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Exoskeleton Leg Brace

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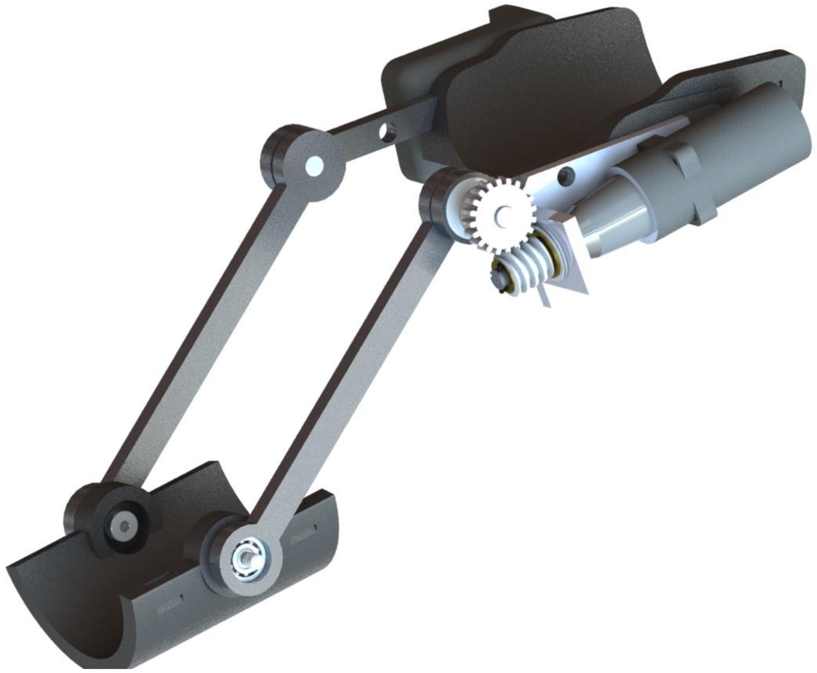

Acknowledgements

We would like to give thanks to Dr.Williams and his associate, Melissa from Discovery Lab Global. The budget and ordering of components were provided to us by DLG and our project would not be possible without them.

In addition we would like to thank Aaron’s brother and father for their engineering and machining support.

Lastly we would like to thank our readers and advisor, Dr. Keszenheimer, Dr. Nadkarni, and Dr.Wang.

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Executive Summary

This report details the design process of a lower limb exoskeleton leg brace for elderly people with walking disabilities or others with disabilities that limit mobility. While there are other similar products on the market, the general design can be improved and these improvements have been implemented into the design presented within. Among these improvements are progress in

efficiency, weight, user comfort, and cost. The results of the study are the design of a novel leg brace that improves on existing designs in each of these areas.

Our design solution incorporates the use of a single leg brace with no additional hip supports that utilizes an electric motor mounted to the side of the brace on the upper leg. The power is transmitted to the joint with a worm gear which will exert force when the user climbs stairs. The frame of the leg skeleton will be made of aluminum and the components which rest against the body will be 3D printed with ABS plastic. This choice of materials will allow our brace to have enough strength to support an adult male climbing stairs while still being comfortable to wear.

The design of the brace presents significant advantages over other similar products as it will be worn only on one leg and will be easier to take on and off when desired. This means easier mobility and greater quality of life for the users of such products.

1.0 Introduction

1.1 Background

These days the population demographic of the United States is shifting to a larger elderly population. The baby boomer generation born post WWII are in their aging years and many of these individuals suffer from limited mobility due to a variety of reasons. There are currently a few options for leg braces that these individuals can use but they are on the verge of being full body suits since they wrap around both legs and the hips of the user. Our design will be much more versatile.

The single leg design will set our design apart and will allow for easy removal for when it isn't necessary. It will take up much less space and can be folded and carried in a bag. The leg brace will be partially made of 3D printed plastic which will help keep costs low and will also be lightweight.

1.2 Principle of Operation

The primary operation of the leg brace is to help elderly people climb stairs with mechanical assistance. The user will wear the brace on their strong leg to give assistance to them as they climb. The brace will be pre programmed to apply a specific amount of force depending on the weight of the user and the percentage of assistance desired. It can be changed between users. It will be controlled by an Arduino based microcontroller.

There are several aspects that need to be taken into account when designing this leg brace. The main topics are user safety and power transmission. Due to the high loads required to assist climbing, the main brace must be designed of a high strength alloy. There should be a sufficient safety factor between the force exerted and the force at which the material would deform. We need the brace to be safe for the user and to be designed for years of wear and tear. If it was to break while in use the individual could be seriously hurt.

1.3 Product Definition

- The design shall be capable of assisting an elderly person in climbing stairs assisted by the lower-limb exoskeleton easily worn by the stronger leg.
- The design shall be capable of assisting with up to 25% of the efforts of the user to provide the ability to control the stair climbing experience.
- The design shall be capable of high volume use.

- The design shall provide safety for the user.

2.0 Conceptual Design

During the conceptual design phase, a number of ideas were generated using methods such as brainstorming and the use of a morphological chart. The results of these processed are given below.

Preliminary Design Phase:

We were tasked with designing a lower limb exoskeleton leg brace, essentially a prosthetic leg brace designated for elderly people who have mobility limitations due to a lack of strength in either leg. The device will utilize sensors to determine muscle contractions, an electric motor to power the motion of the leg brace, and a worm gear and sprocket to transmit the power. This project was sponsored by a non profit organization: Global Discovery Labs, and we had the support of Dr. Robert Williams and his assistants over the course of the last year. The budget for the development phase of this project was originally planned to be 150$, but we quickly realized that the cost of the motor and drivetrain components would exceed that, let along the electrical sensors and miscellaneous parts. We were able to have our budget increased to $500, and we managed to come in right under budget. The schedule that we followed was to have the design thought out in the fall semester and for the prototype to be built, tested, and finalized in the spring. Our deadline is April 26. 2019. The target audience of this device will be elderly people with mobility problems, but also hospitals, nursing homes, and elderly care communities that tend to deal with individuals with mobility issues regardless of their age or ailment. The plan is to have the device worn on the stronger limb so that while the user climbs stair they don’t put excessive force on their joints, bones, and muscles. Once the device is completed, we will conduct testing on different individuals from a variety of sizes. All the members in our group are men weighing around 200 lbs. We will test the device on ourselves as well as others who are smaller and lighter. Our goal is to have a fluid motion with a significant mechanical assistance for climbing stairs.

We experimented with several design ideas before deciding on our final design, our initial plan was to use a chain driven system where an electric motor would turn a sprocket that would have a chain going down to another sprocket at the joint and would allow for turning and effectively assist in the climbing motion. We later realized that this may not be strong enough and having a greasy moving chain on the leg brace was not an ideal solution.

We decided to change the drive train components on the leg brace, and now will be using a worm gear to sprocket set up. The worm gear will turn directly under power from the motor and will connect to the sprocket at the joint. Other changes we made from the original design are having aluminum supports on both sides of the leg.

Expanded Design Brief:

Once the final design was agreed upon, we redesigned our existing prototype. Key changes included replacing the chain driven system with a worm gear and sprocket system. Power would be supplied by an electric motor sourced from a Milwaukee 20V drill. The reason for choosing the drill rather than an off the shelf motor and battery was that we knew that the drill and battery combination we have will be safe and reliable. We didn’t want to risk purchasing a motor and battery where either the motor would spin too quickly for our application, or the battery would be insufficient to power our leg brace. We decided to keep our plastic components mostly the same, with the only key changes being the addition of slots for our aluminum bars. We plan on making most components connections through pressfits. This is the most effective way of reducing additional hardware and keeping costs low. The downside is that we need to maintain tight tolerances during our manufacturing processes, and if we do make this into a commercial product down the road we would need to maintain extreme consistency between components for a fluid assembly process.

2.1 Brainstorming

Many designs were conceived during the brainstorming sessions. The sessions provided an atmosphere that facilitated creative, unique, and at times ridiculous ideas. While the majority of these concepts would never make it out of the conceptual design phase, there were elements from many designs that influenced the evolution of the design that won as it entered the embodiment design phase. A few select sketches from the brain storming session are included here.

2.3 Function Structure Diagram

Another important approach to designing a system is function segmentation. Systems tend to only grow in complexity and one can often lose sight of the goal by trying to design too many components at once. Function segmentation breaks down a complex system into easy to tackle subsystems. This can lead to a more optimal design as the performance of each subsystem can be analyzed independently and then interfaced with the superior designs for other subsystems.

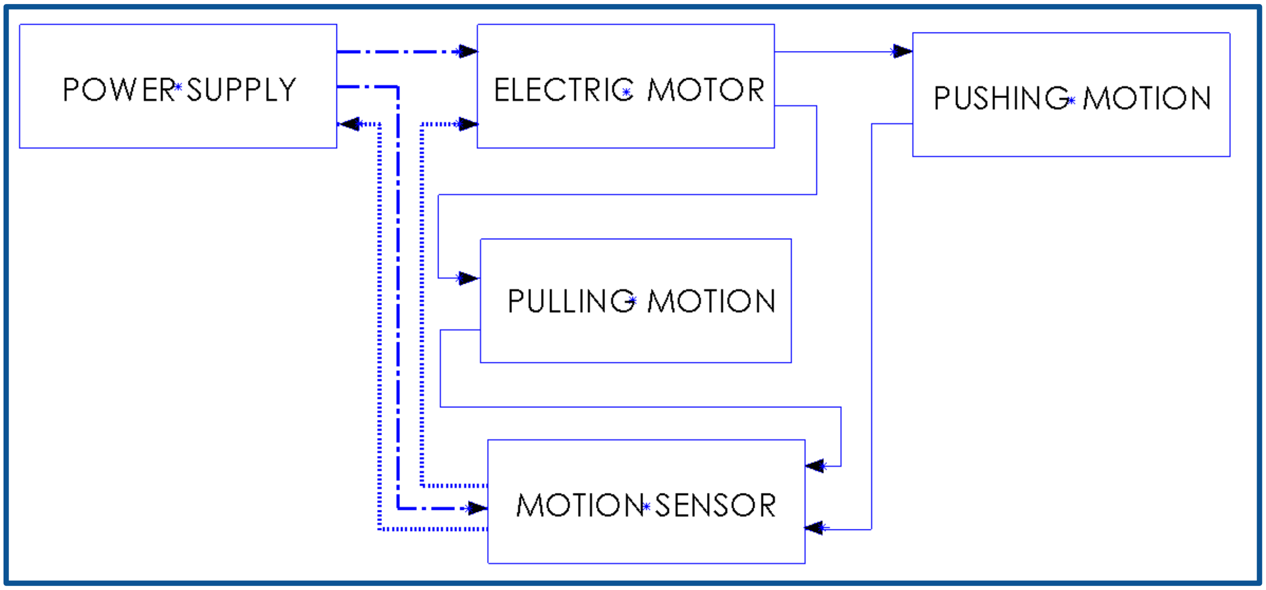
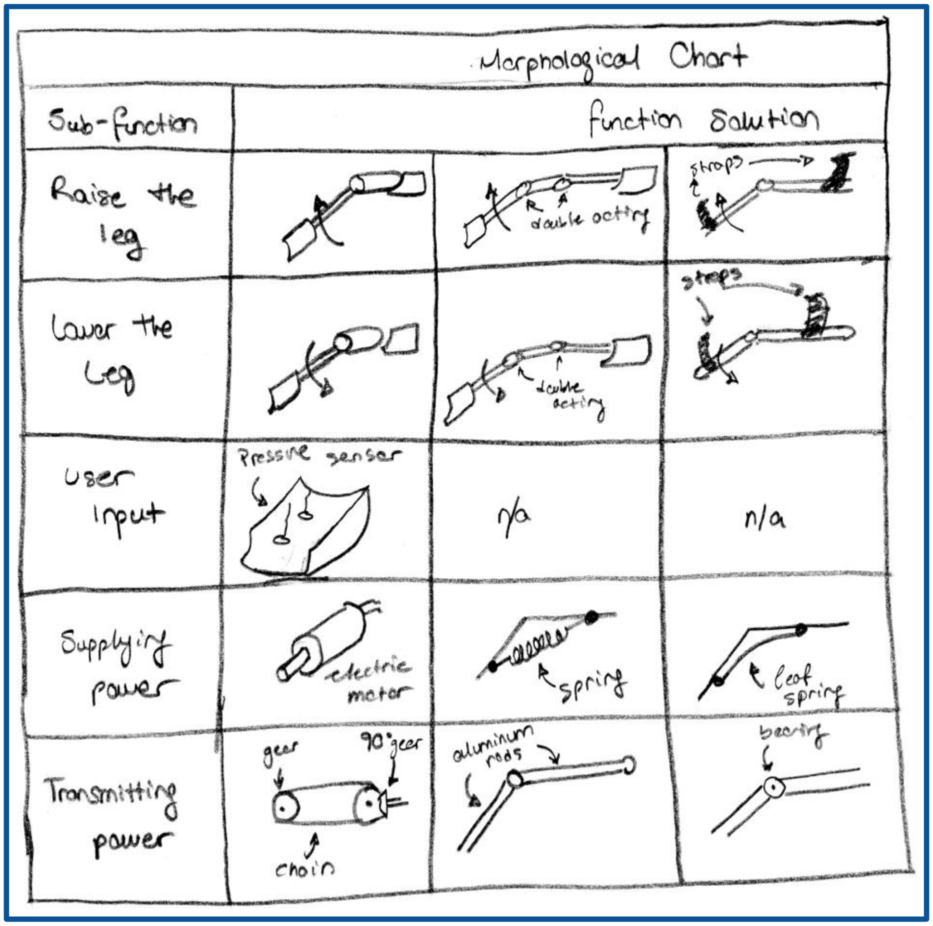


Figure 1: Simplified Blackbox

2.3 Morphological Chart

During the conceptual design phase, it is important to analyze the effectiveness of the different devices within a concept of idea. One tool to help determine the best solution is the Morphological Chart, which helps to organize individual device functions as a part of a whole concept. This chart can be used to evaluate past conceptual designs in a broken down method, to better understand which parts of a design are successful and those parts that are unsuccessful.



Morphological Chart

Sub-function	Function Solution		
Raise the leg		double acting	straps
Lower the Leg		double acting	straps
User Input	Pressure sensor	n/a	n/a
Supplying power	electric motor	spring	leaf spring
Transmitting power	gear 90° gear chain	aluminum rods	bearing

Figure 2: Morphological Chart

2.4 Concept Sketch

The concept sketch is a tool we used to combine our ideas from our morphological chart to visually see our layout and configuration of our design. This is an effective tool to ensure everyone is on the same page.

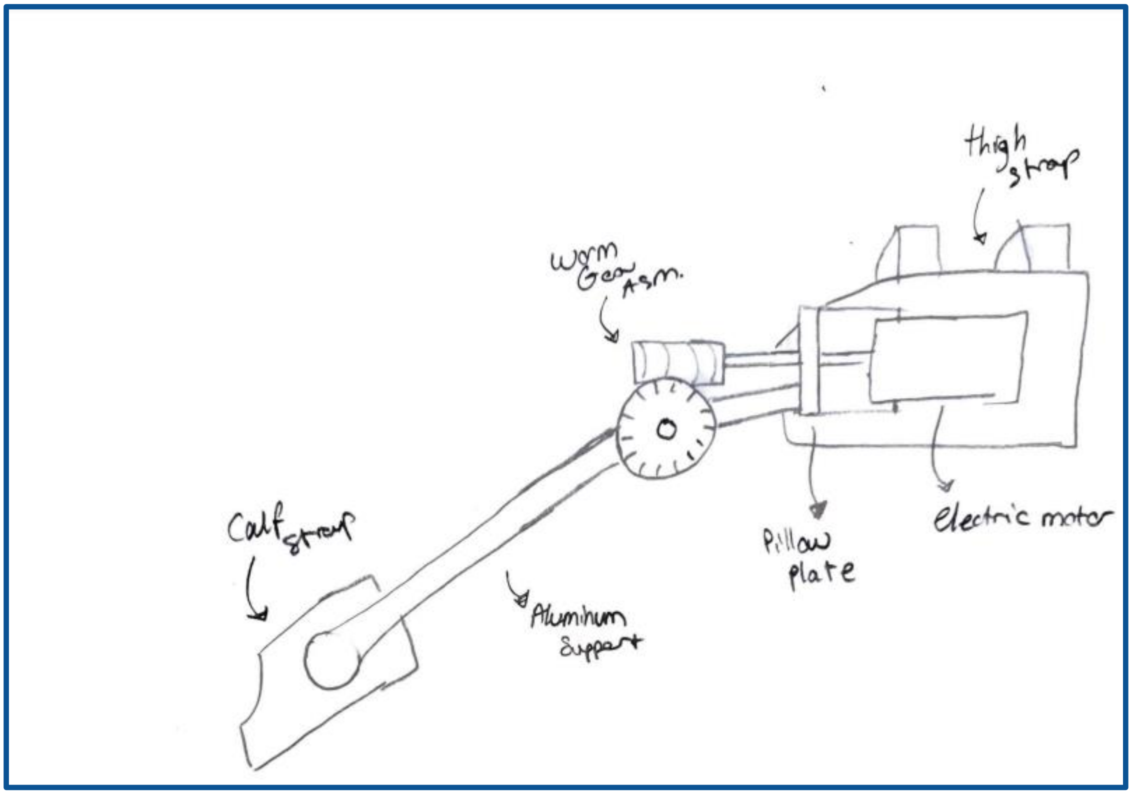


Figure 3: Hand sketches of the Exoskeleton 2.0

2.5 Objective Tree

The design of the finalized product is further developed by using a objective tree to determine which features are prioritized. With this tree we see that cost, quality, and functionality are the three most important factors we took into consideration throughout the design process. A value is assigned to each of these factors to assign a weight value of importance. The sum of these values is equal to 1. Moving further down the Objective tree there are more specific details that we take into consideration. The sum of the sub branches are equal to the value of their parent branch. In the cost branch we have distributed it equally between R&D, and materials. In the quality branch we have distributed this between durability, and reliability, with an emphasis on durability. In the functionality branch we have distributed it between comfort, power transmission, and mobility. With power transmission and mobility having a larger significance, and then comfort.

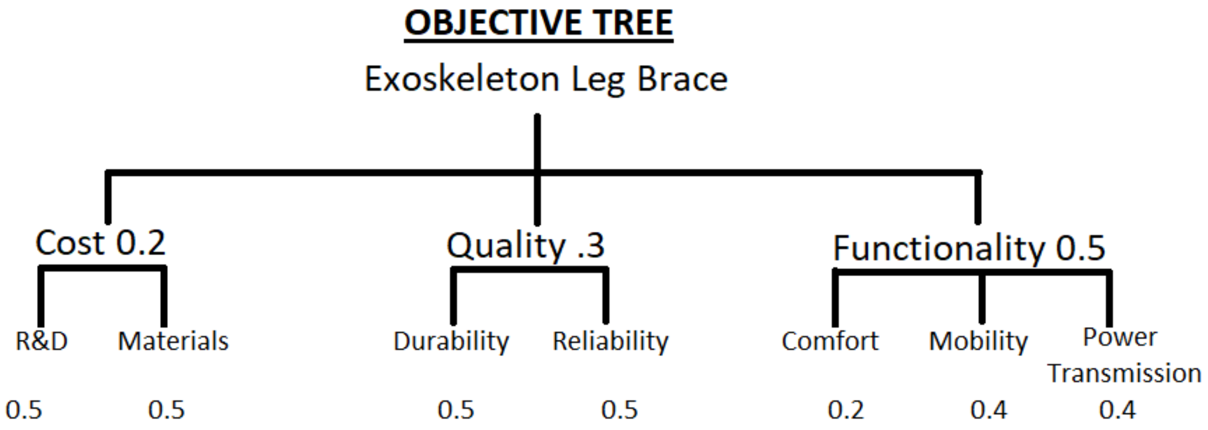
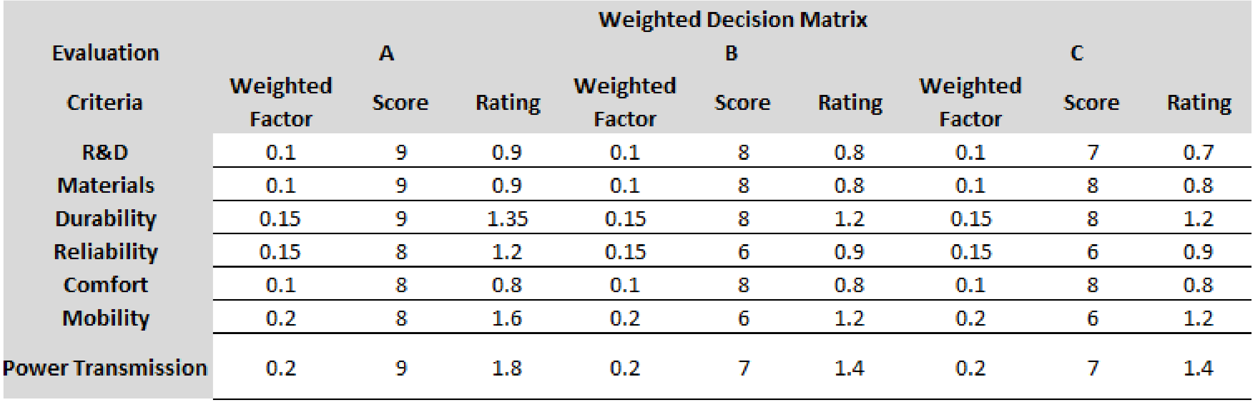


Figure 4: Objective Tree

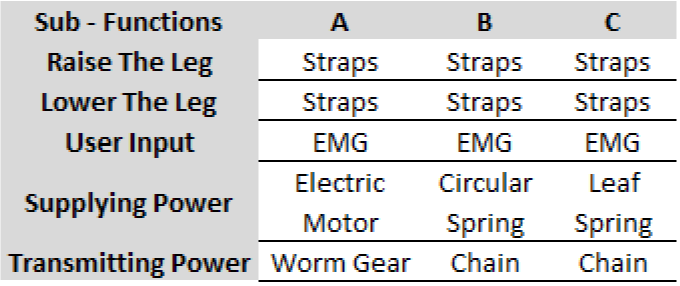
2.6 Weighted Decision Matrix

The weighted decision matrix is a tool we used to narrow down our top design choices down to the best one. This was done by taking our top three choices from our morphological chart and assigning weighted factors based off our results from our objective tree. After adding up the ratings for each choice design A is our best choice and our chosen design moving forward.



	Weighted Decision Matrix								
Evaluation	A			B			C		
Criteria	Weighted Factor	Score	Rating	Weighted Factor	Score	Rating	Weighted Factor	Score	Rating
R&D	0.1	9	0.9	0.1	8	0.8	0.1	7	0.7
Materials	0.1	9	0.9	0.1	8	0.8	0.1	8	0.8
Durability	0.15	9	1.35	0.15	8	1.2	0.15	8	1.2
Reliability	0.15	8	1.2	0.15	6	0.9	0.15	6	0.9
Comfort	0.1	8	0.8	0.1	8	0.8	0.1	8	0.8
Mobility	0.2	8	1.6	0.2	6	1.2	0.2	6	1.2
Power Transmission	0.2	9	1.8	0.2	7	1.4	0.2	7	1.4

Table 1: Weighted Decision Matrix



Sub - Functions	A	B	C
Raise The Leg	Straps	Straps	Straps
Lower The Leg	Straps	Straps	Straps
User Input	EMG	EMG	EMG
Supplying Power	Electric Motor	Circular Spring	Leaf Spring
Transmitting Power	Worm Gear	Chain	Chain

Table 2: Work Distribution for the Weighted Decision Matrix

2.7 Design Selection:

The design selection was sound initially due to foreseeable function predictions of the device until we came across some problems regarding the safety and usability of bevel gears. While it was not critical for us to change the design of the brace since the initial Exo 1.0 still capable of overcoming the torque requirements and keeping mechanical rigidity, we as a team deemed to change to design from the usage of bevel gears to worm gears to provide mechanical force transfer.

Once the Conceptual Design is selected from several different design ideas, the Exoskeleton was drawn on a CAD program called SolidWorks in order to further develop the idea and bring it to a reality.

3.0 Embodiment Design

3.1 Schematic Diagram:

A schematic is created to illustrate the main components of the needed for the functionality of the leg brace. Each major component for functional movement is shown. The schematic provides a visual aid of the design we are aiming for and what we aim to reach. The schematic is a very rough version of what we intend our finalized design to look like. The small fasteners, bearings, and other essential components are not shown.

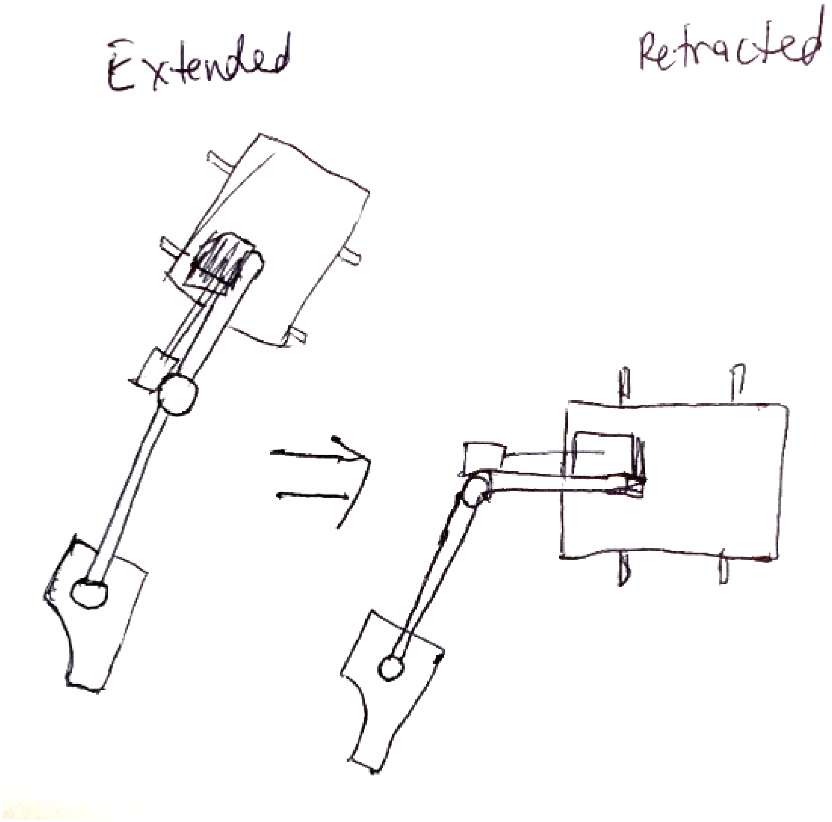


Figure 5: Schematic Diagram

Embodiment Design Rules

1. **Unambiguous** - The use of the product has to be clear and uncomplicated
2. **Simple** - There are no unnecessary shape or function other than for fulfilling the main function.
3. **Reliable** - The product is useable in a myriad of conditions without harming the user or environment.

Embodiment Design Principles

Division of Tasks - Makes the system more efficient overall. It becomes easier to do repairs, and is cheaper and simpler which results in higher utilization levels.

Self Help - The system uses the external effect to increase its abilities, or has an effect to cancel it out.

Self Reinforcing - Under normal load, the design ensures that main or auxiliary factors provide a reinforcing overall effect.

Self- compensating - Under normal load, the design ensures that outside factors counteract the original effect and therefore provides compensation to achieve greater overall effect.

Self Protecting - The load on the device increases its load bearing capability. The faster a motorcycle drives, the harder it is to topple it. The door of a submarine is harder to open under water, because the water pressure pushes against it.

Failure Mode and Effects Analysis (FMEA)

Failure Mode and Effects Analysis is a step by step approach for identifying all possible failures in a design, a manufacturing or assembly process, or a product or service. In our case we will be focusing on the regions of the motor, the thinner parts of our 3D printed leg supports, and our drive train components of the gears and bearings. The results of this phase of the project will determine the readiness of the leg brace for use by the general public. If any weak points are noticed, these components will be revised and retested before final release.

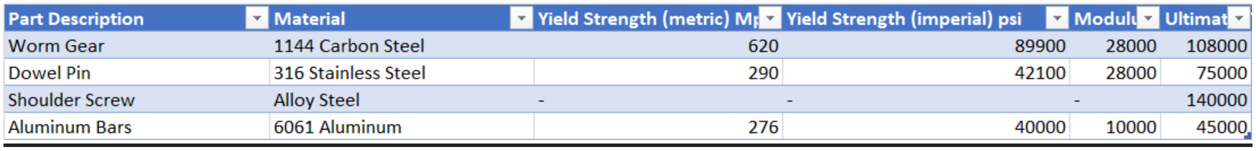
Preliminary Selection of Materials and Manufacturing Processes

The material for the leg supports of the device were made of 3D printed ABS plastic. This was one of our original design requirements, to implement the use of 3D printed materials as much as possible to reduce costs. The braces going in between the leg supports to the joint are made of 6061 Aluminum and were machined with a water jet cutter courtesy of Aaron's brother who works at WardJet. The remainder of the drivetrain components were purchased from McMaster Carr and Amazon. We ordered components such as a worm gear and sprocket combination for power transmission, two dowel pins for the joint to rotate about, shoulder screws, and a series of miscellaneous parts for the final construction. The final construction took place in Aaron's families workshop where we had access to a variety of machining tools. The first step was to make the aluminum rods fit into the plastic leg guard. Due to a sizing error on behalf of the University Printing Center, our plastic parts were shrunk by 3% and we had to grind down the aluminum pieces to fit. Once they were properly sized, we placed them in the intended slots and secured them using super glue. The next step of our assembly process required press fitting the bearings into our holes on the aluminum bars. We experienced some difficulty at this portion of the process due to the fact that the tolerances on the cut parts were not perfect. Some were too tight while others were too loose. For the pieces that were too tight, we used a torch to heat up the aluminum in order for it to expand and then used a vise to press in our bearings, for the parts that were too loose, we hammered around the edges of the circle to force additional material into the slot for the bearing to hold onto.

The most advanced part of our manufacturing process was the creation of our own drive shaft meant for the drill. We found a piece of aluminum rod with a diameter of ½”. We used a mill to cut a key hole and then cut a key for the rod. We also drilled two holes on both ends to keep the worm gear from sliding back and forth and kept in place with pins that were pressed in.

The next step of the process was mounting the motor onto the leg brace. We had not designed this ahead of time due to the awkward shape of the motor, and our uncertainty of how the final configuration would look once cutting the top end of the drill. We also knew we needed a pillow block to help stabilize the shaft. We decided to incorporate the motor mount and pillow block into the same piece. We took a ⅜” aluminum plate and used the mill with a rotary table to cut a hole that was exactly the rights size for a bearing. Then, we heated and bent this piece 90 degrees so that the bearing would be aligned with the motor. We used a hose clamp to secure the motor to the unbent section of the plate. We also added another roll pin on the other side of the bearing. This was used along with some washers to completely mount the shaft independent from the motor. This made it such that the motor would not have to take any reaction forces except the torque which it provides.

Material Properties for Manufactured components



Part Description	Material	Yield Strength (metric) Mp	Yield Strength (imperial) psi	Modulu	Ultimat
Worm Gear	1144 Carbon Steel	620	89900	28000	108000
Dowel Pin	316 Stainless Steel	290	42100	28000	75000
Shoulder Screw	Alloy Steel	-	-	-	140000
Aluminum Bars	6061 Aluminum	276	40000	10000	45000

Table 3: Material Properties

Powertrain Calculations

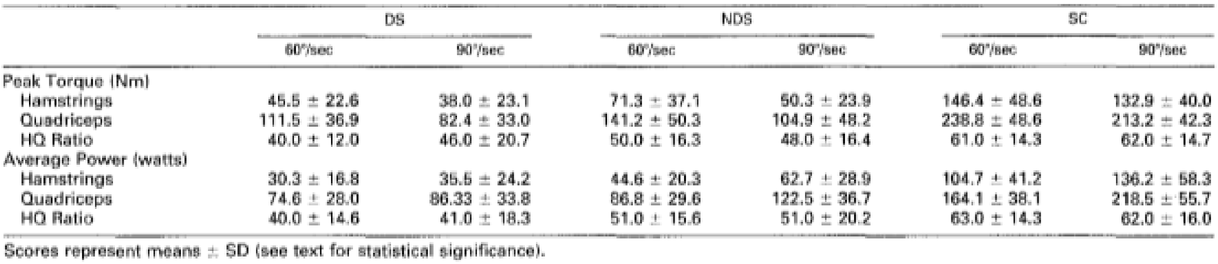
3.2 Motion Analysis

There are several requirements for the leg brace to meet in order to be accepted as a product that could serve as an aid to a patient in the field. While we conceptually achieved some there are some that could be achieved with future development. Some of the specific key aspects that stands out in this project are further explained under Torque Analysis and Motor Selection.

3.2.1 Torque Analysis

This tab coves the torque required for the leg brace to be experimentally ready to demonstrate and possibly be used in the market to aid patients. Although the data collected were not our own experimented data, but we do have values that are usable for the intent of this project.

According to a study *Peak Torque, Average Power, and Hamstrings/Quadriceps Ratios in Nondisabled Adults and Adults With Mental Retardation* the study suggest as following:

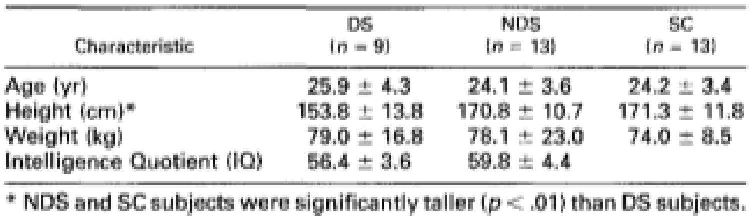


	DS		NDS		SC	
	60°/sec	90°/sec	60°/sec	90°/sec	60°/sec	90°/sec
Peak Torque (Nm)						
Hamstrings	45.5 ± 22.6	38.0 ± 23.1	71.3 ± 37.1	50.3 ± 23.9	146.4 ± 48.6	132.9 ± 40.0
Quadriceps	111.5 ± 36.9	82.4 ± 33.0	141.2 ± 50.3	104.9 ± 48.2	238.8 ± 48.6	213.2 ± 42.3
HQ Ratio	40.0 ± 12.0	46.0 ± 20.7	50.0 ± 16.3	48.0 ± 16.4	61.0 ± 14.3	62.0 ± 14.7
Average Power (watts)						
Hamstrings	30.3 ± 16.8	35.5 ± 24.2	44.6 ± 20.3	62.7 ± 28.9	104.7 ± 41.2	136.2 ± 58.3
Quadriceps	74.6 ± 28.0	86.33 ± 33.8	86.8 ± 29.6	122.5 ± 36.7	164.1 ± 38.1	218.5 ± 55.7
HQ Ratio	40.0 ± 14.6	41.0 ± 18.3	51.0 ± 15.6	51.0 ± 20.2	63.0 ± 14.3	62.0 ± 16.0

Scores represent means ± SD (see text for statistical significance).

Table 4 : Average torque and angular velocity values on Hamstrings and Quadriceps.

Due to given data and the movement of a leg in regards to climbing stairs or walking on a straight road, both Hamstrings and Quadriceps are utilized to create the motion. While it is important to understand that the values given above are the peak torque output of the following subjects:



Characteristic	DS (n = 9)	NDS (n = 13)	SC (n = 13)
Age (yr)	25.9 ± 4.3	24.1 ± 3.6	24.2 ± 3.4
Height (cm)*	153.8 ± 13.8	170.8 ± 10.7	171.3 ± 11.8
Weight (kg)	79.0 ± 16.8	78.1 ± 23.0	74.0 ± 8.5
Intelligence Quotient (IQ)	56.4 ± 3.6	59.8 ± 4.4	

* NDS and SC subjects were significantly taller ($p < .01$) than DS subjects.

Table 5 : Physical attributes of subjects experimented on in the study mentioned previously.

Collected data is expected to be much greater than the actual use of the device because it is strictly a prototype designed for an elderly person that weighs 160 lbs.

Motor Selection

We used a motor from a Milwaukee 18V drill. The torque of the 18V motor is rated at 500 in-lbf, which is equal to 41.67 ft-lbf. We selected the drill as our source of power due to the fact that we knew it would be compatible with the provided battery. We determined that the torque from the motor would be sufficient to power the leg brace for an adult weighing 160lbs.

$$500\ in - lbf\ * \frac{1\ ft}{12\ in} = 41.66\ ft - lbf$$

Gear Selection

We used a worm and worm gear set from McMaster Carr. The worm is inserted into the chuck of our Milwaukee drill so the maximum rpm of our worm is the same as that of the drill, which is 500 rpm on the low speed setting. We chose a worm gear set which had a ratio of 20:1, meaning the final drive speed of the worm gear sprocket is 25 rpm. We estimated that this would be fast enough to move the brace.

$$500 \frac{revolutions}{minute} \div 20 = 25 \frac{revolutions}{minute}$$

With the 20:1 gear ratio, it put our maximum torque up to approximately 800 ft-lbs. This is way more that we would actually expect our brace to be able to take. Obviously, there will be a lot of loss of torque in the friction between the gears. Also, it is doubtful that the motor would actually be able to consistently put out 500 in-lbf. This calculation assured us that the motor-gear combo would be sufficient.

FEA Analysis:

The image below illustrates the forces when the leg brace is in use.

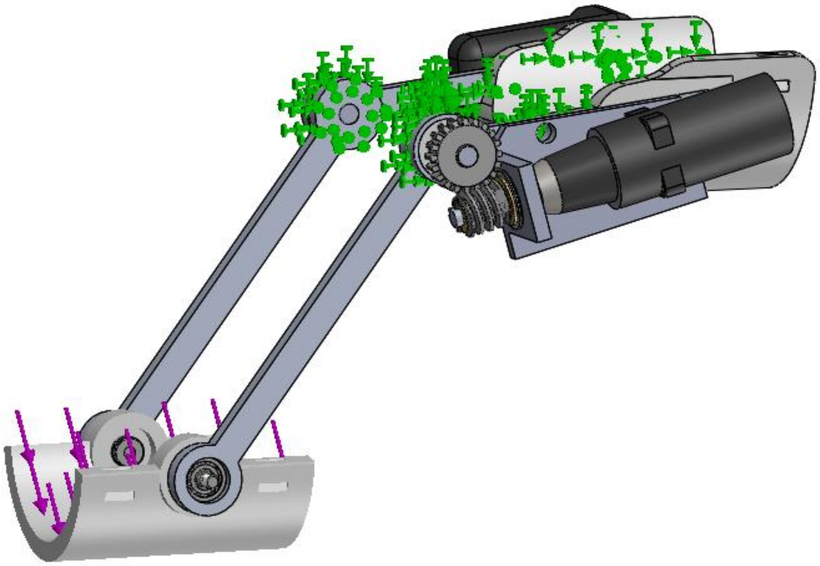


Image 1: Forces under load

Lay-out Drawings

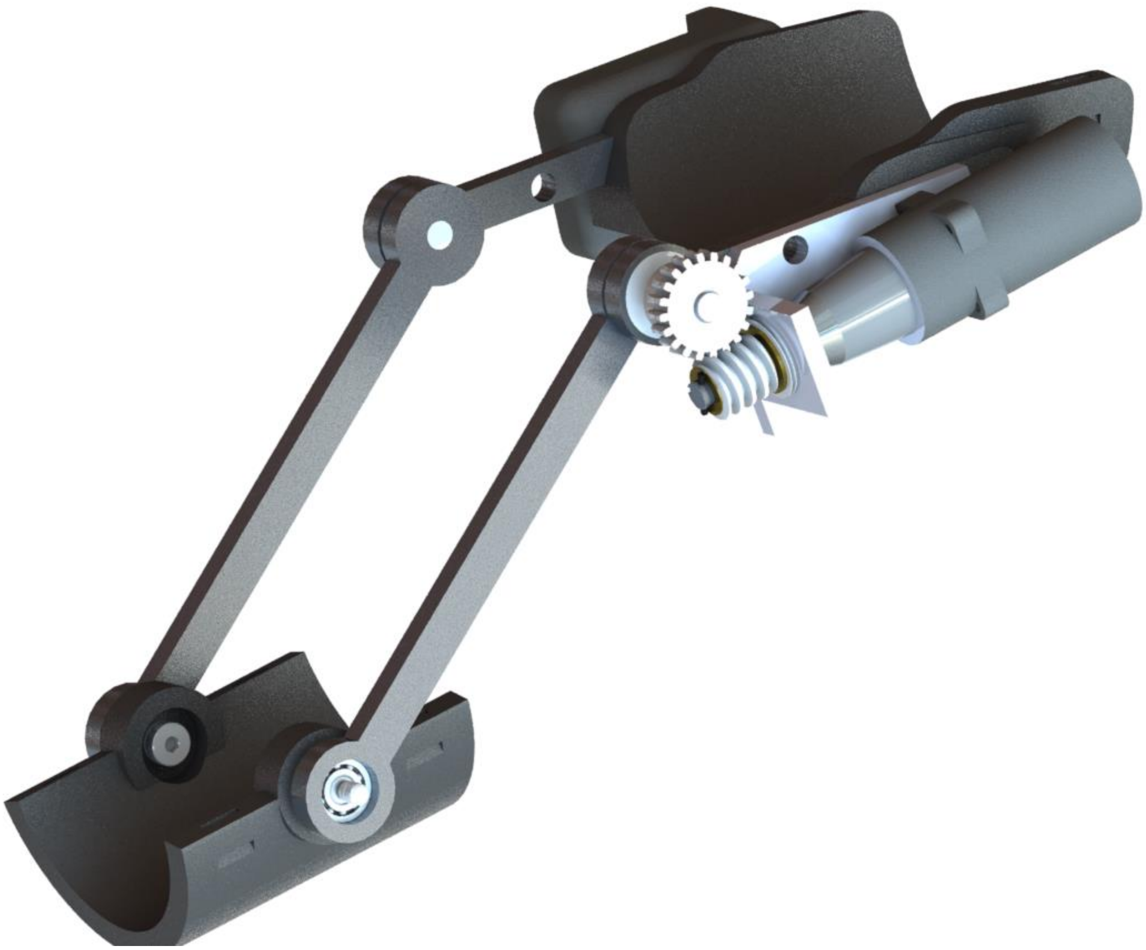


Image 2: 3D view of CAD design of the Exo 2.0

- **Thigh Brace:** The black brace type of part on the upper corner is the thigh brace that straps around the subject's leg to grip and provide structural support. This allows the motion of leg to be linked with the Exoskeleton.
- **Electric Motor:** The electric motor will be used to power the worm gear as seen with its assembly. It will be used to power the motion of the Exoskeleton. Using Electric motor gives us the advantage of high response to motion and lightweight power supply.

- **Connecting Rod:** The Connecting Rod, grey, holds the Shin Brace and transfers the motion from the Chain Link to Shin Cover. This way the lower part of the leg, under knee, can move up and down.
- **Shin Cover:** Shin Cover, black on the bottom, is the strap that attaches to the subject's shin to hold it in place and secure the exoskeleton. This allows the Exoskeleton to properly aid the subject in walking and climbing the stairs.
- **Worm Gear:** The gearing used to increase torque with reduced movement speed is achieved via the worm gear as seen in the image. The Worm gear will be attached to the Electric Motor, not shown in the image, with Pillow block.
- **Pillow Block:** The intent of using a Pillow Block is to stabilize the motor to gear connection and eliminate the vibrations and rotational vibration.

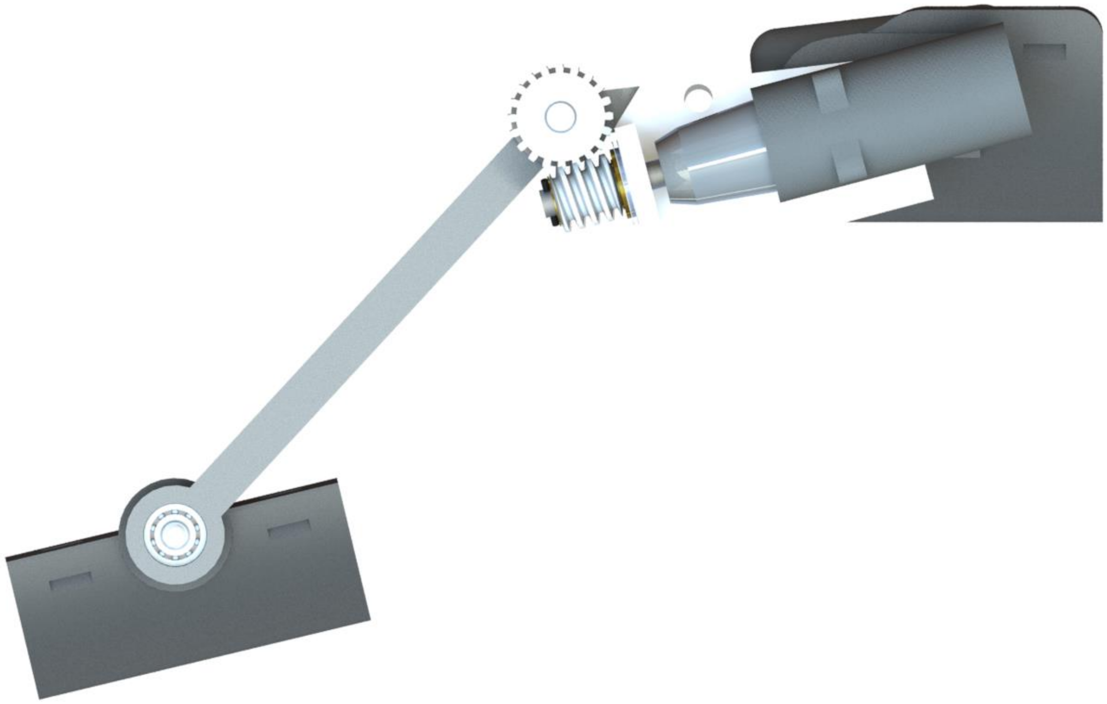


Image 3: Side view of the Exo 2.0

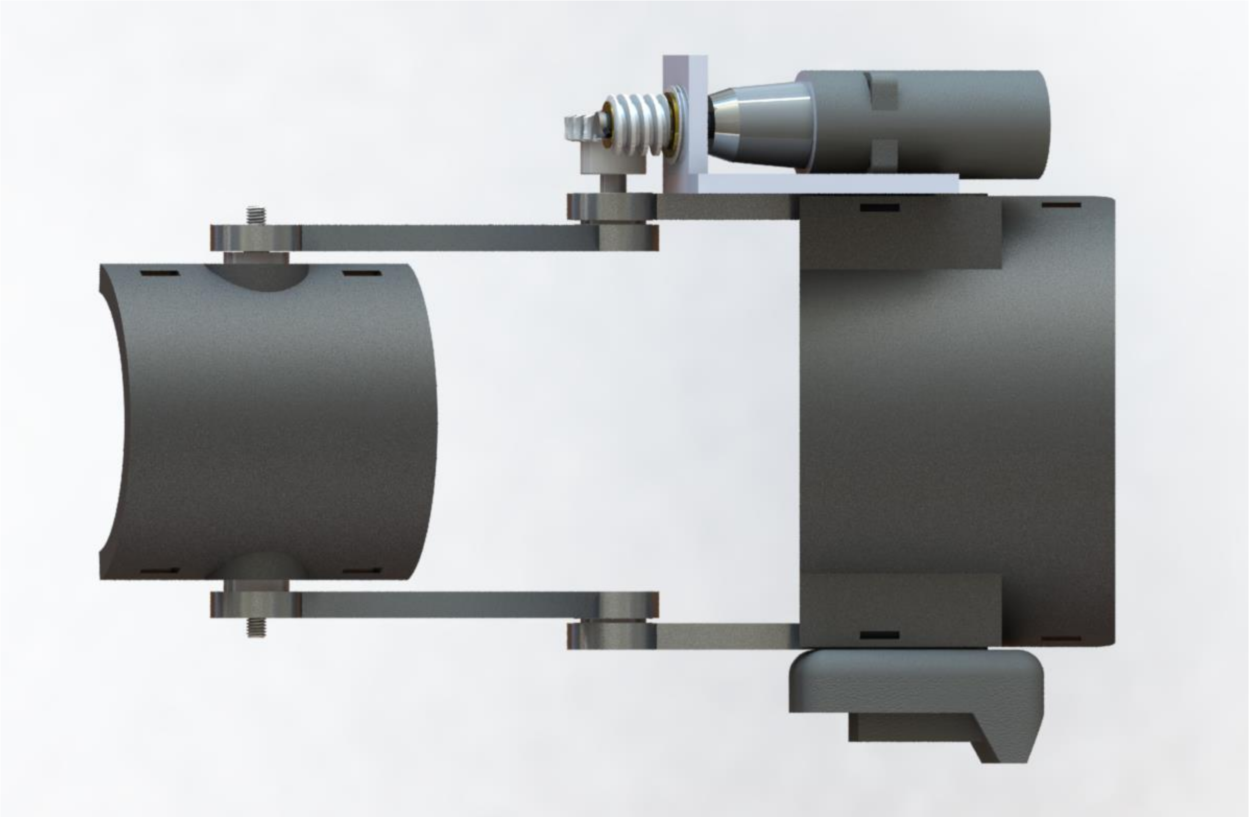
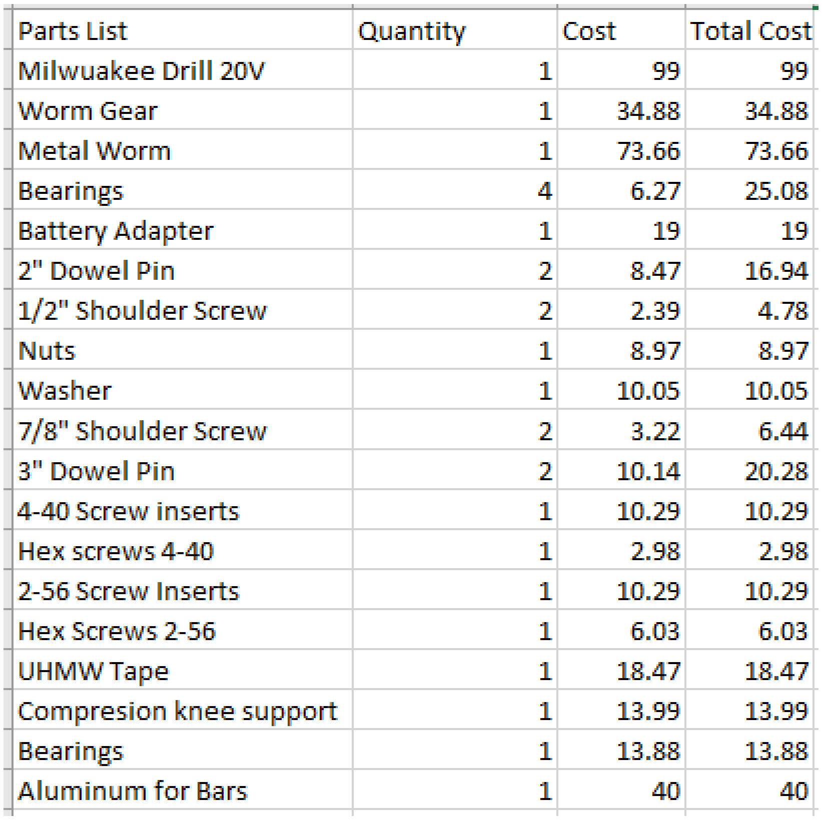


Image 4: Bottom view of the Exo 2.0

4.0 Detail Design

Standard Components from Catalogues

Purchased Parts List

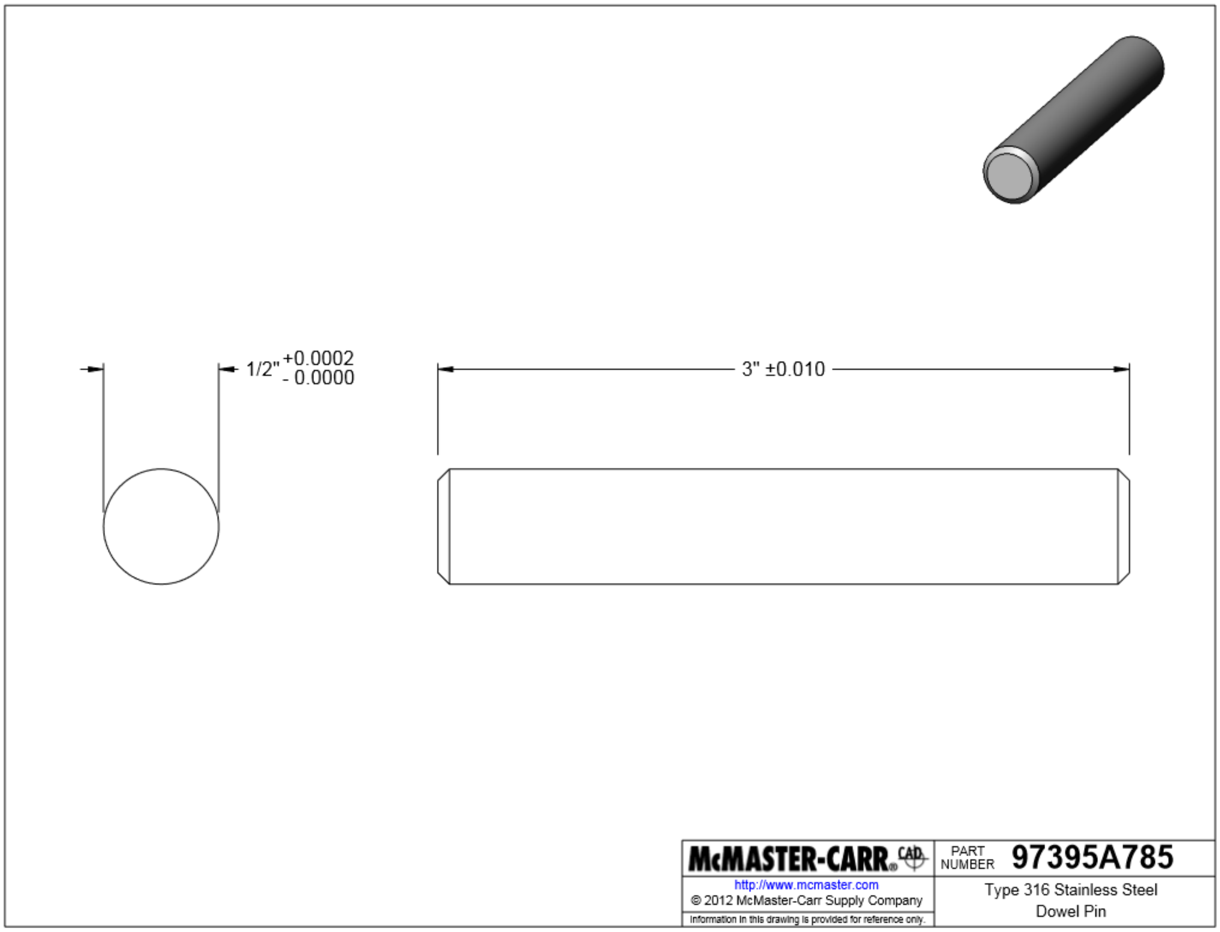


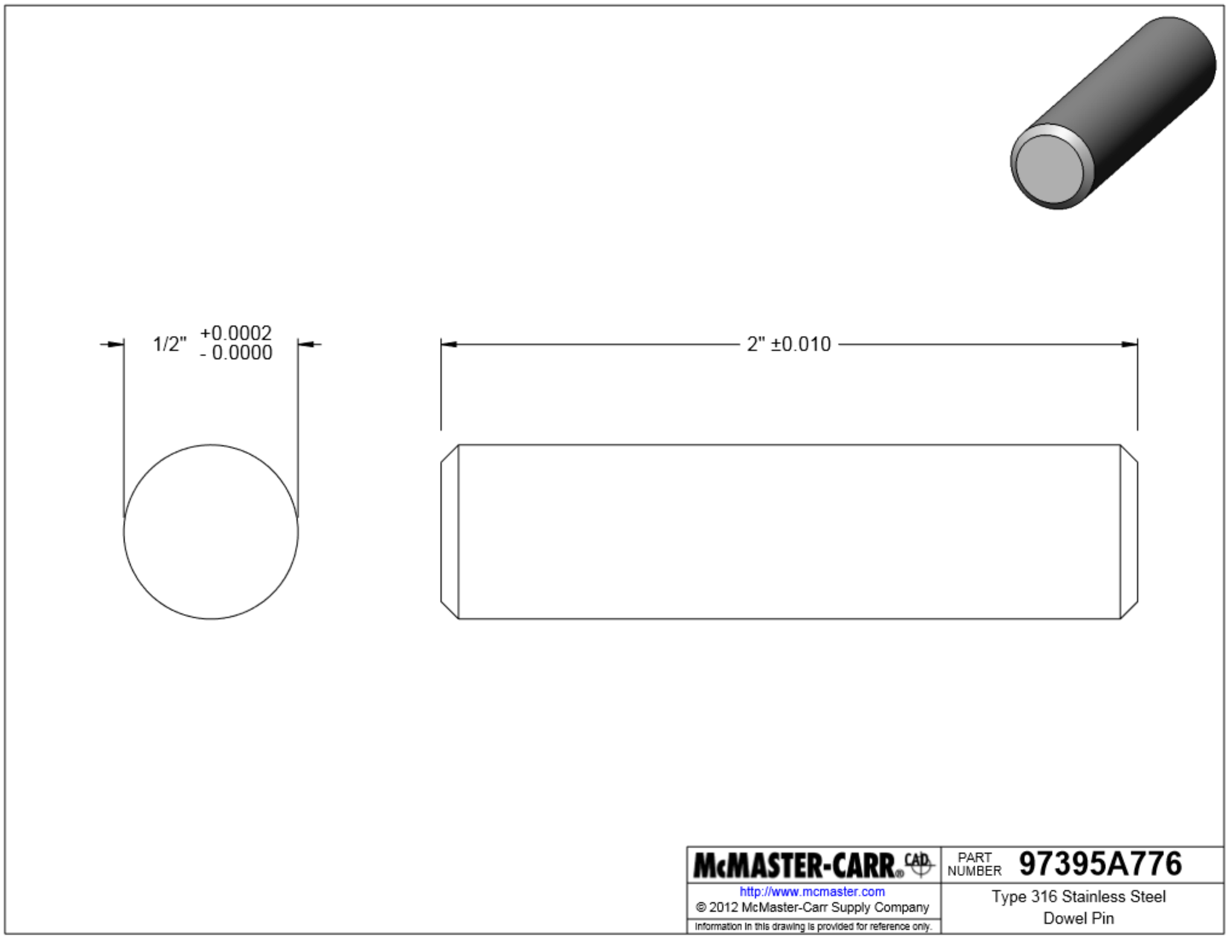
Parts List	Quantity	Cost	Total Cost
Milwuakee Drill 20V	1	99	99
Worm Gear	1	34.88	34.88
Metal Worm	1	73.66	73.66
Bearings	4	6.27	25.08
Battery Adapter	1	19	19
2" Dowel Pin	2	8.47	16.94
1/2" Shoulder Screw	2	2.39	4.78
Nuts	1	8.97	8.97
Washer	1	10.05	10.05
7/8" Shoulder Screw	2	3.22	6.44
3" Dowel Pin	2	10.14	20.28
4-40 Screw inserts	1	10.29	10.29
Hex screws 4-40	1	2.98	2.98
2-56 Screw Inserts	1	10.29	10.29
Hex Screws 2-56	1	6.03	6.03
UHMW Tape	1	18.47	18.47
Compresion knee support	1	13.99	13.99
Bearings	1	13.88	13.88
Aluminum for Bars	1	40	40

Table 6: Parts List

Total Cost: $435

4.1 Part Drawings (isometric, multiview)


1/2" +0.0002 - 0.0000
3" ±0.010
McMASTER-CARR CAD
PART NUMBER 97395A785
http://www.mcmaster.com
© 2012 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Type 316 Stainless Steel Dowel Pin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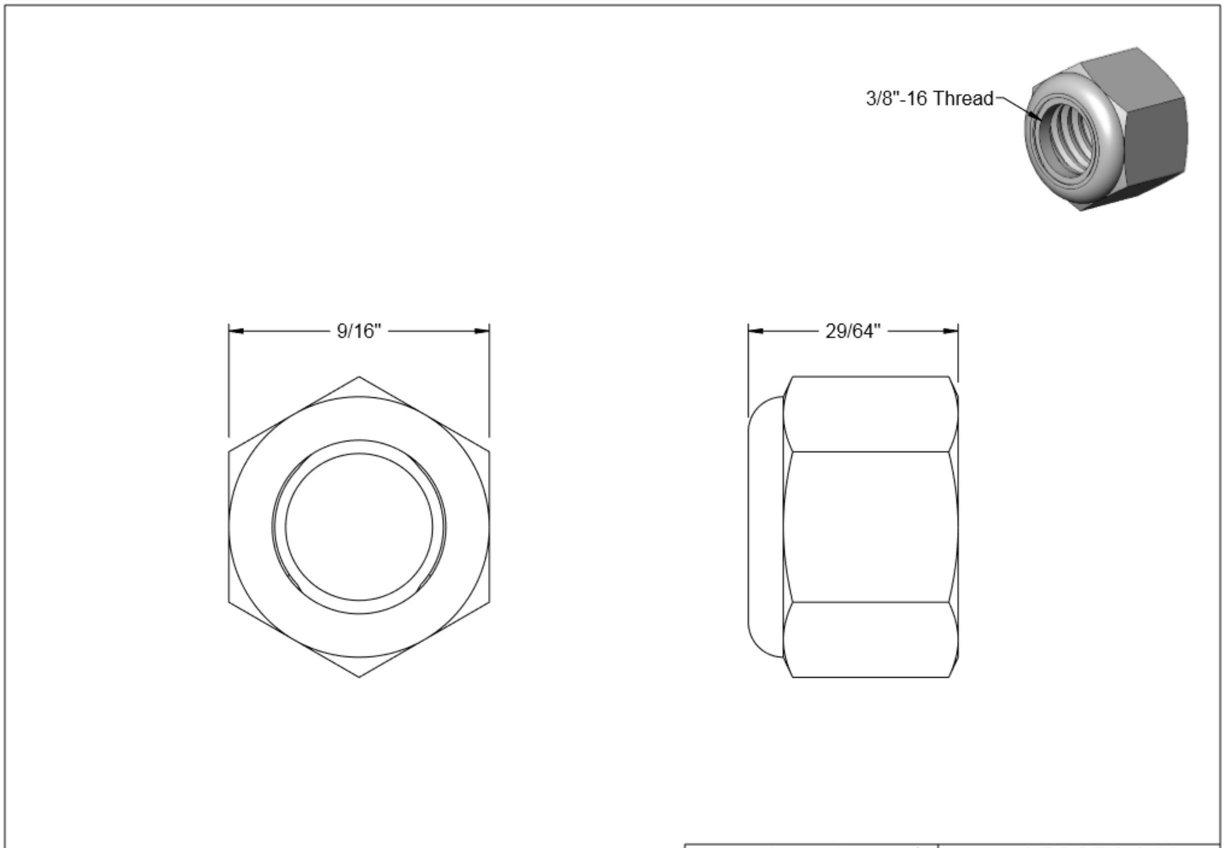
- 0.0000
2" ±0.010
McMASTER-CARR CAD
PART NUMBER 97395A776
http://www.mcmaster.com
© 2012 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Type 316 Stainless Steel
Dowel Pin

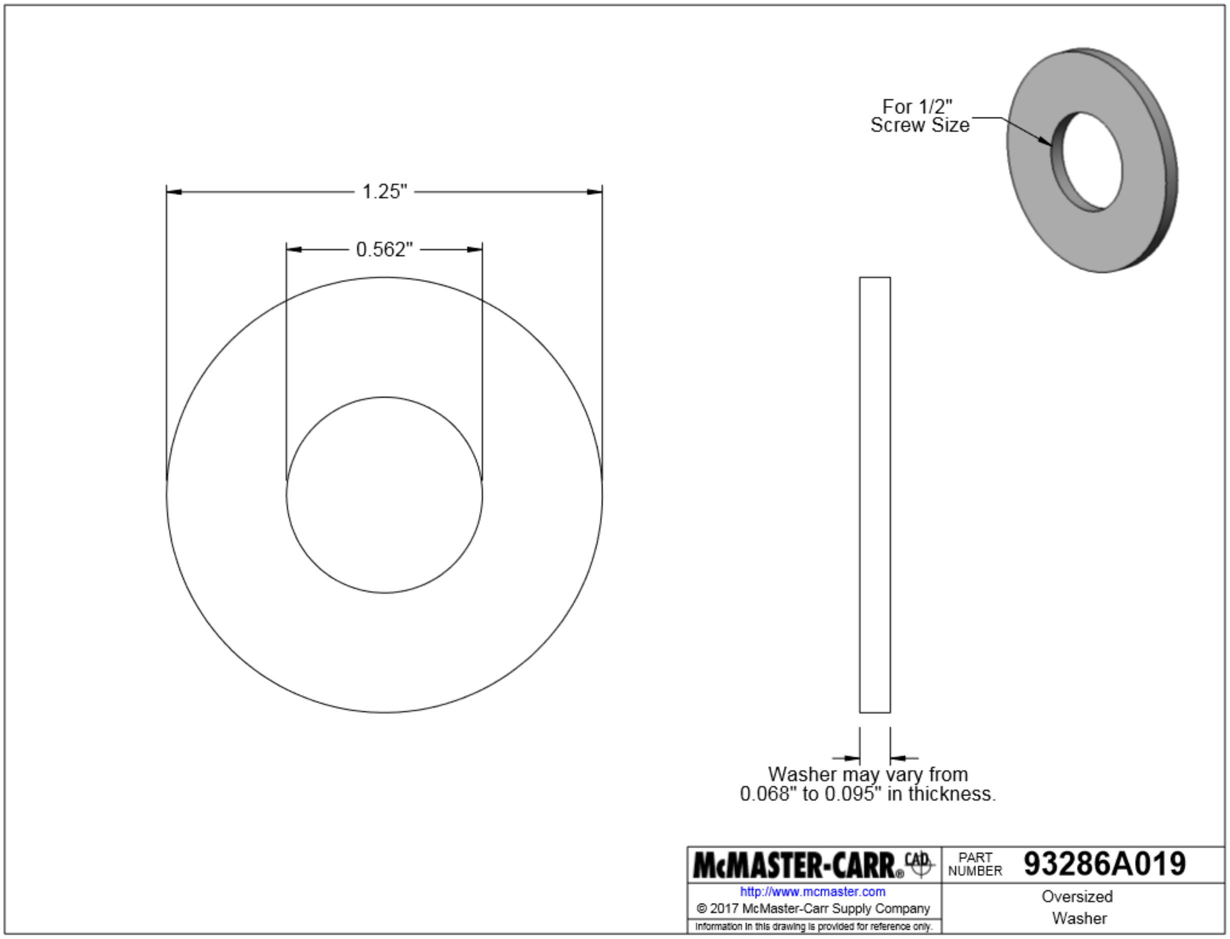


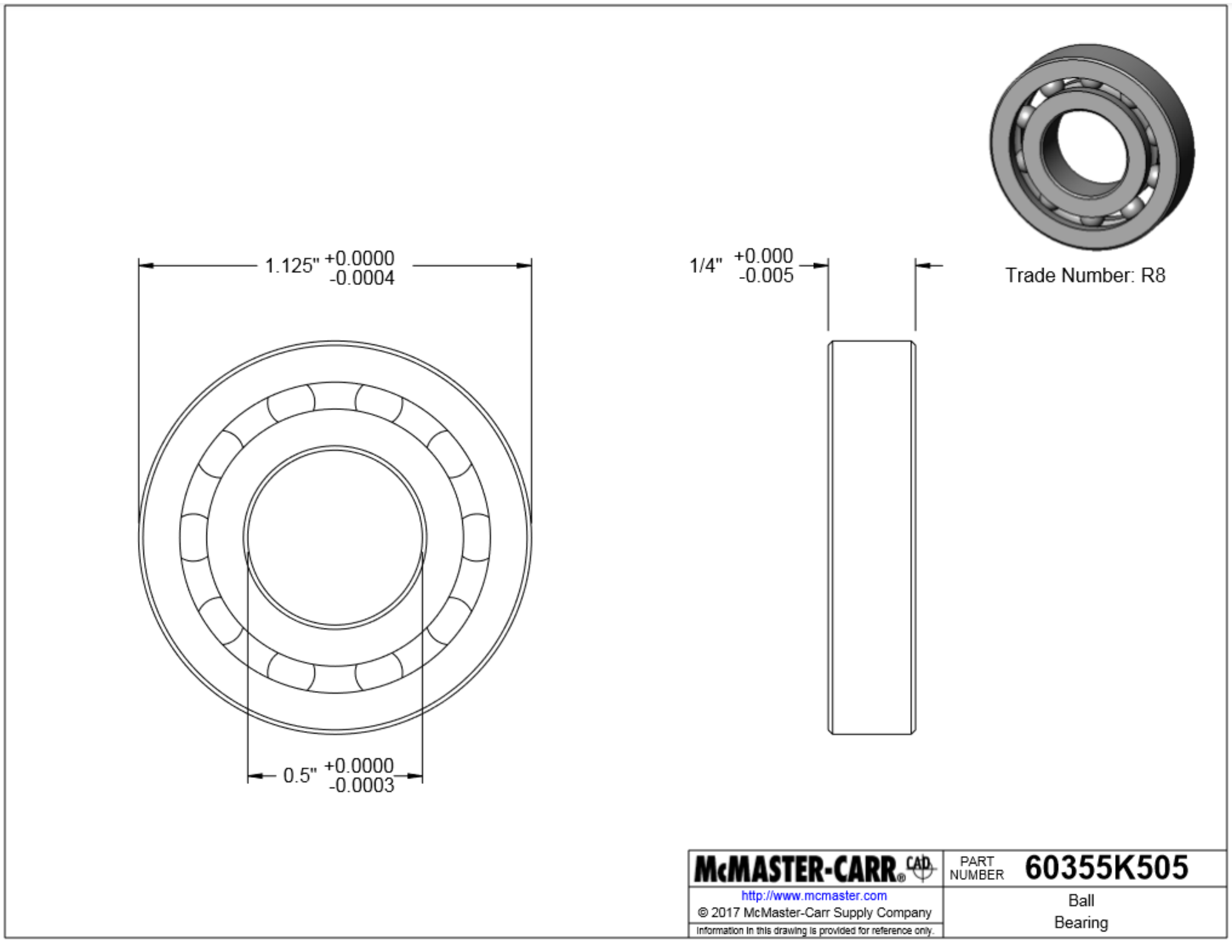
McMASTER-CARR CAD

http://www.mcmaster.com

PART NUMBER **95615A140**

Nylon-Insert
Locknut


1.25"
0.562"
For 1/2"
Screw Size
Washer may vary from
0.068" to 0.095" in thickness.
McMASTER-CARR® CAD
PART NUMBER
93286A019
http://www.mcmaster.com
© 2017 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Oversized
Washer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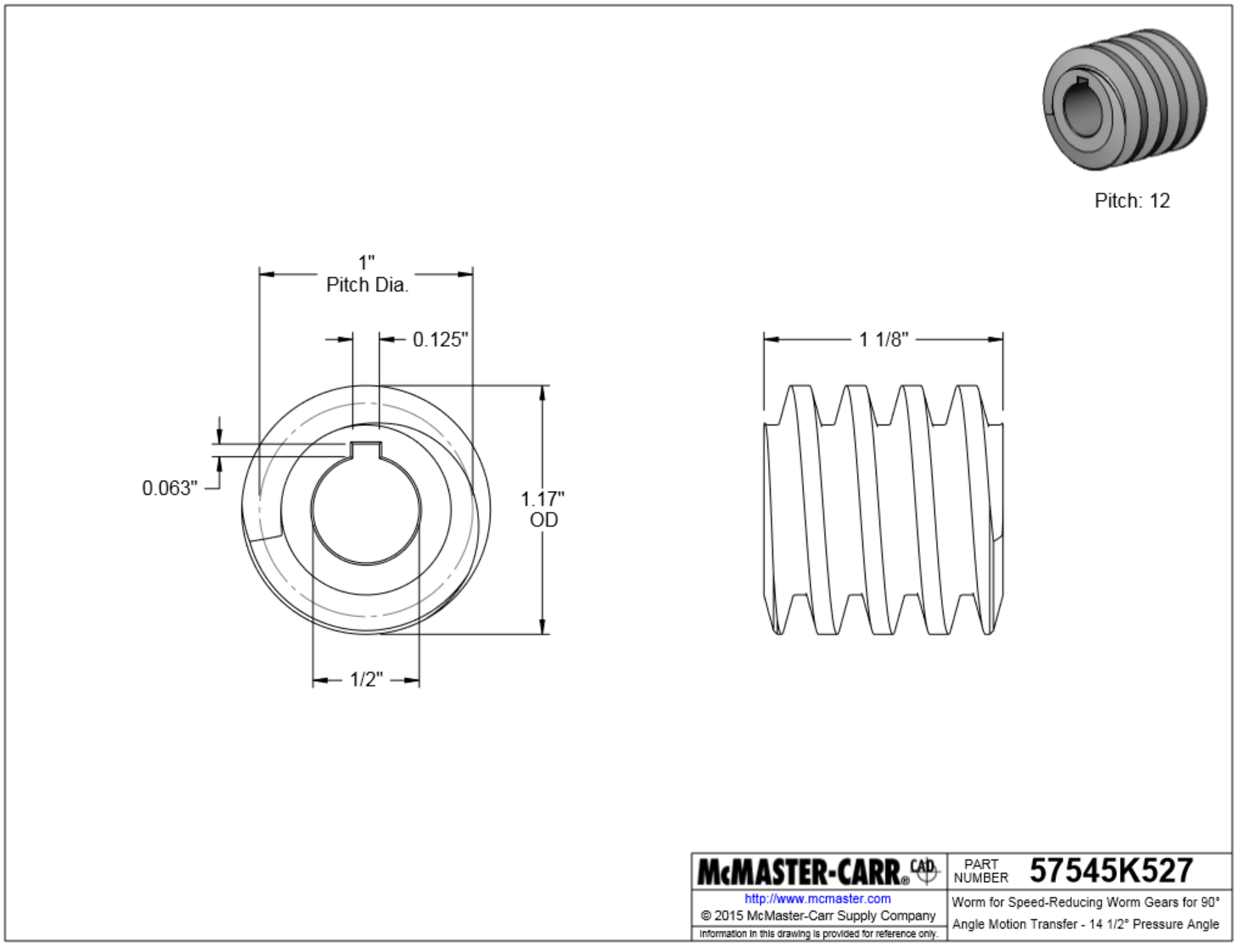
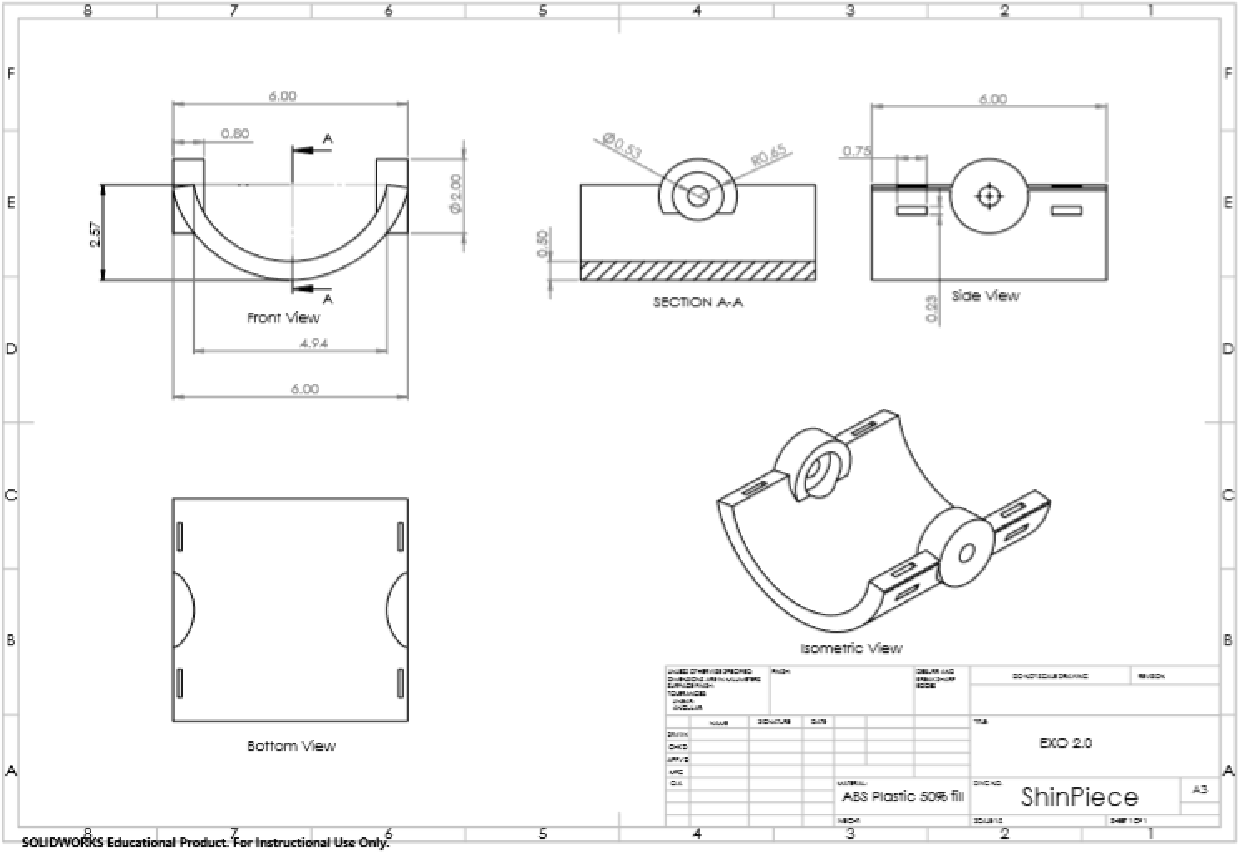
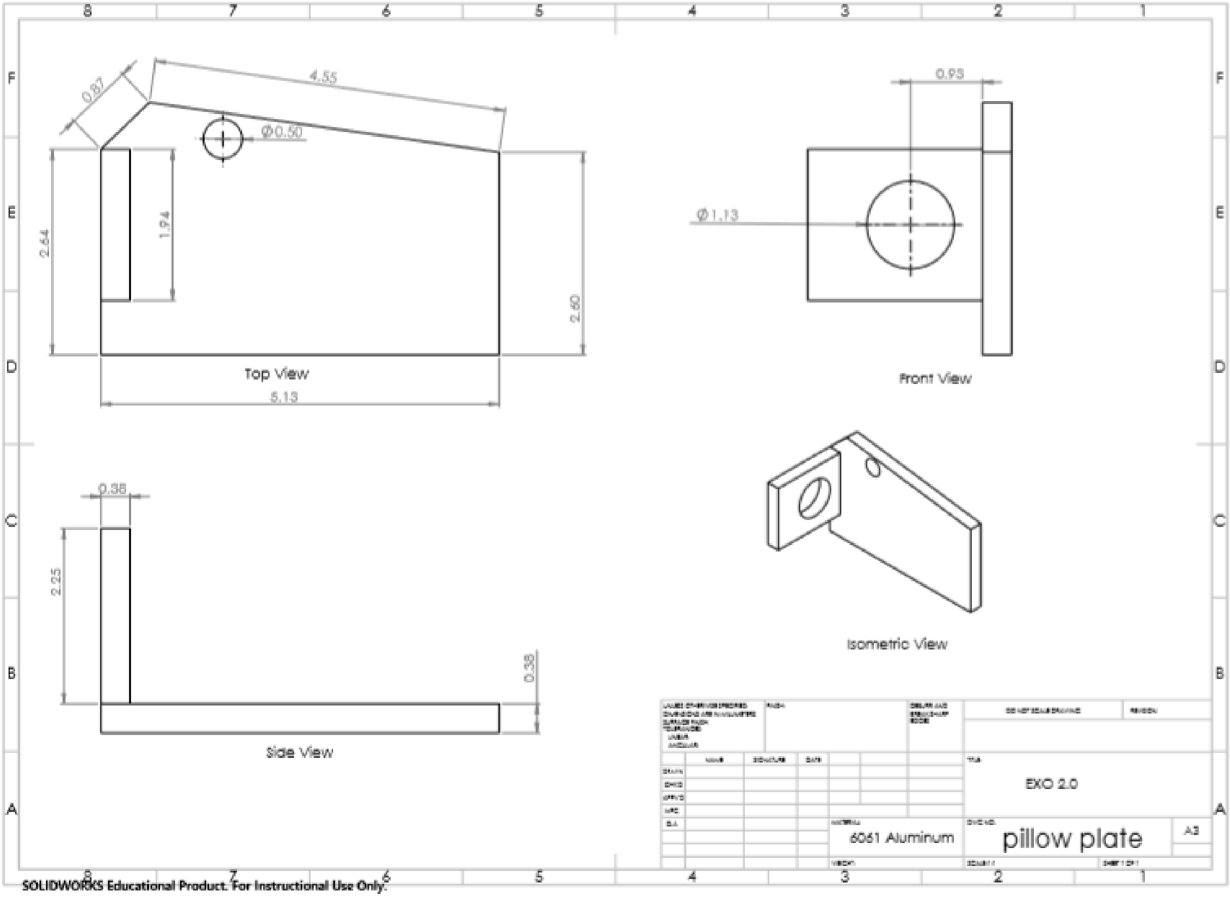
1/4" +0.000 -0.005
Trade Number: R8
0.5" +0.0000 -0.0003
McMASTER-CARR® CAD
PART NUMBER 60355K505
http://www.mcmaster.com
© 2017 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
Ball Bearing



McMASTER-CARR CAD
http://www.mcmaster.com

PART NUMBER **57545K527**
Worm for Speed-Reducing Worm Gears for 90° Angle Motion Transfer - 14 1/2° Pressure Angle


6.00
0.80
A
2.57
Ø2.00
A
Front View
4.94
6.00
Ø0.53
R0.65
0.50
SECTION A-A
6.00
0.75
0.23
Side View
Bottom View
Isometric View
EXO 2.0
ABS Plastic 50% fill
ShinPiece
A3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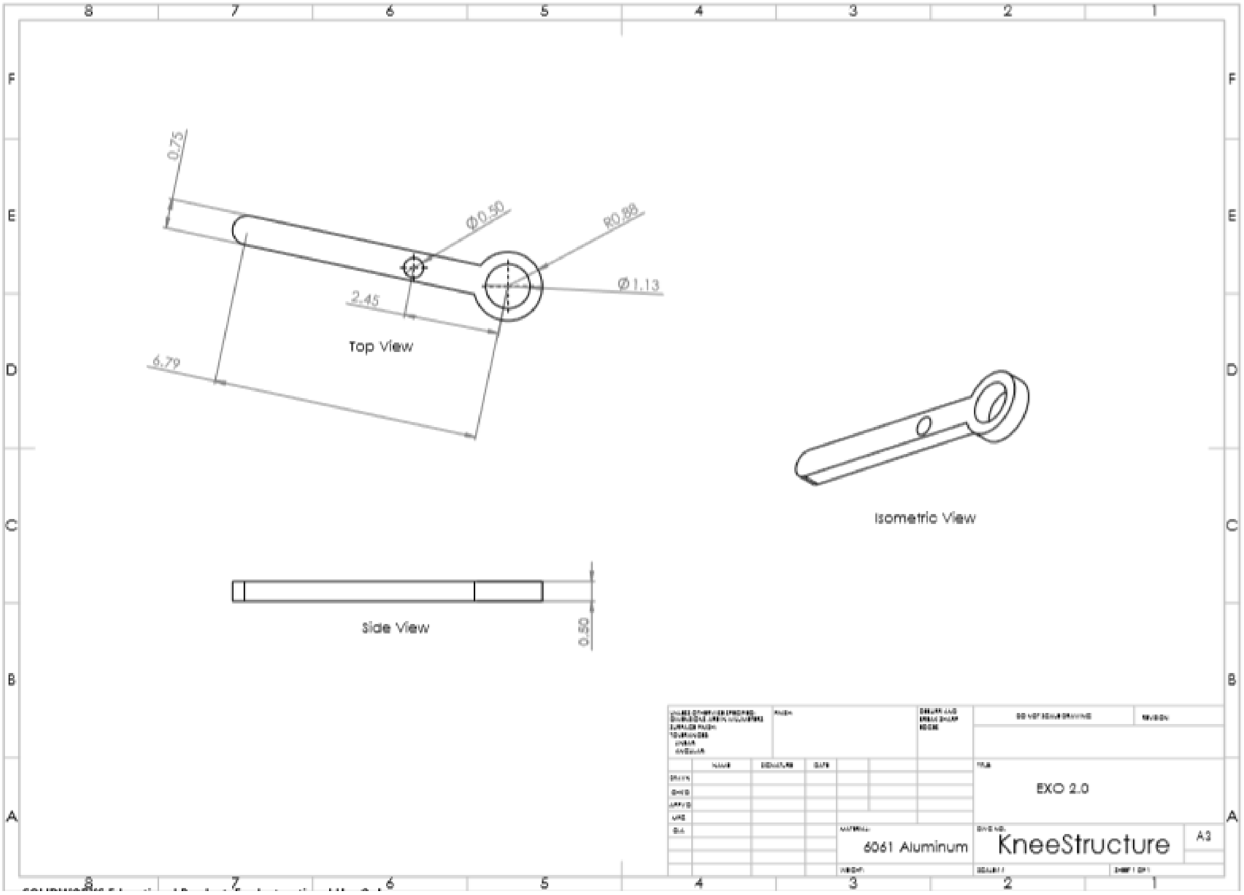
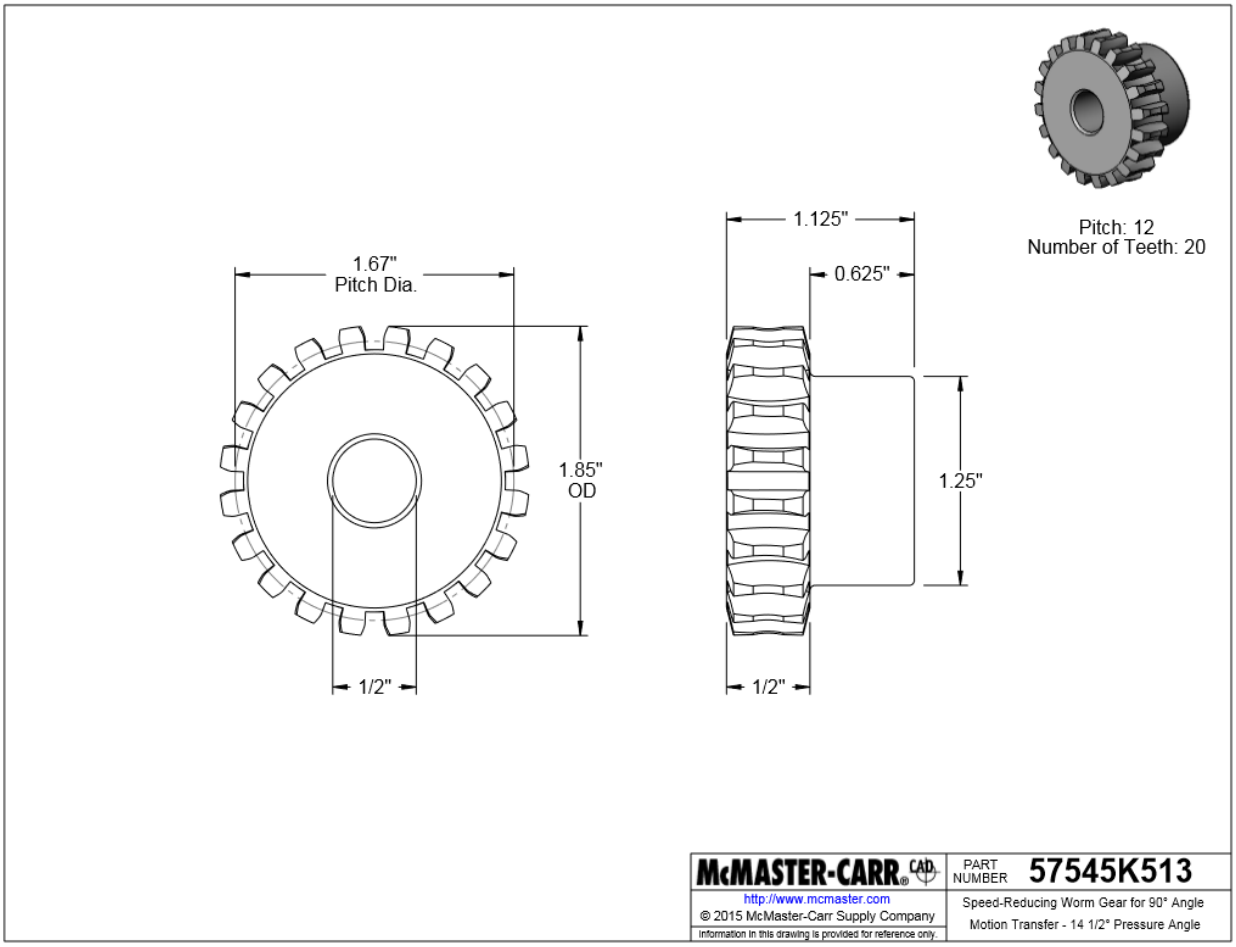
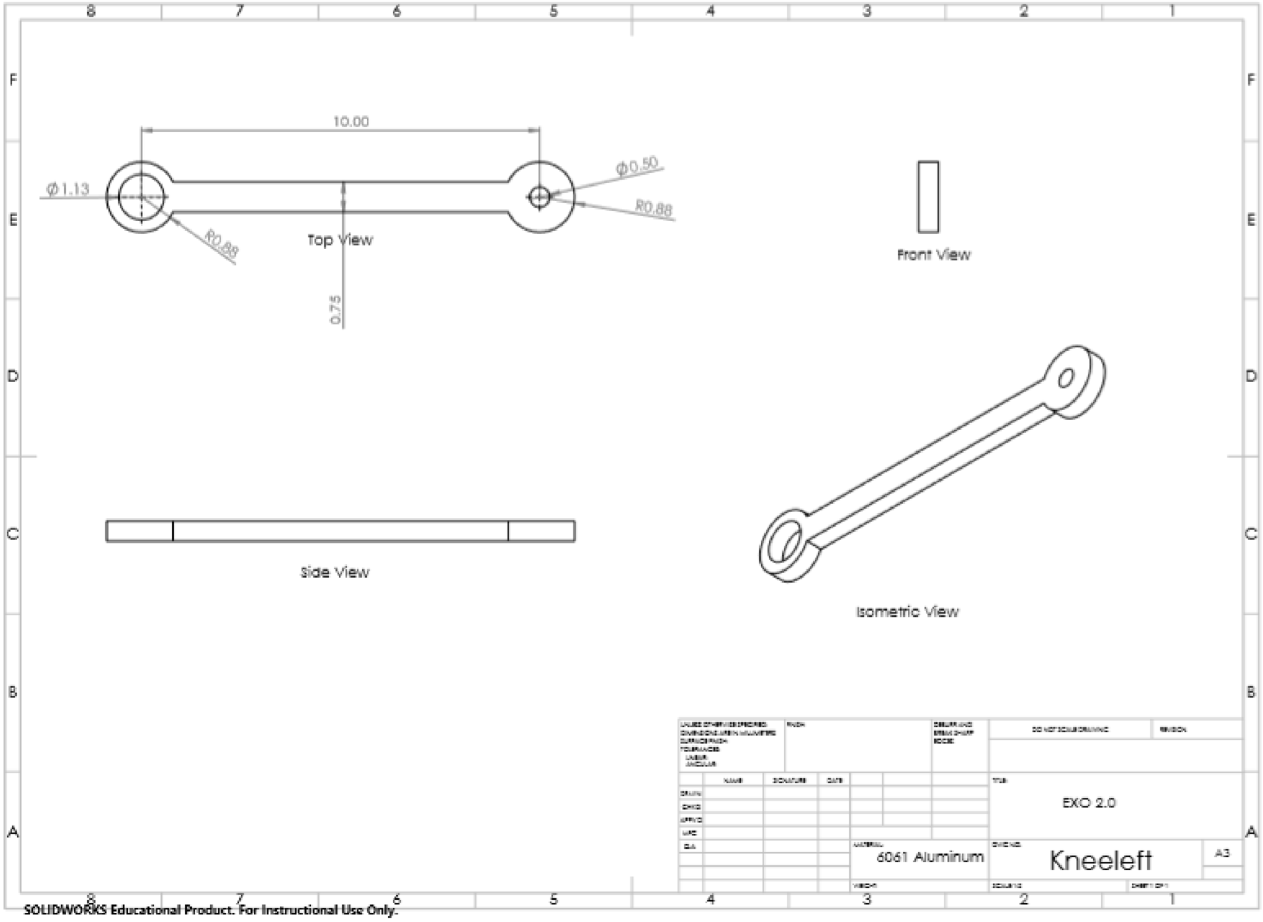
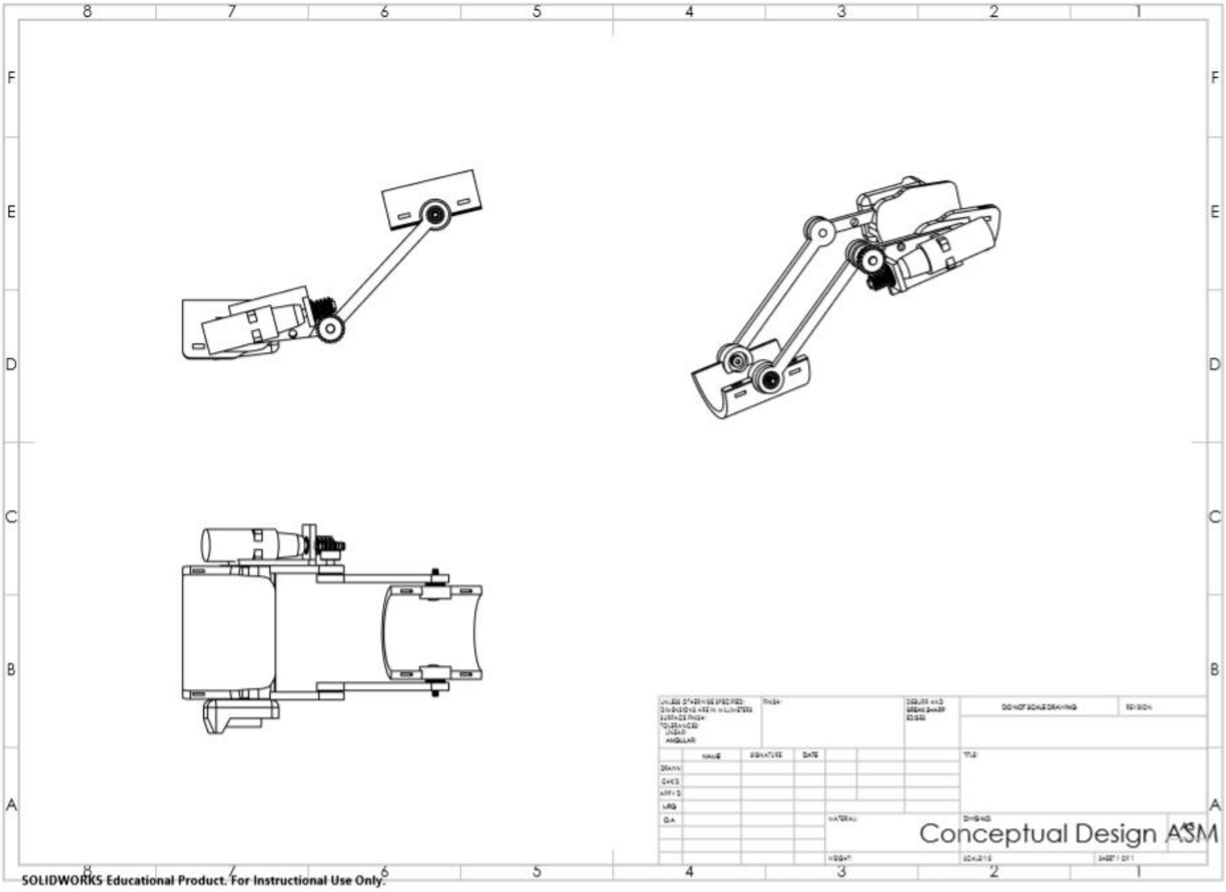
4.55
Ø0.50
2.64
1.94
2.60
Top View
5.13
0.93
Ø1.13
Front View
Isometric View
0.38
2.25
0.38
Side View
EXO 2.0
6061 Aluminum
pillow plate
A3
SOLIDWORKS Educational Product. For Instructional Use Only.


0.75
Ø0.50
R0.88
Ø1.13
2.45
6.79
Top View
Isometric View
Side View
0.50
EXO 2.0
6061 Aluminum
KneeStructure
A3

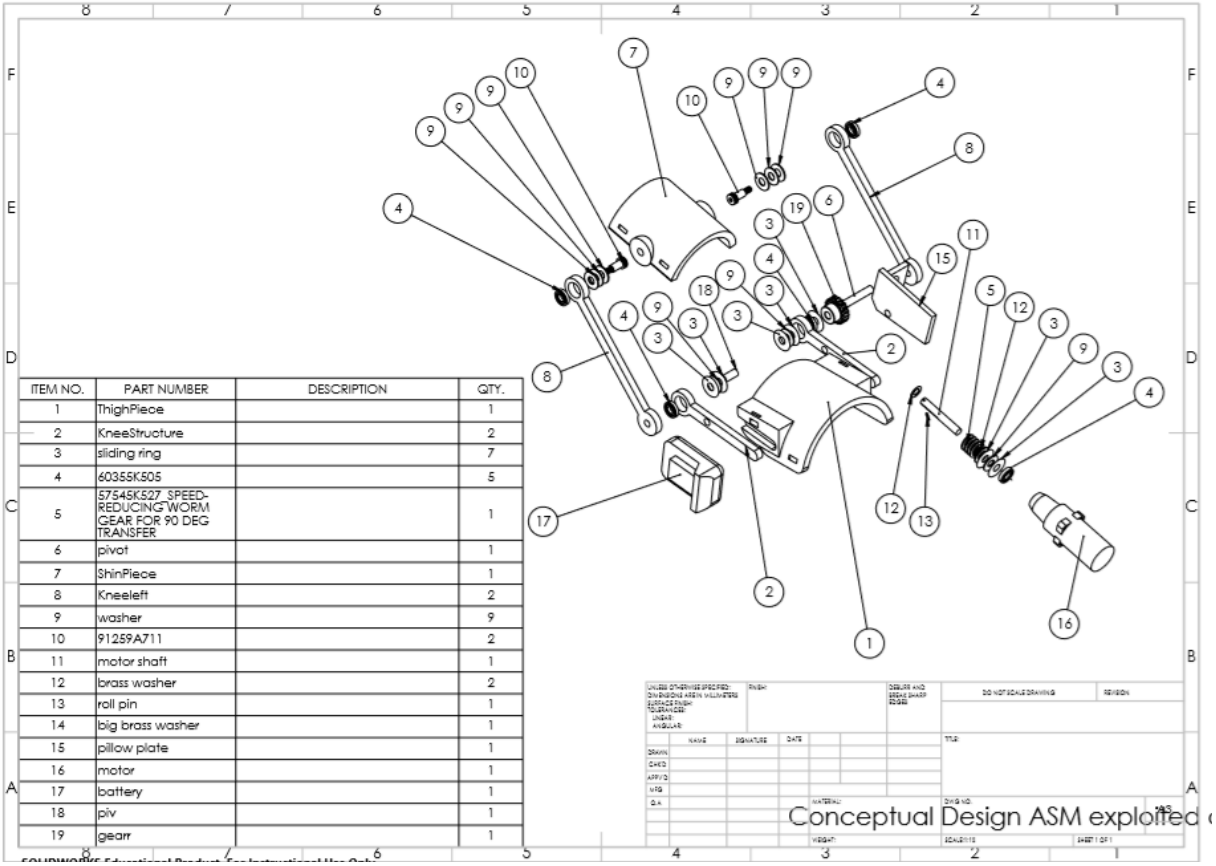

1.67"
Pitch Dia.
1.85"
OD
1/2"
1.125"
0.625"
1.25"
1/2"
Pitch: 12
Number of Teeth: 20
McMASTER-CARR CAD
http://www.mcmaster.com
© 2015 McMaster-Carr Supply Company
Information in this drawing is provided for reference only.
PART NUMBER 57545K513
Speed-Reducing Worm Gear for 90° Angle
Motion Transfer - 14 1/2° Pressure Angle


10.00
ϕ1.13
ϕ0.50
R0.88
R0.88
0.75
Top View
Front View
Side View
Isometric View
EXO 2.0
6061 Aluminum
Kneeleft
A3
8
7
6
5
4
3
2
1
F
E
D
C
B
A

4.2 Assembly drawings (Assembled)



4.3 Exploded-View/Bill of Materials



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	ThighPiece		1
2	KneeStructure		2
3	sliding ring		7
4	60355K505		5
5	57545K527_SPEED-REDUCING WORM GEAR FOR 90 DEG TRANSFER		1
6	pivot		1
7	ShinPiece		1
8	Kneeleft		2
9	washer		9
10	91259A711		2
11	motor shaft		1
12	brass washer		2
13	roll pin		1
14	big brass washer		1
15	pillow plate		1
16	motor		1
17	battery		1
18	piv		1
19	gearr		1

Costs

The total cost of the project to our group was $435, this does not account for the machining of our metal bars which was provided by Aaron's brother, the 3D printing, which was provided by the University, and the time of our team. Realistically if we had to create another leg brace we could reduce costs in certain areas by using pieces of hardware which we already have, but on the other hand the costs of the manufacturing of the plastic and aluminum rods would exceed the savings. Assuming we streamlined the manufacturing process we could build these leg braces much quicker but it would still be very time consuming and would have to sell for close to the going market rate to make it a worthwhile business.

Prototype Testing Results

Our prototype fit together and worked without any major flaws. There are, however, a few areas which could use some improvement. First off, the spur gear was only held to the shaft using a set screw. It really surprises me that it did not come with any type of keyway or set screw hole. We had to drill and tap a hole for a set screw. Under heavy loads, the gear slips on the shaft which is definitely not acceptable. One way that we could remedy this is by cutting a keyway in the shaft and using the set screw as a sort of pin which would lock into the keyway. This too has its problems because the set screw might not be strong enough and could shear off.

Another issue we ran into is the how it mounts to the leg. The straps worked well to keep it tight to the leg, however, the brace is heavy, and when you stand up, it has the tendency to slide down the leg. The only solution to this is to reduce weight and get bigger straps. Traditional leg braces mount the same way so if we can get our weight much lower, then we will be a lot better off.

Also, we realized how important it is that the leg brace is custom fit. Cevat did most of the design on the prototype so it really only fits his leg well. When it doesn't fit well, it tends to slide up and down the leg as it extends and retracts.

One more thing that would definitely change is the way that the electronics mount. Now, they are just stuck to the bottom side of the brace. If this was to be produced professionally, all of the components would be on a single circuit board and there would be very few wires to worry about.

4.4 Mechanical Design

The main concern after selecting the specific conceptual design was to be able to provide enough torque and rpm, revolutions per minute, to be able to generate a responsive and efficient system. While there are many design parameters were taken into account in doing this project, we will define the most notable ones here. Due to simplicity of the explanation and keeping a coherent understanding of the design process, the explanation was detailed in functionality matter. Such as follows: Structural (quality), Motion (electronic functionality), Ergonomics (mechanical functionality).

4.4.1 Structural

The structural segment of this paper consists of selection of correct material and design to provide the most stable leg brace for its functionality needs. We used combination of steel, aluminum, and plastic components needed at specific functions to achieve the most out of each material. While it is important to keep the exoskeleton as sturdy as possible, we also need to take into account the weight of this brace since it is expected to be worn by the patient on a regular basis. For the Shin Cover and Thigh Brace we used ABS Plastic manufactured via 3D Printing methods to be able to have lightweight yet sturdy structure for the application. The fill composition of these parts selected to be 50 percent due to keeping the parts lightweight and increasing the lead time on preparing these parts.

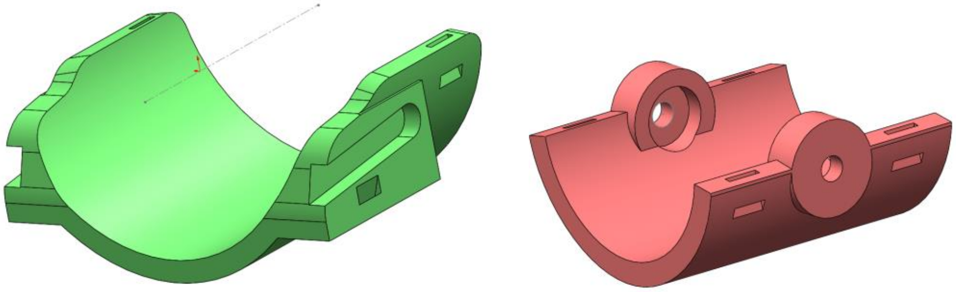


Image 5: Thigh Brace, left; Shin Cover, right

For parts such as Structural Rod and Connecting Rod, we decided to go with 6061 Aluminum due to high material strength, light weight; compared to its steel counterpart, and ease of machinability. With that being said, we also needed a to use either steel or aluminum to press in the bearing to hold in place and also keep it rigid during movement.

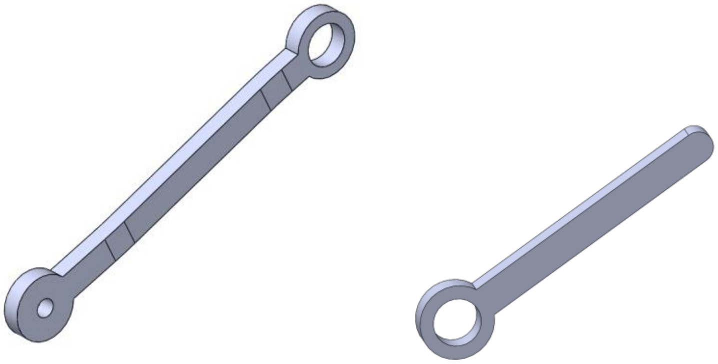


Image 6: Connecting Rod. left; Structural Rod, right

For bolts and nuts we used standard over the counter parts as our design selection due to their complexity of machining and ease of availability in the market. We also used Dowel Pins as our shaft pieces for connecting bearings from Structural rod to Connecting Rod since they are precision cut to be used as shaft and due to its sizing we could press them into our bearings to ensure the rigidity of the brace. These parts are made from high strength steel which is more than capable to withstand the required workload without giving out.

Worm Gear assembly is the far most specialized part in this device as it being a very specific part with high precision machining. Due to the capabilities of our reach, budget, and time given for this project limit our options, we decided to go with another over the counter part since it is widely available part on the market. The garing will give us the 20:1 ratio being 20 times the torque but 20 times less rpm which is acceptable for our application for this project.

4.4.2 Motion

Providing an easy and smooth motion is the key to our leg brace. While it is impossible to eliminate the friction between the physical parts of the device, we used certain measures to eliminate this factor to increase the ease of movement and power loss while increasing the longevity of the use of certain parts. In areas where there is a rotation needed such as:

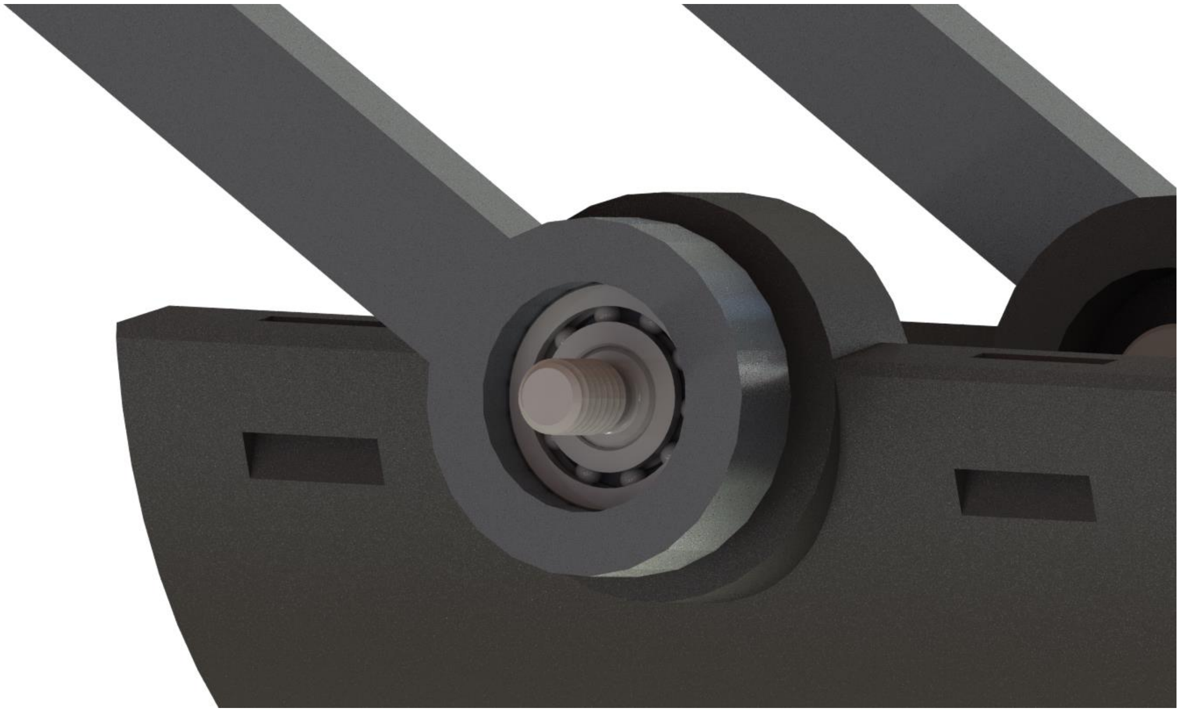


Image 7: Connection between the Connecting Rod and Shin Cover

Where you can see we used ball bearings to provide the rotation without sacrificing too much force on friction. In doing so we were able to achieve high response system with minimal wear and tear.

Another area where we were concerned with friction were the spots in between the Connecting Rod and Structural Rod. The reason for that is due to the metal-on-metal contact where there is high friction. This would have yielded surface irregularities on the material and damaged the parts on the exoskeleton. To prevent this from happening we used UHMW, Ultra High Molecular Weight Polyethylene, to reduce the friction to minimal and minimize the material wear.

4.4.3 Ergonomics

Another section where the design selection of the exoskeleton plays a key part is the Ergonomics of the parts. We understand that the patient will be wearing this device constantly so in order to keep a comfortable orientation on a leg, we used dimensions of a 6’0” 195 lb male as our design parameter for our research purposes. While we are using a subject for our research and development it is not critical in our design aspect to keep it specific since it is designed to be one size fit all product. However, the 3D parts could easily be redimensioned and the rest of the parts could stay the same to keep consistency. It is not necessary to change the dimensions of the 3D printed parts such as the Thigh Brace and the Shin Cover for a person smaller than our subject, which was the original design objective.

4.5 Electrical Design

A big challenge which we ran into was controlling the drill motor. The motor is normally driven by a switch which provides 3 functions. It controls the direction, speed, and provides power to the drill. We carefully dissected the switch while paying attention to each wire and its function.

The direction of the motor was controlled using 3 wires. The white wire was common or ground. The red and black wires were both tied high with pullup resistors. To make the drill go one way or the other, the slider on the drill would actuate an internal switch which would connect either the red or black wire to ground. The control chip would see which one was connected to ground and thus know which way to spin the motor. The speed of the motor was controlled via a simple slide potentiometer. The blue wire was connected to ground, the yellow wire was high, and the green wire was the wiper. Putting the green wire to ground causes the motor to stop, while pulling it high causes the motor to spin full speed. The switch also was a cutoff for the power going into the drill. When the trigger is squeezed slightly, a switch allows power to travel to the motor controller.

Interfacing with all of these components proved to be a challenge. To mimic the direction switch, two VN2222L MOSFETs were used. These are N-channel MOSFETs which can basically be thought of as electric switches. By applying voltage to the gate, current is allowed to flow from the drain to the source. These worked quite well at mimicking the switching action.

To simulate a potentiometer, we used a digital potentiometer. It is an MCP4131. It is an 8-bit chip so it has 256 different levels. This would be plenty for what we were trying to do. It is controlled via an SPI or I2C interface. Since we are using SPI for some other things, we chose to use that. One hiccup with this is that there are not enough pins to do a traditional 4-wire SPI. Instead, the MOSI and MISO pins are duplexed onto a single pin. We just connected the MOSI line since we did not have any need to read the value of the potentiometer.

The large power switch may have had the most cumbersome solution. We used a generic car relay to provide the switch. It is normally operated off of 12 volts but we decided to try using the 18 volts which we already had. Another MOSFET was used to connect the 18-volt supply to power the relay. This would then enable the main power to reach the drill.

We did run into a few problems while trying to connect to the drill. We figured out that the controller has a lot of safety features. For example, if we were to pull both the red and black wires to ground simultaneously, the controller would shut off and would not restart unless we unplugged the battery. To get around problems like this, our sequence had to mimic exactly how it would have normally. First, set the direction, then, enable the power, then write the potentiometer value.

We needed some way to be able to determine how fast and what direction to run the motor. First, we sat and did a few thought experiments to find what would work. One idea that a lot of people suggested to us was using pressure sensors on the brace to determine which way the leg is moving. This would definitely be a simple way to control it, but its concept is flawed. The brace would literally just be moving out of the way of the leg. It seemed the only feasible option was to measure the actual effort exerted by the person. One way of sort of doing this is by using EMG sensors. EMG sensors measure the voltage difference across a muscle on your body. This is a pseudo-representation of the effort being exerted by the person.

To start, we purchased 2 MyoWare chips from Advancer Technologies. These are surface mount EMG sensors with built in amplification, rectification, and integration. This means that it outputs a “smooth” curve. We tested them out and found that they work well on small muscle groups such as your bicep, and mediocre on large muscle groups like the hamstring. Since we would be measuring large muscles, this was an issue. The sensor picked up well on large exertions of force, but had a lot of low end noise. We thought that this would be unacceptable to control the motor by itself. It would be constantly twitching back and forth because of the noise. We needed another solution.

Our plan was then to use some sort of filter with the EMG sensors. The best solution seemed to be to train an AI algorithm. MATLAB has a great application for this called Neural Net Time Series which is fairly easy to use. IT requires a training set of inputs labeled with outputs. We decided that the variable which we want to predict is speed. Our inputs would be from two EMG sensors (one on top and one on bottom of leg). To complement these signals, we decided to use the current position of the brace, as well as the acceleration of the brace in 3 dimensions. The hope was that the acceleration would give the network an idea of what the leg overall was doing. We purchased a breakout board from AdaFruit which had an LIS3DH accelerometer. This also interfaced using SPI. Overall, our neural network would have 6 inputs and 1 output.

Obviously, to train the neural network, we needed a bunch of data. Luckily, our output and inputs were configured in such a way to make it easy. The plan was to disconnect the motor and attach the brace to someone’s leg. Then, that person would walk around, climb stairs, stand, etc. Meanwhile, the data would be logged onto a microSD card. We purchased another breakout board from AdaFruit which had a socket for a microSD card. Once again, it uses an SPI interface, so we had 3 different devices connected using SPI.

We knew our design wouldn’t work perfect the first time, so we decided to create a control box to give the user some power. The control box consisted of 3 potentiometers, one on-off switch, and one mom-off-mom switch. The momentary switch would give the user capability to jog the brace in or out. This would override the AI algorithm. If, one wanted to completely disable the AI algorithm, we provided the on-off switch. Finally, the 3 potentiometers were to be used to fine tune the machine. One was going to control sensitivity, another would control the bias or trim, and the last would control the dropout threshold. Both of the switches acted to pull their connected wires to ground. The respective pins on the microcontroller were tied high with internal pullup resistors. The outputs of the potentiometer were connected to 3 additional AD converters on the LIS3DH board. This was done so as not to use up pins on the microcontroller.

To tie all of this together, we needed a capable microcontroller. DFRobot sells a very small bluetooth capable microcontroller called the Beetle BLE. We chose this one because we needed bluetooth to interface between the sensors on the leg and the brace. Looking in the future, the sensors would be integrated into some type of compression shorts. These would be worn under regular clothes and transmit wirelessly to the brace. We purchased 2 Beetle BLEs. One was to be used for the brace, and the other for the sensors. These microcontrollers are also Arduino compatible which is very nice.

We ran into a major roadblock when programming the microcontroller. The SPI interface proved to be much more difficult than expected. We were able to get the microcontroller to enable the power to the motor and choose a direction, but the digital potentiometer did not work as planned. We still connected all of the electronics that we had purchased, but only the jog function works on the brace.

Old Design: Exo 1.0

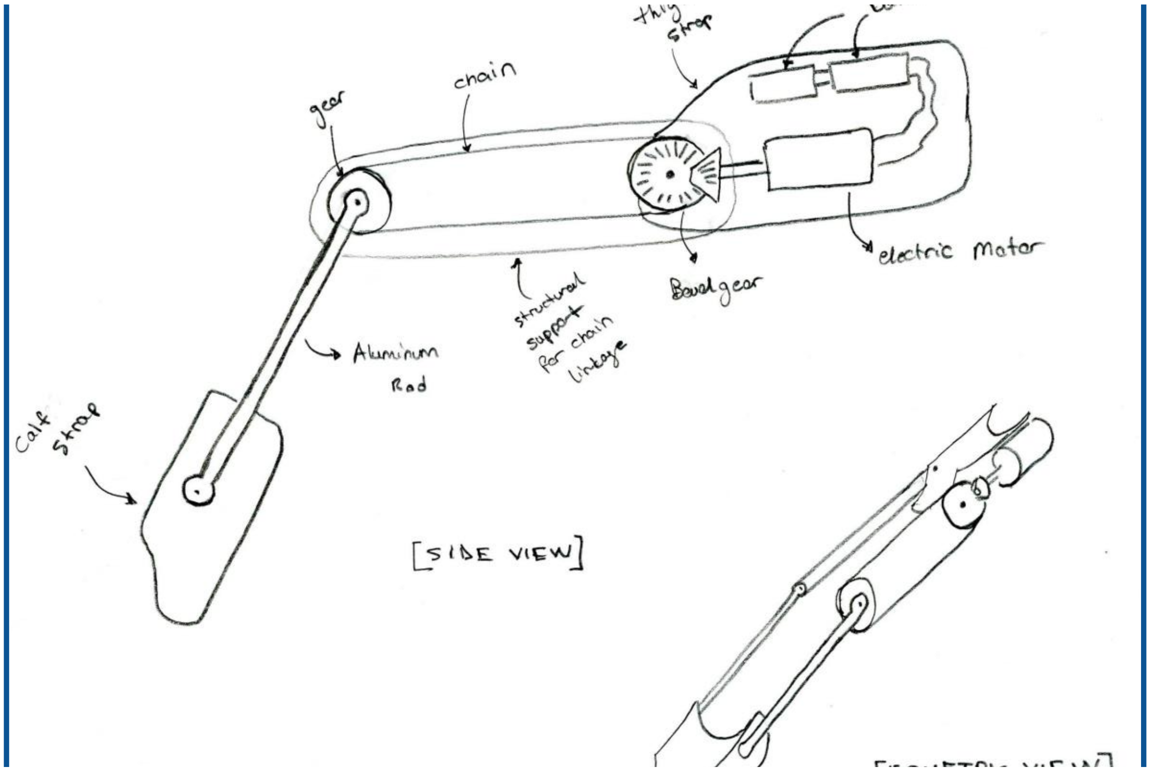


Figure 7: Hand sketches of the Exoskeleton 1.0

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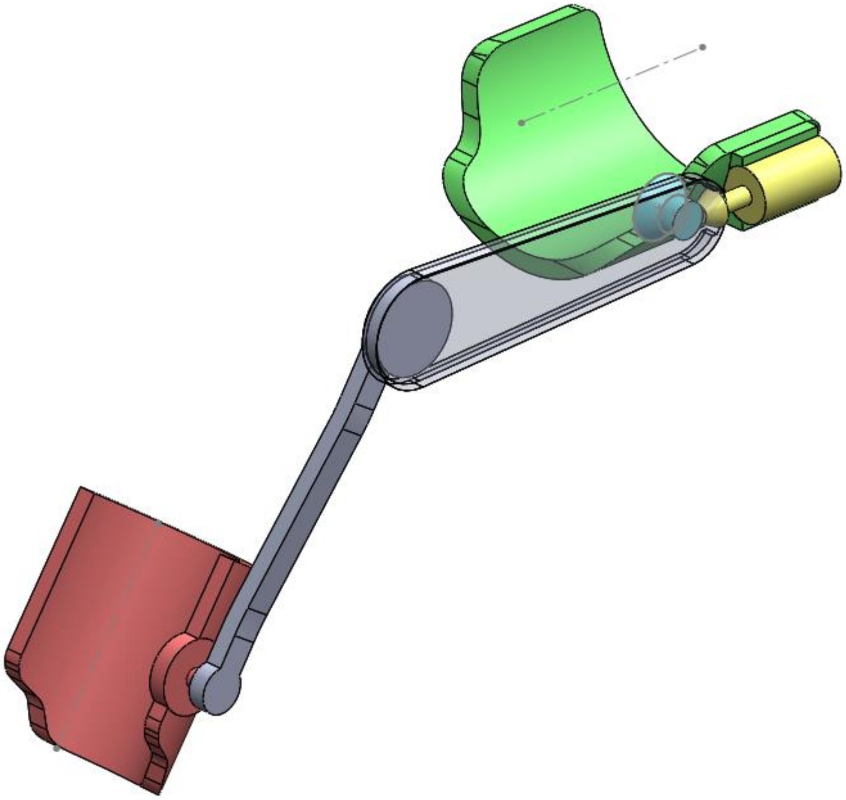


Image 8: 3D view of CAD design of the Exoskeleton 1.0

Exo 1.0 Component Description:

- **Thigh Brace:** The green part on the upper corner is the thigh brace that straps around the subjects leg to grip and provide structural support. This allows the motion of leg to be linked with the Exoskeleton.
- **Electric Motor:** The yellow piece on the upper right corner, attached to the Thigh Brace, is the electric motor that will be used to power the motion of the Exoskeleton. Using an electric motor gives us the advantage of high response to motion and a lightweight power supply.

- **Chain Cover:** The transparent part that runs between the electric motor to the Connecting Rod is the housing for the Chain Link. This provides a housing for the chain and structural support for the whole piece to stay in tact.
- **Chain Link:** Chain is not shown in the drawing but it transfers power between the electric motor and the Connecting Rod. It is stored in the Chain Cover.
- **Connecting Rod:** The Connecting Rod, grey, holds the Shin Brace and transfers the motion from the Chain Link to Shin Brace. This way the lower part of the leg, under knee, can move up and down.
- **Shin Cover:** Shin Cover, burgundy, is the strap that attaches to the subjects shin to hold it in place and secure the exoskeleton. This allows the Exoskeleton to properly aid the subject in walking and climbing the stairs.

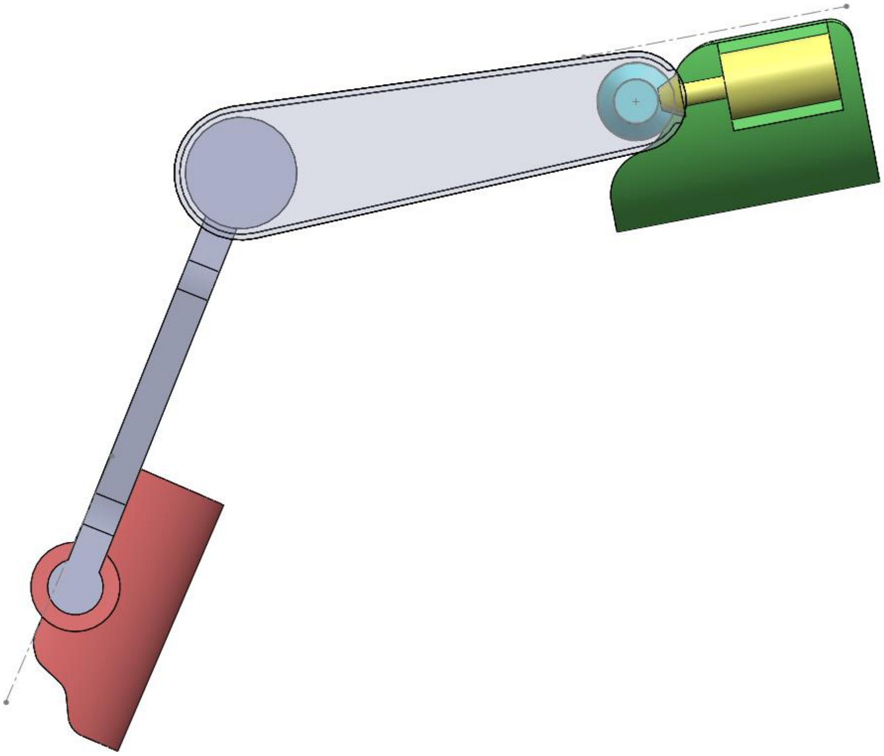


Image 9: Side view of the Exoskeleton.

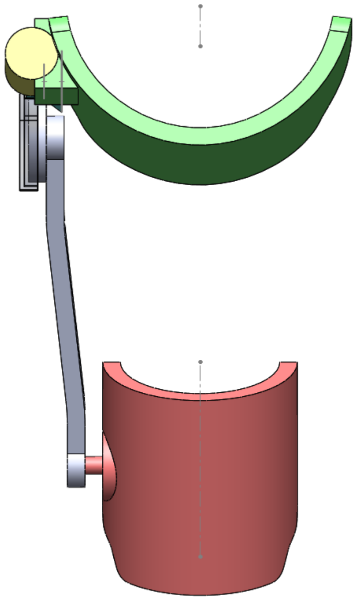


image 10: Rear view of the Exoskeleton.

5.0 Discussions

This year long project was a great learning experience as it allowed us to put to use much of the theoretical knowledge learned over our time at the University of Akron into a practical application. Now that we are finished with it, we can look back and see what we would have done differently the next time around. Our drivetrain system is effective since we used the proven technology of a worm gear and sprocket system, however this sort of arrangement is cumbersome, heavy, and may frighten some users to see such a large gear driven system moving about right next to their leg. If we could do it again, we would use the same type of gear system but with smaller components, and a dedicated motor where the casing of the drill wouldn’t take up as much space. We would also have a enclosure around all of this to keep it out of the elements and to ensure reliable usage.

Another thing we struggled with was getting the Arduino to connect correctly with the sensors. This part of the project was very time consuming and we were not able to complete it within our given time frame. This part of the experiment was more of a computer science project and if we had a multi-disciplinary team it may have been finished.

The aluminum bars we used for the project are very thick, and more than strong enough for anyone this product is designed for. The next iteration of leg brace can have much smaller aluminum bars which will drastically improve the ergonomics of the leg brace and also lower the cost.

6.0 Conclusion

The lower limb exoskeleton leg brace was designed to be a device which assisted elderly people in climbing stairs. The project was sponsored by Global Discovery Labs in Dayton, Ohio. Throughout the design process we realized that this device can be used for more than applications than we intended and can be a general purpose mobility aid. This machine will meet industry demands, as all of the other existing machines that have similar functionality are much more cumbersome and wrap around the waist, and also cost much more.

7.0 References

"316 And 316L Stainless Steel Sheet, Coil & Bar - AMS 5524, 5507, UNS S31600, S31603." *United Performance Metals*, 29 Jan. 2019, www.upmet.com/products/stainless-steel/316316l.

"Alloy Steel Shoulder Screw." *McMaster-Carr*, www.mcmaster.com/91259a707.

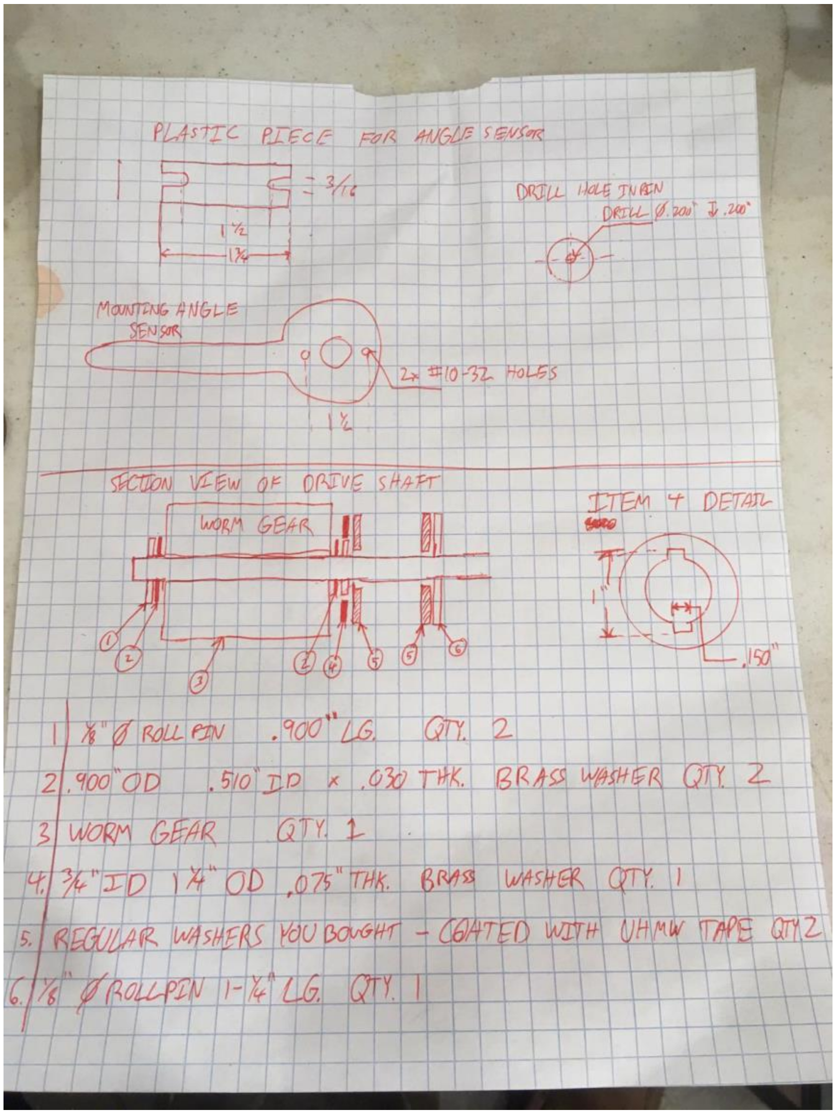
AZoM, Written by. "AISI 1144 Carbon Steel (UNS G11440)." *AZoM.com*, 19 Feb. 2018,

Croce, R V, et al. "Peak Torque, Average Power, and Hamstrings/Quadriceps Ratios in Nondisabled Adults and Adults with Mental Retardation." *Archives of Physical Medicine and Rehabilitation*, U.S. National Library of Medicine, Apr. 1996, www.ncbi.nlm.nih.gov/pubmed/8607761.

Engineercampus. "Embodiment Design - Part 1: The Basic Rules and Principles." *Steemit*, steemit.com/engineering/@engineercampus/embodiment-design-part-1-the-basic-rules-and-principles.

"Failure Mode & Effects Analysis (FMEA)." *ASQ*, asq.org/quality-resources/fmea.

8.0 Appendices



1 | 1/8" Ø ROLL PIN .900" LG. QTY. 2

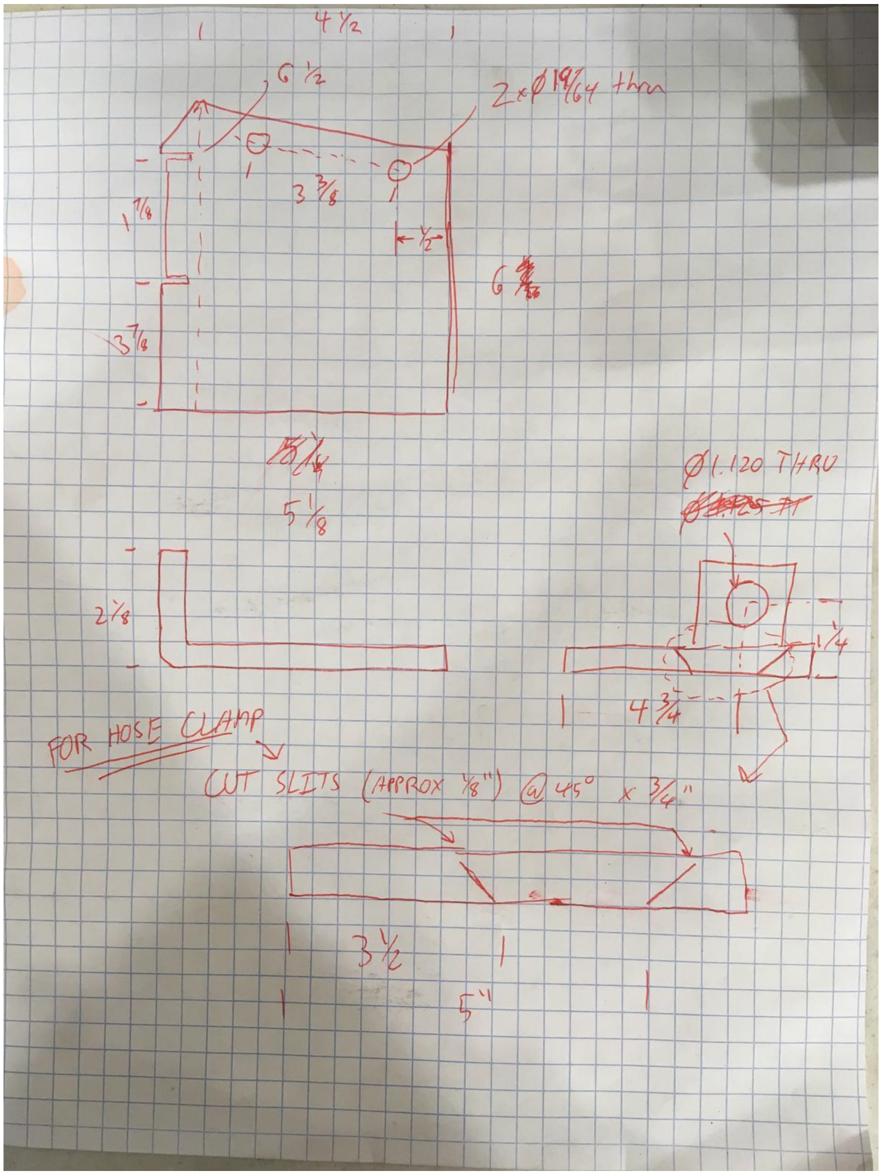
2 | .900" OD .510" ID x .030 THK. BRASS WASHER QTY. 2

3 | WORM GEAR QTY. 1

4. | 3/4" ID 1 1/4" OD .075" THK. BRASS WASHER QTY. 1

5. | REGULAR WASHERS YOU BOUGHT – COATED WITH UHMW TAPE QTY 2

6. | 1/8" Ø ROLLPIN 1-1/4" LG. QTY. 1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6 1/2
2× ∅ 19/64 thru
3 3/8
1 7/8
1/2
6 ~~?~~/16
3 7/8
~~?~~ 1/4
5 1/8
2 1/8
∅ 1.120 THRU
~~∅ 1.125 TH~~
1/4
4 3/4
FOR HOSE CLAMP
CUT SLITS (APPROX 1/8") @ 45° x 3/4"
3 1/2
5"


14
16
18
Milwaukee
BRUSHLESS


BRUSHLESS

$\Rightarrow$