷ 0.8 Mpa
- Working temperature: from +0° to +45° C
- Noise level: <70 dB
- Consumption: from 30 Nl ÷ 150 Nl per working cycle
- The explosion-proof execution is possible according to ATEX Standard

http://www.dalmec.com/ing/manipulators/Industrial_manipulators_Partner_PS.htm

17/18/11 Google search: Industrial Manipulator

Not exoskeleton
Limited field of motion
Good range of motion
Fluid motion
Takes load from operator
Lifts heavy loads
Easy to use
Material handling uses
Durable
Operated by one person
Hard safety limits
Expensive
The Mayo Clinic Elbow Brace, featuring an innovative control knob and adjustable hinge, provides exceptional stability and comfort while allowing for immobilization, static stretch or free motion option of the elbow.

The sturdy metal uprights provide stability, while the straps with aircells securely hold the brace in position which ensures patient comfort and avoid pressure points.

**The Mayo Clinic Elbow Brace Features:**

- Lock/unlock mechanism enables a rapid switch between immobilization, static stretch, and free ROM
- Calibrated control knob is easy to read and assists in monitoring therapy progress
- Repositionable hinge stops control ROM
- Universal design can be applied to right or left arm
- Size adjustment feature accommodates varying humeral/radial circumferences
- Includes Arm Sling for patient comfort
- Optional ARC™ Forearm Rotational Brace controls pronation/supination (sold separately)


7/18/11
Google search: Arm Brace

---

Appendix A8
Myomo® is a new generation medical device company that has combined innovative robotics technology with leading rehabilitation expertise to revolutionize stroke therapy. Myomo's technology was originally developed at Massachusetts Institute of Technology (MIT) in collaboration with medical experts affiliated with Harvard Medical School. Its rehabilitation professionals have been trained at the best hospitals in the country including, Rehabilitation Institute of Chicago (RIC), New York University (NYU) and UPMC.

Patented EMG (electromyography) control software continuously monitors and senses, but does not stimulate, the affected muscles. The patient self-initiates and achieves natural movement patterns by their own muscular signals that indicate intention to move. The system senses even a very weak EMG muscle signal and then processes data to a motor on the device that enables desired motion. This processing occurs so quickly that it is not apparent to the patient. Importantly, EMG-driven robotics requires that patients are actively engaged throughout the therapy session; if they stop, the device stops. No electrical stimulation or invasive procedures are employed.

http://www.myomo.com/  7/18/11 Google search: MYOMO

Not exoskeleton
Hard safety limits
Not designed for combat
Designed for rehab
Low power consumption
One person use
Ergonomic
Expensive
Uses operators brain signals to control.
Interview with customer, August 4, 2011
First Lieutenant Brent Kreckman USMC Pilot 7157 Pine Blossom Rd. Milton Florida 32570 (937) 631-8994

Power source needs to be cheap
Infantry less prone to have a full suit
(Person) Needs to be mobile all the time
Needs to be low profile
Carries 150 lbs. Guns, food, supplies, ammo, armor (20-40lbs),
Could drop it if needed (disposable, cheap)

Combat engineers: mine clearing, building Forward Operating Base
Motion common for combat engineers: getting up and down a lot, overall small size, to get closer to disarm explosives,
Bomb workers: needs fast motion, normal range of motion, easy and fast assembly of suit, suit needs little maintenance must be simple, make sure it doesn’t make the user excessively large, hands completely free with full range of motion,
Armor now is very restrictive, hard to move with current armor, hard to throw a grenade.

Be able to hold a M16/M4 (collapsible but stock) rifle, may have a three point sling.
Arms to bring the rifle up to shoot and aim. Keep the butt stock against the armpit/shoulder.
Elbows and knees see the most ware and tare from getting up and down.
APPENDIX B - SURVEY

Assisted Robotic Exo-Skeleton (A.R.E.S.)
CUSTOMER SURVEY

The project is to develop a portion of an external skeletal structure in which to later mount armor to. This proof of concept design will focus on protecting the arm of an operator in hostile environments, not give it super strength. By answering these questions below you will help determine the relative importance of each feature.

How important is each feature to you for the design of an exo-skeleton?
Please circle the appropriate answer. 1 = low importance 5 = high importance

<table>
<thead>
<tr>
<th>Feature</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>N/A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smooth Motion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Normal Range of Motion</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Safe for the operator/bystanders</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Be Light Weight</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Easy to Operate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Easy to Repair/ Maintain</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Have a Compact Design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Be Durable</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Low Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Have an ergonomic fit</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
<tr>
<td>Loudness</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N/A</td>
</tr>
</tbody>
</table>

If you would like to donate or have any questions, please contact Nick Plataniotis or Frank Ricciardi for further information. Any contribution would be greatly appreciated.

Nick Plataniotis – platanna@mail.uc.edu
Frank Ricciardi – ricciafn@mail.uc.edu

Thank you for your time.
## APPENDIX C – QUALITY FUNCTION DEVELOPMENT CHART

<table>
<thead>
<tr>
<th>Feature</th>
<th>Smooth Motion</th>
<th>Normal Range of Motion</th>
<th>Safe for the operator/bystanders</th>
<th>Be Light Weight</th>
<th>Easy to Operate</th>
<th>Easy to Repair/ Maintain</th>
<th>Have a Compact Design</th>
<th>Be Durable</th>
<th>Low Cost</th>
<th>Have an ergonomic fit</th>
<th>Loudness</th>
<th>Abs. importance</th>
<th>Rel. importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force to change directions (in-lbs)</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>9</td>
<td>1</td>
<td>-1</td>
<td>1</td>
<td>1.32</td>
<td>0.09</td>
</tr>
<tr>
<td>Range of Motion (deg.)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1.44</td>
<td>0.09</td>
</tr>
<tr>
<td>Safety Factor (#)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>3</td>
<td>9</td>
<td>3</td>
<td>3</td>
<td>1.79</td>
<td>0.14</td>
</tr>
<tr>
<td>Weight (lb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>0.96</td>
<td>0.12</td>
</tr>
<tr>
<td>Sensors or switches (y/n)</td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>0.92</td>
<td>0.06</td>
</tr>
<tr>
<td>Training Time (hrs.)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>2.19</td>
<td>0.06</td>
</tr>
<tr>
<td>Assembly/Maintenance (as of people)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>0.29</td>
<td>0.06</td>
</tr>
<tr>
<td>Modular Assembly (y/n)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>0.10</td>
<td>0.05</td>
</tr>
<tr>
<td>Drive system Contained (y/n)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>0.47</td>
<td>0.05</td>
</tr>
<tr>
<td>Cost ($)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>1.51</td>
<td>0.05</td>
</tr>
<tr>
<td>Operator Protected (y/n)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>0.77</td>
<td>0.04</td>
</tr>
<tr>
<td>Decible level (db)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>15.5</td>
<td>0.01</td>
</tr>
<tr>
<td>Customer importance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>46.4</td>
<td>1.0</td>
</tr>
<tr>
<td>Designer's Multiplier</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Modified Importance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>0.96</td>
<td>0.09</td>
</tr>
<tr>
<td>Relative weight</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>0.92</td>
<td>0.09</td>
</tr>
<tr>
<td>Relative weight %</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
<td>9</td>
<td>9</td>
<td>3</td>
<td>1.92</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Frank Ricciardi Nick Plataniotis
(A.R.E.S.) Assisted Robotic Exo-Skeleton (arm)
9 = Strong
3 = Moderate
1 = Weak
APPENDIX D – PRODUCT OBJECTIVES

Product Objectives

Assisted Robotic Exo-Skeleton (A.R.E.S.)

The following is a list of product objectives and how they will be obtained or measured to ensure that the goal of the project was met. The product objectives will focus on a portion of an exo-skeleton suit. We are focusing on the right arm. The project is to design an adequate skeletal structure to protect the operator. The prototype arm will not be customizable and will be designed for a specific individual. The arm will not have power enhancing features, but it will be motorized enough to hold its own weight including estimated armor weight.

Normal Range of Motion (11.8%)
• Normal ranges of motion will be referenced from cited texts.

Smooth Motion (10.9%)
• Joints will be lubricated.
• Moving parts will not contact others causing them to bind.

Safe for the operator/bystanders (10.3%)
• Pinch points will be designed out or the operator will be guarded against them.
• An Emergency Stop will be included.
• Hard safety stops will be included into the joints to prevent hyperextension.

Be Durable (9.9%)
• Fasteners will be Grade 8 or equivalent.
• Safety factor from cited texts.
• Correct materials will be chosen according to the design loads.
• Loctite will be applied to the fasteners to prevent them from backing out.
• A factor of safety agreeing with cited texts.
• All bolts will be tightened to the allowable torque in cited texts.
• Electrical connections will be soldered and then covered with heat wrap if needed.

Easy to Repair/ Maintain (9.7%)
• All fasteners will be bought and not made.
• Parts will not be welded.
• Sections will be modular.
• Quick connect electronic connectors will be used.

Easy to Operate (9.0%)
• Approximately 3 hours of training will be enough to qualify someone to be able to use it.
• No more than two people will be needed to assemble and put on the hardware.
• It will be easily controlled through sensors or switches.

**Be Light Weight (8.8%)**
• The arm will weigh less than 50 pounds, excluding armor.

**Have an Ergonomic Fit (8.4%)**
• The operator will be protected from coming in contact with the hardware.

**Have a Compact Design (7.4%)**
• All drive and control systems will be contained in the skeleton.

**Loudness (7.3%)**
• The arm will be no louder than an electric shaver.

**Low Cost (6.5%)**
• Easily obtainable materials and fasteners such as steel or aluminum will be used for construction.
APPENDIX E - SCHEDULE

<table>
<thead>
<tr>
<th>Nick Plataniotis</th>
<th>Frank Ricciardi</th>
<th>A.R.E.S. (Exo-Skeleton)</th>
</tr>
</thead>
</table>

**TASKS**  
Proof of Design to advisor 23  
Concept sketches to advisor 23  
Initial Modeling 17  
Design Freeze 4  
Final Modeling 14  
Powered Movement Solid Works Modeling 14  
Oral Report 28  
Design Report 6  
Purchase Material 27  
Fabricate 10  
Assemble 24  
Field Test 1  
Tune 1  
Advisor Demo 8  
Faculty Demo 15  
Oral Report 29  
Final Report 22

*KEY*  
Proposed Schedule  
Key Event Deadlines  
Actual Timeline
# APPENDIX F – BUDGET

<table>
<thead>
<tr>
<th>Item</th>
<th>Forecasted Cost</th>
<th>Actual Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Research Trip</td>
<td>$1,500.00</td>
<td>$1,500.00</td>
</tr>
<tr>
<td>Batteries</td>
<td>$400.00</td>
<td>$307.28</td>
</tr>
<tr>
<td>Control Electronics</td>
<td>$1,500.00</td>
<td>$538.48</td>
</tr>
<tr>
<td>Mounting Brackets</td>
<td>$200.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Wires</td>
<td>$200.00</td>
<td>$66.18</td>
</tr>
<tr>
<td>Motors (2)</td>
<td>$1,600.00</td>
<td>$107.98</td>
</tr>
<tr>
<td><strong>Controls Sub Total</strong></td>
<td><strong>$5,400.00</strong></td>
<td><strong>$2,519.92</strong></td>
</tr>
<tr>
<td>Aluminum Plate</td>
<td>$1,000.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Steel Round and Plate</td>
<td>$800.00</td>
<td>$333.96</td>
</tr>
<tr>
<td>Bolts and Fasteners</td>
<td>$400.00</td>
<td>$159.84</td>
</tr>
<tr>
<td>Consumable Tooling</td>
<td>$500.00</td>
<td>$64.03</td>
</tr>
<tr>
<td>Machine Time</td>
<td>$2,500.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Heat Treating</td>
<td>$400.00</td>
<td>$0.00</td>
</tr>
<tr>
<td>Mounting Apparatus</td>
<td>$250.00</td>
<td>$41.63</td>
</tr>
<tr>
<td><strong>Material Sub Total</strong></td>
<td><strong>$5,850.00</strong></td>
<td><strong>$599.46</strong></td>
</tr>
<tr>
<td><strong>GRAND TOTAL</strong></td>
<td><strong>$11,250.00</strong></td>
<td><strong>$3,119.38</strong></td>
</tr>
</tbody>
</table>
APPENDIX G – MOTOR DATA SHEET

SPECIFICATIONS

Hennikwell
DC Planetary Gear Brush Motor

DIRECTION OF ROTATION

MODEL NUMBER
PK32KD3B2100-051

A. Operating Conditions:

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Operating Voltage Range</td>
<td>6-12 V DC</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>Rated Voltage</td>
<td>12 V DC</td>
<td>5</td>
</tr>
<tr>
<td>3</td>
<td>Nominal Voltage</td>
<td>12 V DC</td>
<td>6</td>
</tr>
</tbody>
</table>

B. Electrical Characteristics:

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No-load Current</td>
<td>0.85 A (MAX.)</td>
<td>6</td>
<td>Stall Current</td>
<td>35 A (MAX.)</td>
</tr>
<tr>
<td>2</td>
<td>No-load Speed</td>
<td>188±19 rpm</td>
<td>7</td>
<td>Insulation Resistance (500V)</td>
<td>20 MΩ (MIN.)</td>
</tr>
<tr>
<td>3</td>
<td>Rated-load Current</td>
<td>5.0 A (MAX.)</td>
<td>8</td>
<td>Dielectric Strength</td>
<td>250 AC V</td>
</tr>
<tr>
<td>4</td>
<td>Rated-load Speed</td>
<td>163±16 rpm</td>
<td>9</td>
<td>Motor Brush Type</td>
<td>Carbon Brush</td>
</tr>
<tr>
<td>5</td>
<td>Stall Torque</td>
<td>88 kgf-cm (MIN.)</td>
<td>10</td>
<td>Output Power at Max. Eff.</td>
<td>25 Watts</td>
</tr>
</tbody>
</table>

C. Mechanical Characteristics:

<p>| | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Gear Type</td>
<td>Planetary</td>
<td>7</td>
<td>Output shaft Radial Load</td>
<td>3 kgf(MAX.)</td>
</tr>
<tr>
<td>2</td>
<td>Gear Ratio</td>
<td>1/51</td>
<td>8</td>
<td>Output shaft Run-out</td>
<td>0.05 mm (MAX.)</td>
</tr>
<tr>
<td>3</td>
<td>Gear Material</td>
<td>Mixed</td>
<td>9</td>
<td>Shaft End play</td>
<td>0.3 mm (MAX.)</td>
</tr>
<tr>
<td>4</td>
<td>Rated Tolerance Torque</td>
<td>10 kgf-cm (MAX.)</td>
<td>10</td>
<td>Bearing Type</td>
<td>Ball</td>
</tr>
<tr>
<td>5</td>
<td>Momentary Tolerance Torque</td>
<td>30 kgf-cm</td>
<td>11</td>
<td>Net Weight</td>
<td>310±20 grams</td>
</tr>
<tr>
<td>6</td>
<td>Output shaft Axial Load</td>
<td>2.5 kgf (MAX.)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(unit:mm)
Appendix H - LUBRICATION

Lucas Oil 8 oz. White Lithium Grease
Model #: 10533 Store SKU: 504178

4.58

PRODUCT DESCRIPTION

The Lucas Oil 8 oz. White Lithium Grease is a multi-purpose, oil-based lubricant, it helps protect against rust, is water-repellant and is non-conductive.

- Multi-purpose
- Oil-based
- Helps protect against rust
- Non-conductive
- Water-repellant
- MFG Brand Name: Lucas Oil
- MFG Model #: 10533
- MFG Part #: 10533

SPECIFICATIONS

<table>
<thead>
<tr>
<th>Container Size (oz.)</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Container Type</td>
<td>Tube</td>
</tr>
<tr>
<td>Item Package Type</td>
<td>Plastic Container</td>
</tr>
<tr>
<td>Nonconductive</td>
<td>Yes</td>
</tr>
<tr>
<td>Nonconductive</td>
<td>Lubricant base</td>
</tr>
<tr>
<td>Spray on any surface</td>
<td>No</td>
</tr>
<tr>
<td>Sprays on clear</td>
<td>No</td>
</tr>
<tr>
<td>Water-repellant</td>
<td>Yes</td>
</tr>
</tbody>
</table>

CUSTOMER REVIEWS

Do you own this product? Be the first to rate it. Your feedback will help others like you to make informed decisions and will help us to improve our product offerings!

homedepot.com/Tools-Hardware-Hardware-Fasteners-Lubricants-Grease-Fluids/.../ProductDisplay?...
## APPENDIX I - BILL OF MATERIAL

<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>PART NUMBER</th>
<th>DESCRIPTION</th>
<th>QTY.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>91253A220</td>
<td>Flat Head Socket Cap Screw 8-36 Thread, 1/2&quot; Length</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>91253A226</td>
<td>Flat Head Socket Cap Screw 8-36 Thread, 1-1/4&quot; Length</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>92012A532</td>
<td>Precision Hex Socket Shldr Screw 1/4&quot; Shoulder Dia, 5/16&quot; L Shoulder, 10-32 Thread</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>91255A194</td>
<td>Button Head Socket Cap Screw 8-32 Thread, 1/2&quot; Length</td>
<td>47</td>
</tr>
<tr>
<td>5</td>
<td>92012A531</td>
<td>Alloy Steel Precision Hex Socket Shldr Screw 1/4&quot; Shoulder Dia, 1/8&quot; L Shoulder, 10-32 Thread</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>98381A314</td>
<td>Alloy Steel Dowel Pin Black Oxide, 3/16&quot; Diameter, 1-1/2&quot; Length</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>98381A469</td>
<td>Alloy Steel Dowel Pin 1-8&quot; Diameter, 1-1/4&quot; Length</td>
<td>2</td>
</tr>
<tr>
<td>8</td>
<td>98381A487</td>
<td>Alloy Steel Dowel Pin 5/32&quot; Diameter, 1/2&quot; Length</td>
<td>6</td>
</tr>
<tr>
<td>9</td>
<td>91595A108</td>
<td>Metric Alloy Steel Dowel Pin M8 Diameter, 10 mm Length</td>
<td>6</td>
</tr>
<tr>
<td>10</td>
<td>98381A419</td>
<td>Alloy Steel Dowel Pin 1-16&quot; Diameter, 1/2&quot; Length</td>
<td>2</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Lower Arm Elbow Right Support V5</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>Lower Arm Elbow Left Support V5</td>
<td>1</td>
</tr>
<tr>
<td>13</td>
<td></td>
<td>Elbow Forearm Rotating Ring V2</td>
<td>1</td>
</tr>
<tr>
<td>14</td>
<td></td>
<td>Elbow Clamp Right V1</td>
<td>1</td>
</tr>
<tr>
<td>15</td>
<td></td>
<td>Elbow Clamp Left V1</td>
<td>1</td>
</tr>
<tr>
<td>16</td>
<td></td>
<td>Elbow Upper Arm Rotating Ring V1</td>
<td>1</td>
</tr>
<tr>
<td>17</td>
<td></td>
<td>Lower Arm Right Support V4</td>
<td>1</td>
</tr>
<tr>
<td>18</td>
<td></td>
<td>Lower Arm Left Support V4</td>
<td>1</td>
</tr>
<tr>
<td>19</td>
<td></td>
<td>Wrist Rotating Joint Upper Arm Ring V1</td>
<td>1</td>
</tr>
<tr>
<td>20</td>
<td></td>
<td>Wrist Clamp Right V1</td>
<td>1</td>
</tr>
<tr>
<td>21</td>
<td></td>
<td>Wrist Rotating Joint Forearm Ring V3</td>
<td>1</td>
</tr>
<tr>
<td>22</td>
<td></td>
<td>Wrist Clamp Left V1</td>
<td>1</td>
</tr>
<tr>
<td>23</td>
<td></td>
<td>Wrist Clamp Lever V1</td>
<td>2</td>
</tr>
<tr>
<td>24</td>
<td></td>
<td>Wrist Clamp Wire Loop V1</td>
<td>2</td>
</tr>
<tr>
<td>25</td>
<td></td>
<td>Upper Arm Left Support V7</td>
<td>1</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td>Upper Arm Right Support V7</td>
<td>1</td>
</tr>
<tr>
<td>27</td>
<td></td>
<td>Ball Joint Mount V2</td>
<td>1</td>
</tr>
<tr>
<td>28</td>
<td>60745K411</td>
<td>Ball Joint Rod End 10-32 RH Female Shank, 3/16&quot; Ball ID, 1/2&quot; L Thrd</td>
<td>2</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td>Wrist Extension Couple V1</td>
<td>2</td>
</tr>
<tr>
<td>30</td>
<td></td>
<td>Wrist Palm Couple V1</td>
<td>1</td>
</tr>
<tr>
<td>31</td>
<td></td>
<td>Shoulder Track Arc V2</td>
<td>1</td>
</tr>
<tr>
<td>32</td>
<td></td>
<td>Forearm Support Bracket V2</td>
<td>1</td>
</tr>
<tr>
<td>33</td>
<td></td>
<td>Bicept Support Bracket Bottom V4</td>
<td>1</td>
</tr>
<tr>
<td>34</td>
<td></td>
<td>Shoulder Mount V6</td>
<td>1</td>
</tr>
<tr>
<td>35</td>
<td></td>
<td>Bicept Support Bracket Top V3</td>
<td>1</td>
</tr>
<tr>
<td>36</td>
<td></td>
<td>Shoulder support Bracket top V2</td>
<td>1</td>
</tr>
<tr>
<td>37</td>
<td></td>
<td>Shoulder Support Bracket Bottom V1</td>
<td>1</td>
</tr>
<tr>
<td>38</td>
<td></td>
<td>Forearm Support Bracket V3</td>
<td>1</td>
</tr>
<tr>
<td>39</td>
<td></td>
<td>Shoulder Hindge v2</td>
<td>1</td>
</tr>
<tr>
<td>40</td>
<td></td>
<td>6D Piston Stub v1</td>
<td>4</td>
</tr>
<tr>
<td>41</td>
<td></td>
<td>6D Piston outer v1</td>
<td>2</td>
</tr>
<tr>
<td>42</td>
<td></td>
<td>6D Piston v1</td>
<td>2</td>
</tr>
<tr>
<td>43</td>
<td></td>
<td>Motor PK32KD3B2100-051 Planetary Gear Brushed Motors</td>
<td>2</td>
</tr>
<tr>
<td>44</td>
<td>92012A202</td>
<td>Alloy Steel Precision Hex Socket Shldr Screw 3-16&quot; Shoulder Dia, 3/16&quot; L Shoulder, 8-32 Thread</td>
<td>4</td>
</tr>
<tr>
<td>45</td>
<td>98381A489</td>
<td>Alloy Steel Dowel Pin 5/32” Diameter, 3/4” Length</td>
<td>2</td>
</tr>
<tr>
<td>46</td>
<td>98381A474</td>
<td>Alloy Steel Dowel Pin 1-8&quot; Diameter, 7/8&quot; Length</td>
<td>1</td>
</tr>
<tr>
<td>47</td>
<td></td>
<td>Pulley</td>
<td>2</td>
</tr>
<tr>
<td>48</td>
<td>92855A309</td>
<td>Metric M8 SS Low Head Socket Cap Screw M8 Size, 8 mm Length, .5 mm Pitch</td>
<td>8</td>
</tr>
<tr>
<td>49</td>
<td>90965A130</td>
<td>Metric DIN 125 Type 316 SS Flat Washer M8 Screw Size, 7mm OD, 0.45mm-0.55mm Thick</td>
<td>8</td>
</tr>
<tr>
<td>50</td>
<td></td>
<td>Motor Mount</td>
<td>1</td>
</tr>
</tbody>
</table>

Appendix I
APPENDIX J – DRAWINGS
Custom Fabricate to Fit Body

1/8 x 3/8 T-keyway