

The Strays: Final Report

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In loving memory of Cleopatra

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Leading Concepts, Preliminary Drawings, and Associated Tasks

This section will cover the leading concepts and preliminary ideas/designs for our custom dog wheelchair. Final designs and drawings will be presented later in the report, with intermediate adjustments and rationale explained along the way. A Gantt chart and task list is provided in the appendix as Figure 1 and 2. Tasked with designing a custom dog wheelchair for Cleopatra, a 60-pound pitbull-terrier mix, we first sought to analyze her current wheelchair by Walkin' Pets, searching for aspects that could be improved. The goal of our first drawing (shown in Figure 1 below) was to imitate the general structure and design of most major dog wheelchairs while acting as a blank slate for further development.

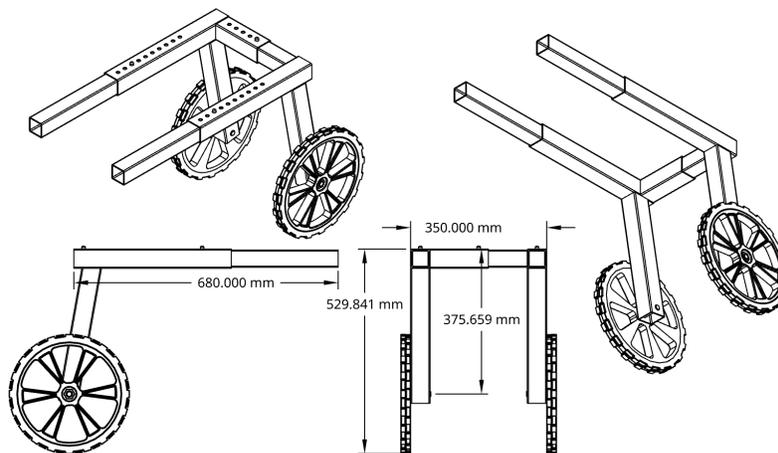


Figure 1. Image of preliminary design idea and drawing.

As shown in the preliminary drawing above, we committed to building a wheelchair with size adjustability. Although it was meant to be a custom wheelchair for Cleopatra, we wanted to design a product that could last past her lifetime and continue to be used for other dogs of various sizes. This versatility makes it easy to adjust the wheelchair's size to match variations in the dog's body size brought on by growth, weight gain, or weight loss. This is especially helpful for puppies, as it is likely that a customer would prefer to make a singular purchase for a wheelchair that would last the dog's entire lifetime. Our initial design for size adjustability is

shown in Figure 2 below, using square telescoping tubing where the inner tubing is tapped, allowing for a screw to fix the size adjustment.

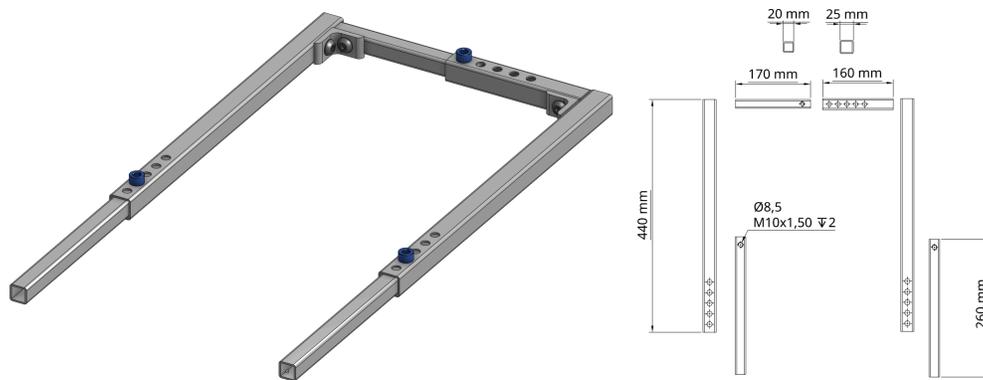


Figure 2. Image of Preliminary Telescoping Frame in CAD and Drawing.

Note that this same size adjustability idea was also used on the leg links to allow for height adjustability, while frame adjustability controls length and width.

Through customer needs analysis (detailed in our project proposal) we found that while not often used in commercial dog wheelchairs due to cost, active dogs such as Cleopatra could benefit from a suspension system on their dog wheelchair, absorbing shock and vibration on difficult or uneven terrain. By lessening the jolting and bouncing that might happen with more rigid wheelchairs, this feature guarantees a smoother ride and reduces the possibility of further stress or harm to the pet's body. To integrate suspension into our dog wheelchair, our initial design was centered around the commercial “ROSTA” suspension unit, shown in Figure 3 below.

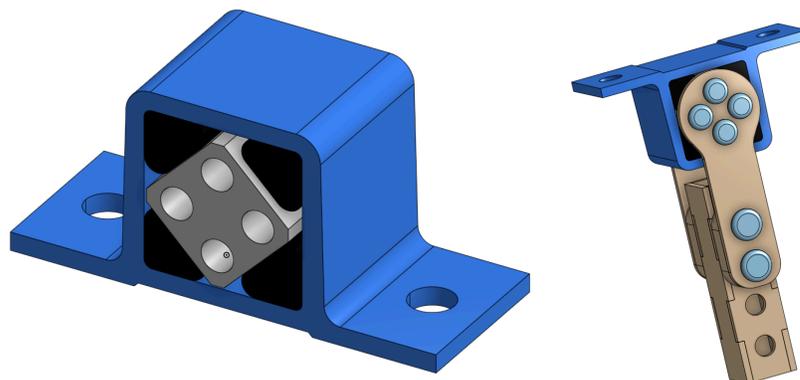


Figure 3. Image of ROSTA suspension unit and connection to legs in CAD.

ROSTA suspension units surround a connection joint with a patented rubber compound. In our case, torque is applied to the rubber through the leg due to the caster angle of the wheel, such that shock is absorbed into the suspension unit.

We also found through our customer needs analysis that another niche we wanted to fill was to allow a dog to sit or lie down in its wheelchair, as using a wheelchair for extended periods creates stress and fatigue in the dog's front legs. Most dog wheelchairs do not have this functionality, as any compliance or lack of structural integrity of the rear wheels and legs can create accidents and damage to a dog's already paralyzed or weak legs. To create this functionality, we made two designs: a 360-degree fully rotational pivot joint that connects to the main frame, and an elbow hinge that allows for the legs to fold up, both of which are shown in Figure 4 below.

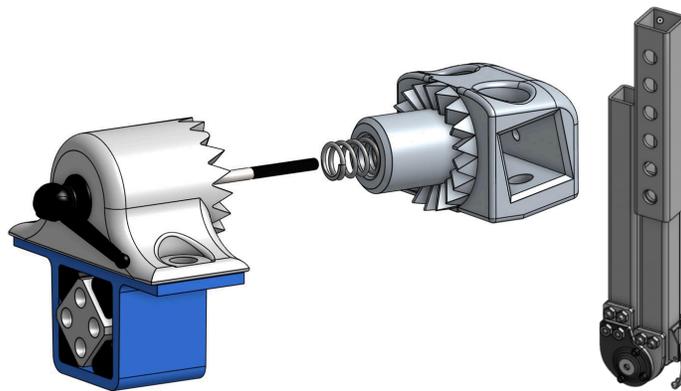


Figure 4. Image of rotational pivot joint and elbow hinge in CAD

The pivot joint works similar to a bicycle quick release, utilizing a spring in compression such that when the quick release is pulled, the joint is free to pivot. Notice that the pivot attaches to the frame at a preset camber angle of 10 degrees. The teeth control the angle of adjustability and force a stopping point. The elbow hinge is a traditional hinge with a guide, which maintains the straightness of the joint until force is applied. Allowing the legs to fold up increases the

wheelchair's portability as well. The pivot joint also gives us control of the caster angle of our wheels. By adjusting the wheelchair's caster angle, we not only control the sharpness of steering but also the amount of torque placed on the ROSTA suspension unit. For example, a larger caster angle puts more torque on the ROSTA unit. Therefore, depending on changing terrain or varying dog weight, the dog owner can adjust the caster angle for a smoother ride.

Our “low-resolution prototype” was quite detailed due to our eagerness to test the viability of our niche technologies, the pivot, suspension, and elbow hinge. Our wheelchair frame and legs were made from puzzle-fit laser-cut wood, with 3D-printed plastic dowels to fix the telescoping mechanism. We created mock ROSTA suspension units using a 3D-printed plastic enclosure and TPU suspension blocks, plastic pivot joints, and laser-cut wood flaps for the elbow hinge. Both the CAD and prototype are shown in Figure 5 below.

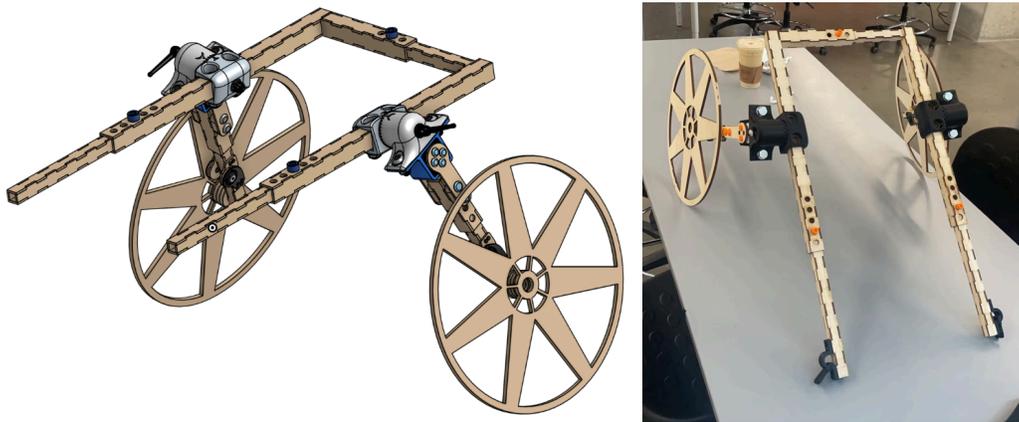


Figure 5. Images of first prototype in CAD and assembled product

From this first prototype, we found that our pivots and mock ROSTA suspension units were functional and showed promise, but our elbow hinge was unnecessary. Because the pivot is fully rotational, there is no need to further fold up the legs, and this additional mechanism would only create more complexity, points of failure, and cost to our design.

FMEA (Preliminary and Final):***Preliminary FMEA***

Prior to manufacturing the preliminary prototype, an FMEA was performed in order to identify the aspects of the design that were at the greatest risk of failing and develop ideas to lessen these risks. One example of this is the preliminary pivot joint design. If the pivot joint has any sort of damage or wear to the teeth, the leg of the wheelchair will become unable to stay in a constant position, making the wheelchair much more difficult, and even impossible to use. Additionally, due to the fact that the joint transfers much of the weight of the dog and the frame of the wheelchair onto the legs, any damage such as cracking or fractures could cause the leg to become detached from the wheelchair and become unusable without replacing the joint, which is custom made. These risks were primarily due to the fact that this component was 3D printed out of PLA, meaning that the material it was made out of was not the strongest, however due to its shape, 3D printing was the only way to manufacture it. Another component that had great risk was the hinge along the leg of the wheelchair. Due to it being along the leg, that meant that it would be supporting the entire weight of the dog. Despite the hinge being made out of aluminum, its size and location leads to concerns about it fracturing and breaking the leg, making the wheelchair unusable. The frame is primarily made out of aluminum with stainless steel fasteners. Aluminum was the primary choice because of its strength-to-weight ratio, the decreased cost in comparison to other materials such as Stainless Steel, and the fact that it is anti-corrosive, allowing for it to be used in any weather condition. The fasteners were stainless steel due to their corrosive resistance as well as their increased strength in comparison to materials such as aluminum. However, if these fasteners are not installed properly, the material properties will not matter as the wheelchair could come apart and possibly damage the dog. The complete preliminary FMEA can be seen in figure 20 in the appendix.

Final FMEA

After assembling our final prototype, an updated FMEA was created including revisions that were made based on the simulations and observations made on our preliminary prototype and the adjusted RPN ratings of each of these components. The major changes made to our design were related to the leg hinge, as well as the usage of the quick-release axles. After assembling the preliminary prototype, we noticed that the leg hinge had difficulties supporting large loads, and its functionality was very similar to that of the pivot joint that we were planning on implementing. To solve this problem, we removed the hinge entirely and adjusted the shape of the pivot joint to allow for the leg to fold entirely upwards, allowing for the dog to enter a sitting position, similar to what it would have been able to do with the leg hinge. Another issue we noticed was that the quick-release skewer that was going through the wheel did not have the stability or strength that we had hoped for. To solve this problem, the ¼in diameter aluminum skewer was replaced with a ½in diameter stainless steel shaft. This shaft had a much more secure fit in the bearing of the wheel and additionally had a lower risk of failing under large stress concentrations in comparison to the skewer.

Prior to the showcase, we were worried about the long-term durability of the PLA pivot joints we had used due to the material's strength. We ended up reprinting them out of carbon fiber-infused nylon instead, giving the joints greater yield strength and lessening our worries about long-term wear affecting the performance of the joint. Figure 21 in the appendix, our final FMEA, provides a list of each component and their failure modes, the updated revisions we made to them in comparison to our preliminary design, and our updated RPN ratings of each.

Experimentation (Design and Results)

Response Variables

To determine the durability and structural integrity of the ROSTA pivot joint, we wanted to test for any failure during normal operating conditions at the joint and beyond. The pivot joint takes the load of the wheelchair's weight along with the dog's weight supported by the wheelchair, which is the weight that should be supported by the rear legs. To test the durability, we expect each pivot joint, when mounted to the leg and frame, to withstand at least 280.23 N of force normal to the ground and a torque of 30.054 Nm at each pivot's teeth, considering a safety factor of 3.0.

In most dogs, the front-rear weight distribution is 60-40, but to be safe in case Cleopatra or any other dog harnessed to our wheelchair needs to be supported or counterbalanced more towards the rear to alleviate front leg stress, we will assume that 60% of their weight will be in the rear. Since she is around 70 lbs, the rear pivots should be able to comfortably support 42 lbs, which equates to 93.4 N at each joint, normal to the ground. This force will need to be supported by each leg as well as each joint, however, each joint will have a torque induced on its hirth teeth by the 93.4 N load. With a 253 mm leg length from axle to ROSTA pivot mount (280mm from axle to pivot teeth center) and a sag leg angle of 25° under the dog's weight with the ROSTA suspension engaging, the torque on each joint is 10.018 Nm. This means that the Hirth teeth on the 3D printed joint must withstand a minimum of 10.018 Nm as well.

Considering a factor of safety of 3.0, similar to that used on automobiles, failure should not occur on any component of each joint under 280.23 N of load normal to the ground from the wheel. Furthermore, each pivot's teeth should withstand up to 30.054 Nm of torque. We opted for a safety factor of 3.0, because, although it is likely overkill, when the dog is moving and hits

a large, square-edged obstacle such as a stair, the momentum of the dog will momentarily induce a larger force and torque on the pivot joint than just the dog's standing weight alone. This should be accounted for with a safety factor of 3.0, as this is similarly used for car suspension systems.

Control Factors

Numerous design factors can contribute to the maximum load and torque able to be endured by each pivot joint. These factors include:

- **Camber angle:** a greater negative camber induces a greater torque on the pivot joint.
- **Leg initial angle:** if the initial leg angle is increased (more caster), then the induced torque will increase since more of the normal load will be transferred as torque
- **Leg sag angle:** when weighted, a more supple suspension (smaller vs. larger ROSTA unit) will pivot the leg more, inducing a greater angle and, therefore, a greater torque
- **Leg length vs wheel diameter:** a longer leg length induces a greater torque on the pivot, but to maintain the correct wheelchair height, the wheel diameter must simultaneously be proportionally decreased
- **Teeth geometry:** generally, the number of teeth should not affect the strength, but the teeth's shape, size, and fitment engagement can affect the torque it can endure because of changes in the total torque contact patch area
- **Pivot cylindrical diameter:** this design factor greatly affects the maximum torque endured, with a larger diameter teeth ring decreasing the torque concentration
- **Width from the frame:** a pivot joint with a longer distance from the frame will increase the torque induced on it

- **Pivot joint material:** Carbon-reinforced nylon is strong, but aluminum can also meet durability requirements but is substantially more expensive to manufacture

To narrow down our approach with constraints, we will focus on the pivot's cylindrical diameter and teeth sizing/geometry because these are the most direct factors in reducing the torque exerted on the pivot joint and one of the easiest to alter in terms of the joint design parameters. We must find a balance in overall joint sizing vs. torque induced on the joint. Every other control factor has been accounted for during the initial design process to minimize the torque exerted on the pivot joint without compromising other design features such as stability, sizing, and weight. This includes our final camber angle of 10° , a maximum leg length of 280mm, and our sag angle of 25° due to our chosen model of ROSTA unit, which has set torque specifications due to the elastomer's properties.

Noise Factors

Noise factors include variables that may influence the strength of the pivot that may be out of our control. These factors include:

- Large, rough-edged obstacles encountered at high speeds, that would exceed a safety factor of 3.0 (beyond regular use of product: user abuse)
- Carbon-reinforced nylon aging: nylon degrades over time with thermal and UV radiation
- 3D printing quality: there are certain things we can do in preparation for the best quality prints, but in the end, it is up to the printer's quality and probability of providing a good quality print with minimized imperfections and proper layering

Experimental Setup

We will narrow down our control factors to 2 (Teeth geometry and pivot cylindrical diameter) because these two design factors are most influential for the level of force and torque the pivot can endure, which are our response variables. Furthermore, we simply do not have the funding to manufacture numerous iterations for each control factor along with multiple control factors to manufacture separate combinations of iterations for, along with duplicates for repeated trials. With 2 control factors, 2 levels for each control factor, and 2 repeated trials, that is already 8 pivot joint units we would have to manufacture, and carbon-reinforced nylon is not cheap. Each pivot joint unit (2 pieces) costs \$40 to 3D print even without the carbon fiber filament. That would be \$320 to test the pivot joints alone until failure for 2 repeated trials, which is simply beyond our budget for this project.

With 2 control factors, and 2 levels ($((2 \text{ levels})^{(2 \text{ control factors})} * 2 \text{ trials}) = 8 \text{ units}$), we will perform a cyclical force loading of 100 cycles on the joint mounted to the frame and leg starting at 100 N with 50 N increments until 350 N, normal to the ground on each of the 4 combinations. If the combination does not fail, which it should not to meet our factor of safety of 3.0, it is ready to move on to the next testing phase: the torque test. Each of the 4 combinations, if not already compromised until failure, will undergo 200 cycles of torque loading from 10 Nm to 60 Nm (F.O.S. of 6.0), in 10 Nm increments. When any part of the unit fails (cracks, plastically bends, or snaps), it will be recorded at the respective force or torque load endured, as well as the number of cycles endured before being discarded from testing.

We will organize the experiment using a Full-Factorial Matrix design. We want our pivot joint to meet or exceed 280.23 N of load normal to the ground and 30.054 Nm of torque on the teeth. The experiment is designed to go past these parameters to get an idea of where their failure

points occur, even if they exceed our required strength specifications. The experimental design is laid out below in Figure 6:

Figure 6: Pivot Joint Strength Experimental Design

Pivot Joint Load Test				
Force Induced on Pivot	Control Factor 1: Teeth Geometry			
	Level 1: 18 Triangular Teeth		Level 2: 36 Rectangular Teeth	
	Control Factor 2: Pivot Cylindrical Diameter		Control Factor 2: Pivot Cylindrical Diameter	
100 cycles at each force (N)	Level 1: 50 mm Diameter	Level 2: 75 mm Diameter	Level 1: 50 mm Diameter	Level 2: 75 mm Diameter
	Iteration 1: 18 Triangular Teeth, 50 mm Diameter	Iteration 2: 18 Triangular Teeth, 75 mm Diameter	Iteration 3: 18 Rectangular Teeth, 50 mm Diameter	Iteration 4: 18 Rectangular Teeth, 75 mm Diameter
100	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)
150	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)
200	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)
250	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)
300	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)
350	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)
Pivot Joint Torque Test				
Force Induced on Pivot	Control Factor 1: Teeth Geometry			
	Level 1: 18 Triangular Teeth		Level 2: 36 Rectangular Teeth	
	Control Factor 2: Pivot Cylindrical Diameter		Control Factor 2: Pivot Cylindrical Diameter	
200 cycles at each Torque (Nm)	Level 1: 50 mm Diameter	Level 2: 75 mm Diameter	Level 1: 50 mm Diameter	Level 2: 75 mm Diameter
	Iteration 1: 18 Triangular Teeth, 50 mm Diameter	Iteration 2: 18 Triangular Teeth, 75 mm Diameter	Iteration 3: 18 Rectangular Teeth, 50 mm Diameter	Iteration 4: 18 Rectangular Teeth, 75 mm Diameter
10	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)	(Pass) OR (Cycles until Failure)

20	(Pass) OR (Cycles until Failure)			
30	(Pass) OR (Cycles until Failure)			
40	(Pass) OR (Cycles until Failure)			
50	(Pass) OR (Cycles until Failure)			
60	(Pass) OR (Cycles until Failure)			

Experimental Procedure

1. Fasten the respective pivot joint to be tested (begin with one of the four iterations) to the aluminum frame and the leg with the axle bolt fastened.
2. Set the teeth alignment to 20° as the initial caster (not under load).
3. Flip the wheelchair assembly upside down and place the side of the frame with the joint to be tested in a vice to secure it in place for the load and torque tests.
4. Attach a digital tensile scale to the wheel axle bolt.
5. Beginning with the normal load tests, apply 100 cycles for each force from 100 N to 350 N in 50 N increments. Perform each cycle by pulling down on the digital scale until the load requirement is met and then completely releasing in a controlled manner to set the load back to 0 N. The cycles should be performed continuously with each cycle taking 1 second of consistent pulling, loading, and releasing.
6. If the joint experiences any plastic deformation, filament cracking, or slippage, end the test and note the number of cycles endured and which load it took place in.
7. If the joint passes all cyclical normal load tests, proceed with the torque tests in a similar manner to the normal loading tests, starting at 10 Nm and increasing to 60 Nm in 10 Nm increments for each cyclic torque test. To pull the correct torque, ensure the digital scale is

now performed tangentially to the leg's pivoting radius instead of directly down as done in the normal force loading. With the leg length set to 280mm, the starting load should be 35.71 N tangent to the pivoting radius for the 10 Nm test. This will be a tangential load of 71.42 N, 107.14 N, 142.86 N, 178.57 N, and 214.28 N for the 20 Nm, 30 Nm, 40 Nm, 50 Nm, and 60 Nm tests, respectively. The cycles should be performed continuously with each cycle taking 1 second of consistent pulling, loading, and releasing.

8. If the joint experiences any plastic deformation, filament cracking, or slippage, end the test and note the number of cycles endured and which torque it took place at.
9. Repeat this process for each of the 4 pivot joint design iterations and perform a repeated trial for each iteration: a total of 8 experimental tests.

Experimental Results

Because of our budgeting constraints, we were not able to perform our Full-Factorial Matrix experimental design on each of our pivot joint design iterations. With the total cost of our wheelchair totaling ~\$650 with just 3D printed PLA joints, we were already struggling with deciding to afford the extra \$80 in printing one iteration of 3D printed nylon joints. We decided to pitch in and pay extra out of our pockets to manufacture the nylon joints for durability purposes, but this was for the final product donation and not for testing purposes. However, we were able to perform stress testing on the PLA joints before switching to nylon. The PLA joints alone exceeded our expectations by surviving a cyclic loading of 100 cycles for 30 Nm, which was our required load with a safety factor of 3. We decided not to go past 30 Nm and try to test until failure for the PLA joints so that we could donate these to Austin Pets Alive as spare parts. With stronger 3D-printed nylon joints along with improved teeth fitment and engagement for our final product, it is safe to say that they go past a safety factor of 3.0 in repeated torque loading.

With our design, we managed to concentrate the load specifically into shear stress so that the teeth were able to endure past normally intended usage. The usage of cammed quick-release skewers ensured that sufficient compression was present to transmit the torque through the joint without teeth slippage or breakage. We decided that an experimental design approach was more appropriate to analyze the strength of the pivot joints rather than a computer-simulated FEA analysis because the real-world testing allowed for failure testing due to fatigue as well as the 3D-printed layer lines, which are not present in FEA mesh analysis.

SOLIDWORKS Simulation (FEA Analysis)

Frame Loading Simulation

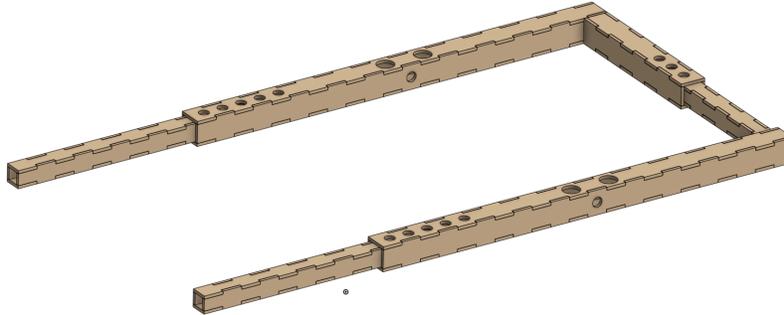


Figure 7. Image of low-resolution wheelchair frame design in CAD

Frame loading simulation was completed on our preliminary or “low resolution” design. Shown above was the initial design for the frame. Note that while the plan was to build the frame using laser cut wood, FEA simulation was completed using 6061 steel as prep for the real product. Each of the individual frame pieces were mated together, as we assumed that our L brackets and corner covers would sufficiently maintain the structural integrity of the frame. Our main purpose was to test the deflection on the frame caused by Cleopatra’s weight. Two point forces of about 3 lbs were placed near the stirrup mounts to represent each of her legs, with two 12 lb points near the pivot joints to represent force supported by the back harness and two 3 lb point forces at the front of the chair where the front harness attaches. Note that we can approximate that 60% of a dog’s weight is supported by its back legs, which in Cleopatra’s case is 36 lbs. Finally, a distributed weight is placed across the top of the frame to account for the weight of the frame itself. These forces sum to 36 lbs.

Boundary Conditions

To run this analysis, the frame-leg connection was fixed. A total FEA analysis including the wheels and legs is not possible due to the complexity of the pivot joints and ROSTA unit

causing issues with creating a mesh. Using a spring support may have been a more accurate representation as we will be utilizing a suspension unit. The final setup is pictured below.

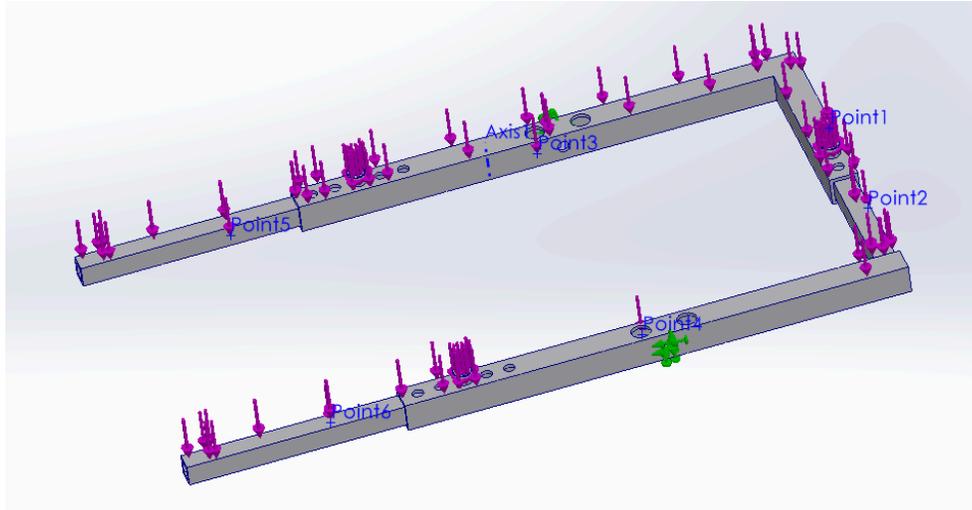


Figure 8. Image of boundary conditions and loading for frame simulation

Results

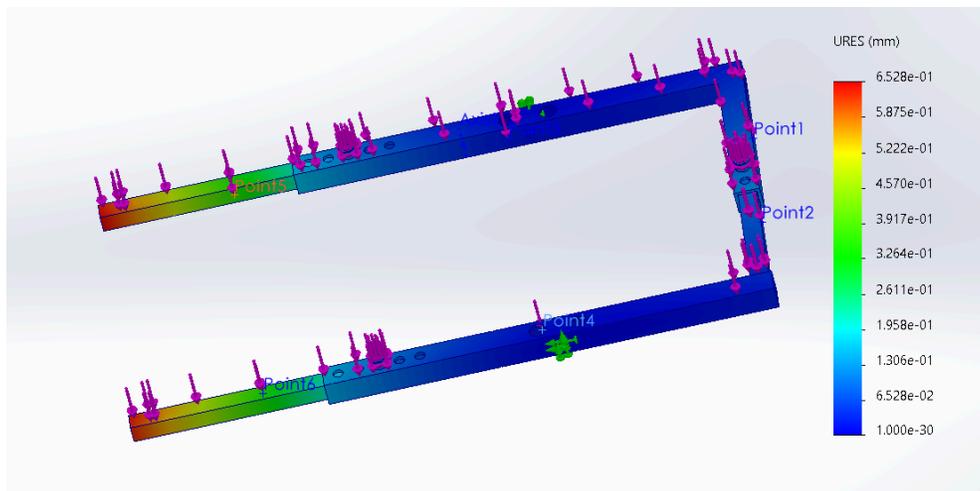


Figure 9. Image of frame simulation results.

As shown in the results above, the largest deformation occurs at the front of the wheelchair, the furthest location from the legs which connect to the ground on the smaller inner

tubing. Maximum deformation is rather small, only reaching 0.6 mm. Because of such a small maximum deformation, further experimentation was not considered needed.

Stirrup Mount Simulation

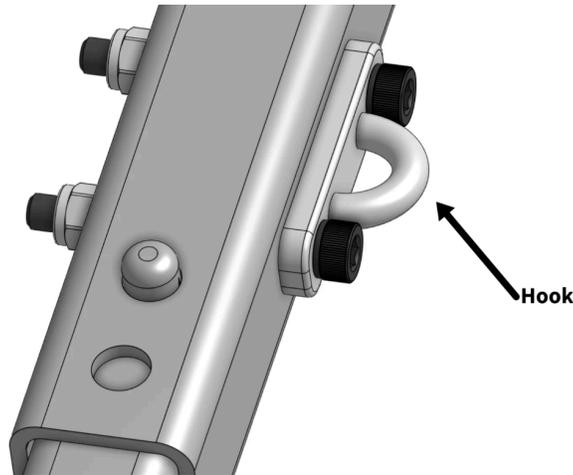


Figure 10. Image of stirrup mount in the CAD assembly.

Above is the final stirrup mount design in the assembly. The stirrup mount is light blue, and it is held to the frame with a bolt that extends through the entire aluminum tubing. On the other end, a lock nut is used to fasten the mount to the frame and prevent loosening over time.

Each stirrup mount must support a stirrup attached to one of Cleopatra's legs. A 5 lb approximation was used for this point force for the static case. Of course, Cleopatra will be moving and the maximum force on the hook could surpass 5 lbs, so the mount must have a sufficient factor of safety. When designing for this application, the thickness of the hook must be adjusted to be able to support a force of this magnitude. To evaluate this component of the final design, SOLIDWORKS simulation was employed. The results can be found in the next section.

Boundary Conditions

To run this analysis, the back face of the stirrup mount was fixed. This is a valid assumption because the bolts will be screwed in tightly, and the back face should not move due

to friction between the frame and the mount. To simulate the force from the preloaded bolt, an external pressure was applied to the contact area between the mount and the head of the bolt. A spring support (using the stiffness of the bolt as the stiffness of the spring support) was applied to the inside face of the hole to simulate the contact force from the bolt to the walls of the mount. This will prevent the mount from deforming into the volume of the hole that the bolt will occupy. Finally, a downwards, distributed force totaling 5 lbs was applied to the hook. The final setup is pictured below.

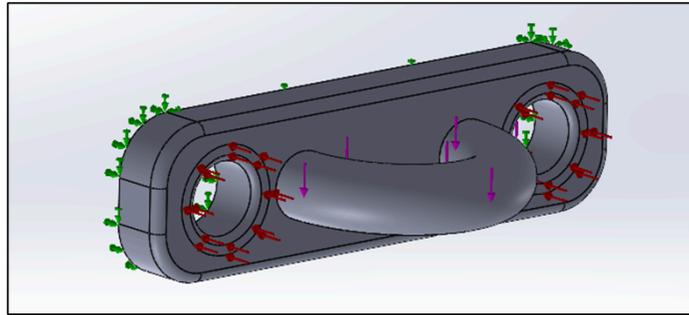


Figure 11. Image of boundary conditions and loading for stirrup mount simulation.

Results

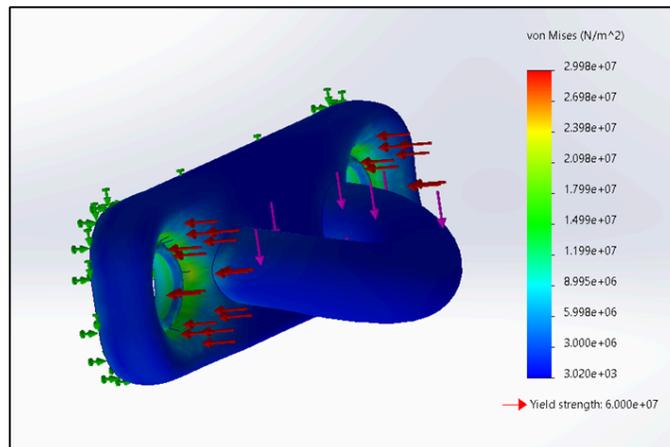


Figure 12. Image of stirrup mount simulation results.

As seen from the results of the simulation above, the area most likely to fail will be the area around the bolt, not the hook. If the bolt is tightened too much, the material may yield.

Although the calculated von Mises stress is about $\frac{1}{4}$ of the yield strength, further physical experimentation would be helpful in confirming this.

An example of this physical experiment could consist of 3D printed mounts made of different materials (independent variable). They will all be loaded with a similar, excessive number of bolt-tightening twists and left overnight. If the mounts show any signs of failure or permanent deformation, they would not be used in the final design. Since the material is seemingly the only independent variable, the design of the experiment does not have to be complex.

An experiment like this was not conducted because the stirrup mounts were not the most high-risk component of the final design. Even if they were to break, the owner could wrap the stirrups around the back bar, which would not greatly affect the stirrup subsystem functionality.

Quick Release Skewer Simulation

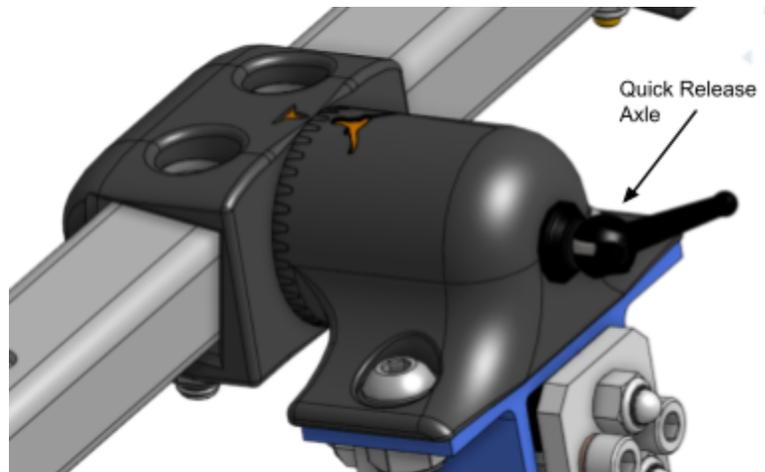


Figure 13. Image of quick-release skewer in the CAD assembly.

Shown in the figure above is the final quick-release skewer design in the assembly. The handle of the quick-release skewer is shown in black and is inserted through the pivot joint and extends throughout the entire joint and frame, and out the other side. The exposed end is then

screwed into a backing that is covered in a resin-printed end cap to prevent it from causing any damage to the dog or any surfaces it might come into contact with.

As each quick-release skewer is the main connecting shaft between the frame and the leg of the wheelchair, each axle had to be able to support the entire weight of Cleopatra just in case she was in a scenario in which her entire weight was supported on only one leg of the wheelchair. This meant that when simulating the static force applied to the skewer, a force of 275N was used which roughly translates to 61.7lbs, around the weight of Cleopatra. Additionally, because this is only a static test and forces could be greater when the dog is in motion, there had to be a sufficient factor of safety to ensure unaccounted-for forces would not deform or fracture the skewers. The SolidWorks simulation conditions and results can be found in the following section.

Boundary Conditions

To run this simulation, the handle, backing, and springs of the skewer were fixed. This was a reasonable assumption because when assembling the joint, the skewer will be tightened enough so that the faces of the handle and backing are securely clamped to the exterior of the joint and the springs are compressed and secured in place by the joint, preventing them from flexing with the shaft. A 275N distributed load was then applied along the shaft to simulate the weight of Cleopatra along the shaft. The final setup is depicted below.

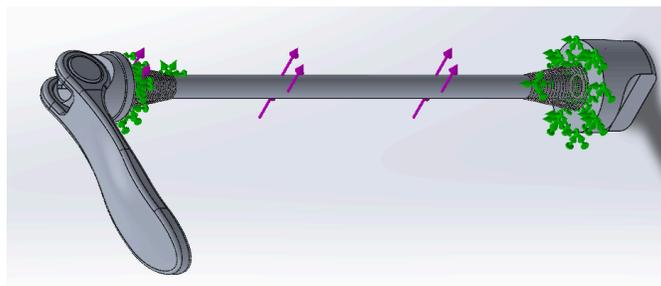


Figure 14. Image of boundary conditions and loading for quick-release skewer simulation.

Results

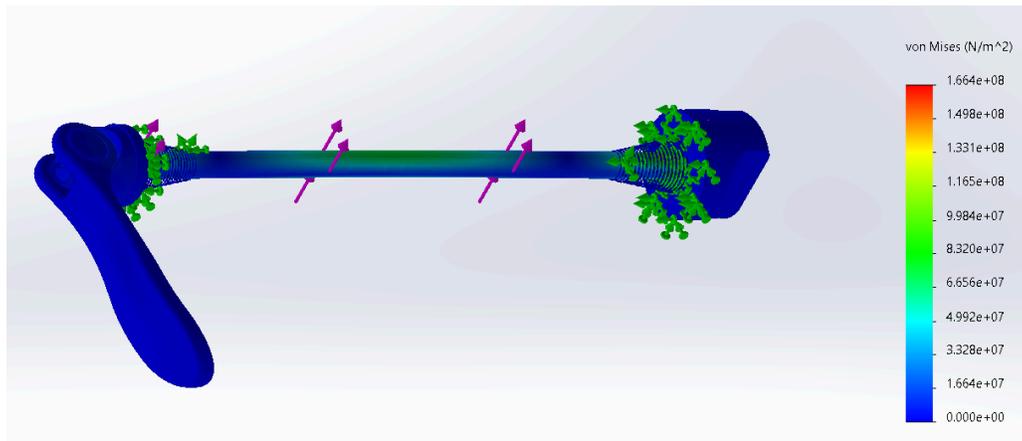


Figure 15. Image of quick-release skewer simulation results.

As seen from the results of the simulation above, the area of the skewer most likely to fail is the center of the shaft. This is because as more weight is applied to the skewer, the center of the skewer will start to bend and could possibly lead to plastic deformation or fracture. However, the calculated Von Mises Stress is approximately $8.5 \times 10^7 \text{ N/m}^2$ whereas the Yield Strength of 6061-T4 Aluminum is $2.27 \times 10^8 \text{ N/m}^2$ according to solidworks, meaning that the calculated stress is less than half of the yield strength of the material. This gives the part a large enough margin of safety in case of scenarios where larger forces than accounted for are applied to it.

Design for Manufacturing and Assembly Analysis

Design for manufacturing (DFM) is a concept that encompasses a broad range of factors that all contribute to creating the highest quality product with the greatest efficiency and lowest cost possible. The factors contributing to DFM analyzed in this report include consideration of the manufacturing process, overall design, material usage, interaction with the environment, and durability and longevity of our dog wheelchair. It should be noted that we designed our dog wheelchair for a specific dog (Cleopatra), and our final wheelchair is highly custom as a result. Below is a discussion of both how we incorporated DFM into our final wheelchair design and how certain aspects of our design might be adjusted if we intended to manufacture the wheelchair at scale. All parts mentioned in the discussion below may be found in our BOM.

Manufacturing Process

Given the nature of this project, the manufacturing and assembly process of our wheelchair was a very manual process. Most of the metal involved in the wheelchair was ordered as stock material and then machined according to the final design. This is not ideal when considering a holistic design for manufacturing at scale because the current process is labor-intensive and takes longer to produce a unit, elevating the cost of production. If we were to take our design with the intention of manufacturing it at scale, we would need to accommodate some sort of mold or die that could be used to produce the frame of the assembly quickly and cheaply.

The aspect of our manufacturing process we performed with DFM in mind was the process of using additive manufacturing to manufacture all of the plastic parts involved in the wheelchair. 3D printing allowed for rapid prototyping, which was significant in the way it let us iterate multiple times throughout the design process. Furthermore, this provided for relatively

short production times of highly complex parts (most notably the pivot joint which connects the frame to the legs of the wheelchair).

Design

Overall, we took great care to create our design with DFM in mind. We focused on minimizing the number of custom parts needed in the assembly, as the cost of production increases with a corresponding increase in custom parts, especially without a custom mold or die to produce them in large quantities. As shown in our BOM, our wheelchair will be comprised almost entirely of standardized/stock parts, including all the fasteners and framing, with most of the custom parts being various brackets used to efficiently integrate the various subsystems of our design. Furthermore, our design is relatively modular, with individual parts being able to be replaced rather than the entire wheelchair should something fail.

The primary area we would focus on when considering ways to improve our design with DFM in mind for manufacturing at scale would be to standardize and minimize the fasteners used. All of our fasteners are standard sizes and easily available, but our custom wheelchair contains several different size fasteners in the various subassemblies of the wheelchair. This is unavoidable in certain circumstances, but it is still something we would make an effort to standardize as much as possible to streamline the manufacturing and assembly process while also making repairs both easier and cheaper. In addition, while we made an effort to remove unnecessary fasteners throughout the design process, greater consideration would be given to how the design might be altered to integrate parts together with fewer fasteners if we intended to manufacture the wheelchair at scale.

Materials & Environmental Interaction

Considering the various terrains to which our dog wheelchair will be exposed, we incorporated materials into our design that ensure the wheelchair's durability over time, especially for an active and dynamic dog like Cleopatra. The wheelchair is frequently used outside and, accordingly, it must be both durable and corrosion resistant. With this in mind, our frame is made of aluminum, and our fasteners are made of either stainless steel, zinc-plated steel, or steel with an anti-corrosion coating. These materials offer enough strength for the stresses put on them during use and are corrosion-resistant, allowing for easy cleaning and long-lasting function. The brackets, joints, and covers in the wheelchair are made out of high-strength plastics (both acrylonitrile butadiene styrene (ABS) and carbon fiber reinforced nylon were used), which have high strength yet allow for highly custom parts to be made at significantly lower costs than if they were made out of metal. Furthermore, the plastic reduces the overall weight of the wheelchair without compromising its structural integrity, which is something that was important to us in the design process. The harnesses are made out of nylon, which is both safe for animals and easily cleanable. Further analysis of the materials involved in our wheelchair is presented in the following "Sustainability Analysis" section (page 27).

Compliance and Testing for Durability and Longevity

We have performed finite element analysis (detailed in the "Solidworks Simulation (FEA Analysis)" section on page 16) on specific subassemblies or parts of our design that will be at the highest risk to eliminate any structural liabilities in our design. However, due to the nature and timeline of this project, we did not have the opportunity to perform methodical physical stress testing on the fully assembled wheelchair. With this in mind, we accounted for this in our DFM by making use of materials and parts that have industry standards well above the needs of our

wheelchair, ensuring the end result is both high quality and safe for use. Were we to be manufacturing the wheelchair at scale, we would perform more rigorous and comprehensive testing on the wheelchair with the goal of understanding and documenting the limits of its capabilities.

Sustainability Analysis

In the design of our final dog wheelchair, several considerations were made regarding wheelchair sustainability. These considerations can be split into three categories: material type, longevity, and waste.

The frame of our dog wheelchair is made of aluminum telescoping tubing. Aluminum has several characteristics that support its application in our dog wheelchairs. First, aluminum is a strong material that will not fail under the expected loads. Also, it is lightweight and resilient, which enables Cleopatra to move more freely in most environments. Finally, and the most relevant to this section, aluminum can be recycled several times with minimal loss of quality of the material. In fact, recycling aluminum can save “90% of the energy it takes to produce new aluminum” (*4 Aluminum Recycling Examples That Aren't Just Cans*). The sustainability of aluminum was one of many factors that contributed to its implementation in our final design.

The longevity of our wheelchair can also be associated with its sustainability. The more an owner has to replace some or all of the dog wheelchair's components, the more potential waste. Along with the aforementioned resilience of the aluminum frame, our fasteners are made of either stainless steel, zinc-plated steel, or steel with an anti-corrosion coating. This reduces the need for frequent disposal of various parts over the course of the wheelchair's lifetime. The long-lasting nature of our final dog wheelchair design contributes to its overall sustainability.

Finally, we ordered our parts with sustainability in mind. We adapted our final wheelchair design to require a quantity of parts that was around the quantity that was offered on the McMaster website. For example, alloy steel socket head screws (45 mm long) were offered in packs of ten. At first, only four of these screws were needed for the stirrup mounts; however, with some adjustments, the other six were put to use in other parts of the frame. In this way, we

completed assembly with minimal extra parts and, consequently, minimal waste. This sustainability practice is consistent throughout our final dog wheelchair design.

Final Functional Prototype

Through the previous analysis, we made several adjustments that allowed us to land on our final prototype design. In summary, our final design is made up of square telescoping tubing for the frame and legs, purchased ROSTA suspension units, 3D printed carbon nylon pivot joints, 12” foam wheels, commercially purchased front+back harnesses and stirrups, various commercially purchased fasteners, and 3D printed plastic stirrup mounts and buckles. Note that telescoping holes made in the frame and legs were done using a mill and some structural metal parts were outsourced to sendcutsend.com. More detailed images and drawings of each component are in the appendix (figures 22-30), along with our full Bill of Materials and budgeting (figure 33). Exploded views of more detailed parts are also to be found in the assembly manual. Below are images of our final functional prototype with the harnesses attached and our handoff to an Austin Pets Alive Representative.



Figures 16-17. Handoff with APA representative and final functional prototype

Final Discussion and Recommendations

One of the biggest challenges we faced was learning Cleopatra had unfortunately passed away, leaving us with the inability to revise our wheelchair to her set of features. This meant that we were unable to see the wheelchair in use, and thus did not get to check the true functionality of the pivot joints for laying/sitting down nor the spring action of our suspension. Ultimately, this led to our group deciding to donate the wheelchair to Austin Pets Alive in order to allow another dog to use it. Luckily, adjustment of width, length, and height was an important design constraint for us, such that we are confident that another dog of a much different size may use the wheelchair and still be comfortable.

In order to optimize comfort for the dog so as to not exacerbate health problems, we would have liked to be able to test the fit of our wheelchair with Cleopatra, such that we could optimize the wheel placements, harness system, and frame geometry overall. Generally, for a custom product like a wheelchair, we would have liked to iterate on our design at least one more time, but sadly we ran out of time with Cleopatra, and further iteration with a new dog is not within the scope of this project.

If we were to reapproach this project with fresh eyes, we would likely place a heavier emphasis on coordination and communication within the team. Each individual was mainly in charge of one subsystem of the wheelchair, such that while we did discuss the interfaces in which our designs would connect, we lacked the standardization that is expected in design for manufacturing. For example, as discussed in the DFM section, we had various fastener sizes where it was unneeded, which added extra cost in purchasing fasteners and cost us time in milling out the holes. Furthermore, differences in imperial and metric hole dimensions and diameters required varying drill bits, costing time to find where those drill bits could be accessed

on campus. Furthermore, for subsystems that did not directly interface with an individual's part, there was little communication and review of designs to give input and criticism of other individuals' parts, leading to confusion and miscommunication on the implementation of separate subsystems, especially in the assembly stage. We would likely have created a more polished final design if, at each deadline, we had first presented our designs to each other, iterated, and then turned in the design to the professor and TA for grading.

For future ME 366J students or other engineers seeking to design their own dog wheelchairs, we have a couple of recommendations. First, one must understand the value of customer needs analysis, especially if the product is being custom-designed for a customer. Generally, commercial wheelchairs are semi-one-size-fits-all, with differences between small, medium, and large, but require adjustability to get close to a dog's true size. Of course, custom wheelchairs do not require adjustability and should more closely fit the intended dog. In our case, we included adjustability for Cleopatra, which cost extra time and money, but paid off as our wheelchair can now be used in the future for various dogs. Another recommendation we have is the importance of team communication and possibly the election of a project manager. While it may be difficult to establish a project manager, we found that because we neglected to do so, we lacked a focal point in terms of decision-making, communication, and project planning. It is difficult to get 7 individuals on a team in sync, and even harder when information is not spread to every member at the same time. Finally, we suggest that individuals attempting to use additive manufacturing such as the 3D printers at Texas Inventionworks attempt to complete their printing as early as possible, as near the end of the semester, many various classes are completing their final projects, such that there are waitlists for all the printers.

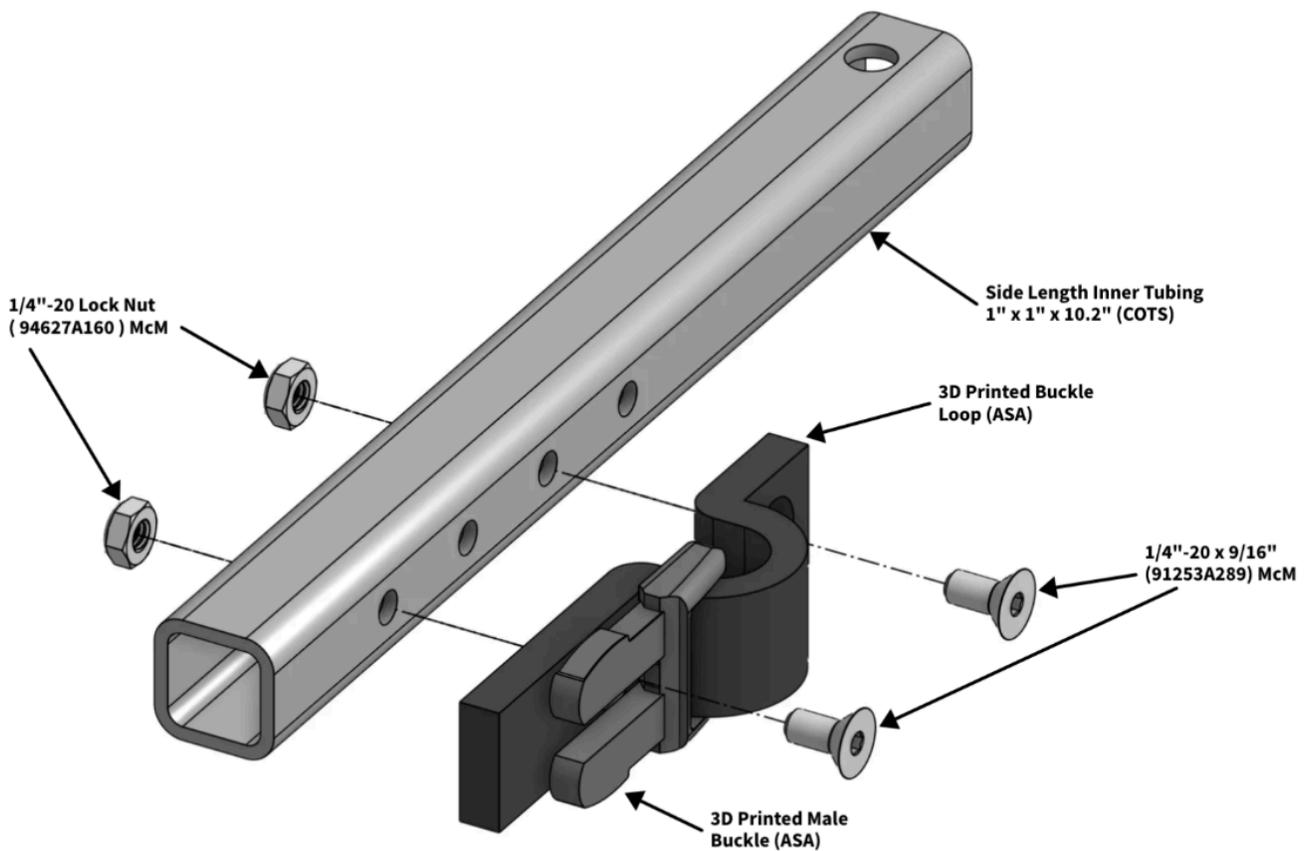
Assembly Manual

Frame:

Harness Buckle Interface:

Parts Needed:

- Customized Off the Shelf Parts (COTS)
 - 1" x 1" x 10.2" Box Tubing (L&R): **x2**
- Fabricated Plastic
 - 3D Printed Male Belt Buckle (ASA): **x2**
 - 3D Printed Belt Buckle Loop
- McMaster (McM)
 - 1/4" - 20 Lock Nut (94627A160): **x4**
 - 1/4" - 20 x 9/16" Screw (91253A289): **x4**



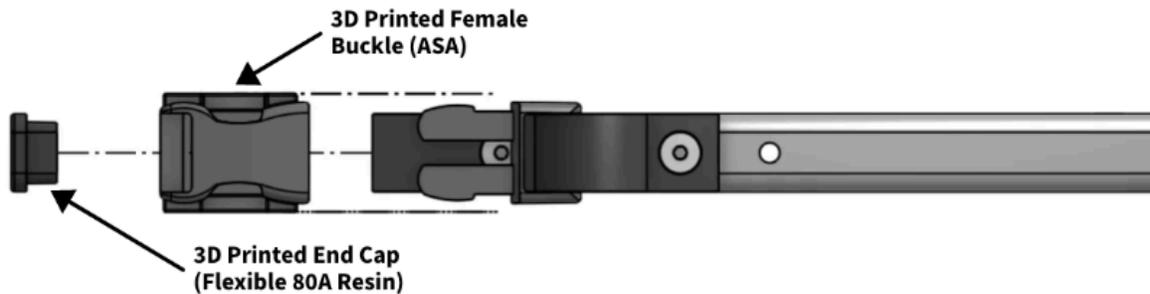
The diagram above shows the assembly for the left tubing. The left tubing is assembled the same way except the mounting holes are mirrored.

1. Slide 3D printed male belt buckle onto the 3D printed belt buckle loop
2. Mount the 3D printed parts to the frame with the 1/4" - 20 screws and locknuts (the nuts are seated inside the tubing)
3. Repeat the above steps for the right piece of box tubing

Harness Buckle Connection/End Caps:

Parts Needed:

- Fabricated Plastic
 - 3D Printed Female Buckle (ASA): **x2**
 - 3D Printed End Cap (Flexible 80A Resin): **x2**



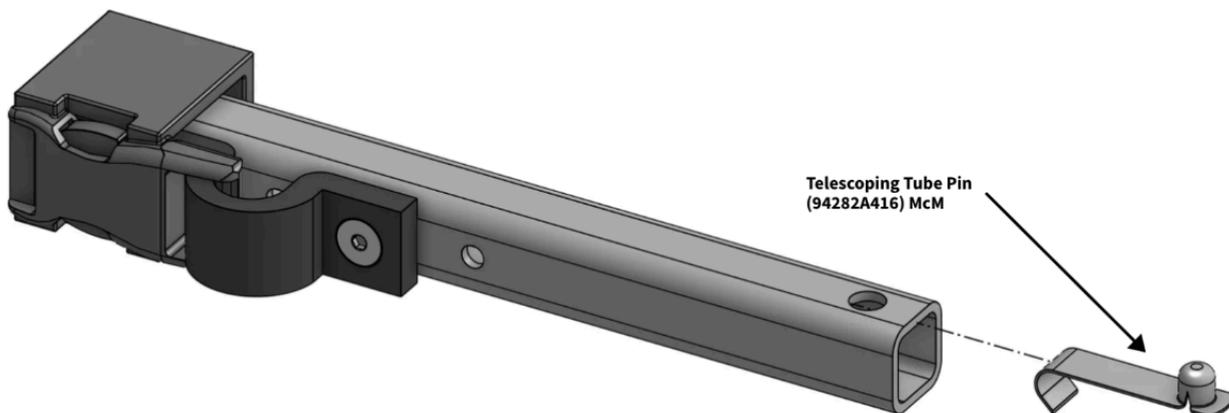
This figure also only depicts the left frame inner tubing.

1. Press fit the end cap on the end of the box tubing
2. The female buckle piece will already be sewn in the harness straps so to attach the harness to the wheelchair just clip the buckle pieces together as shown above
3. Repeat for the right section

Telescoping Pin Insertion:

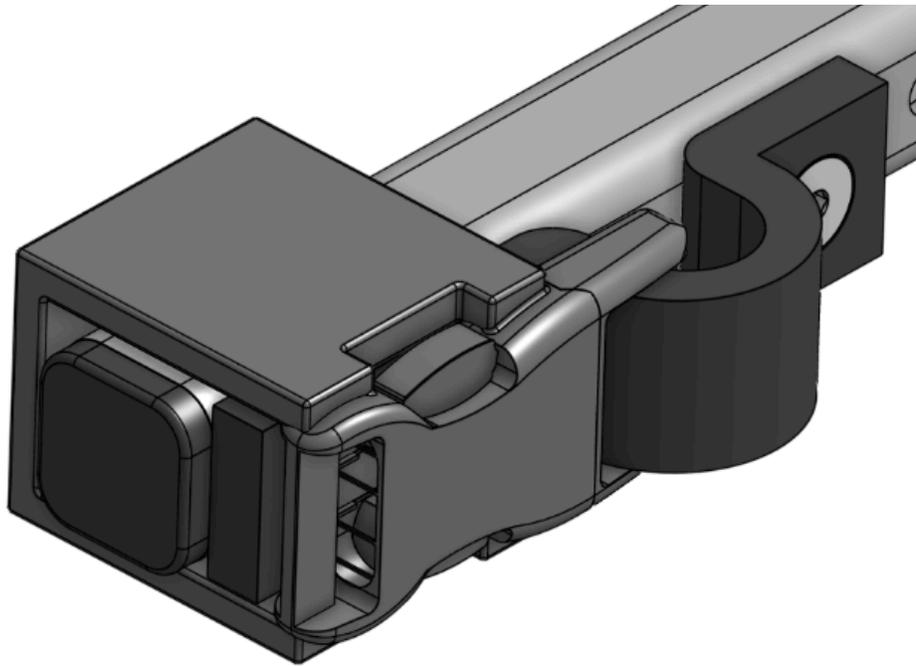
Parts Needed:

- McM
 - Telescoping Tube Pin (94282A416): **x2**

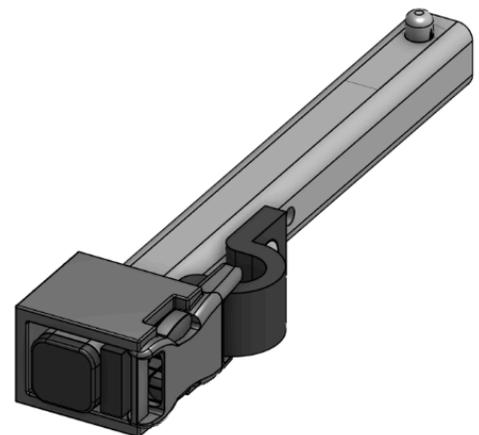
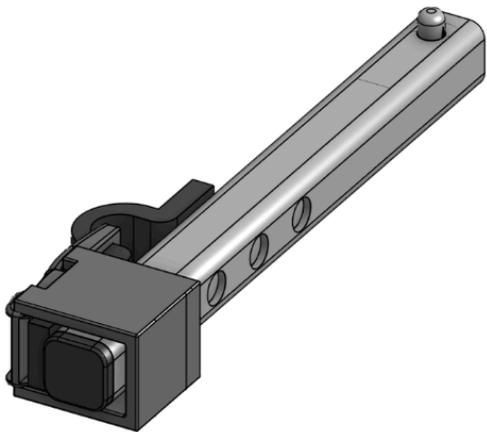


The above steps should create this assembly and a mirrored version for the right side

1. Compress the telescoping pin until you are able to slide it into the tubing
2. Keep sliding the pin into the tubing until the cylindrical pin piece pops out of the drilled hole
3. Repeat for the right assembly



The buckle assembly should look like the figure above

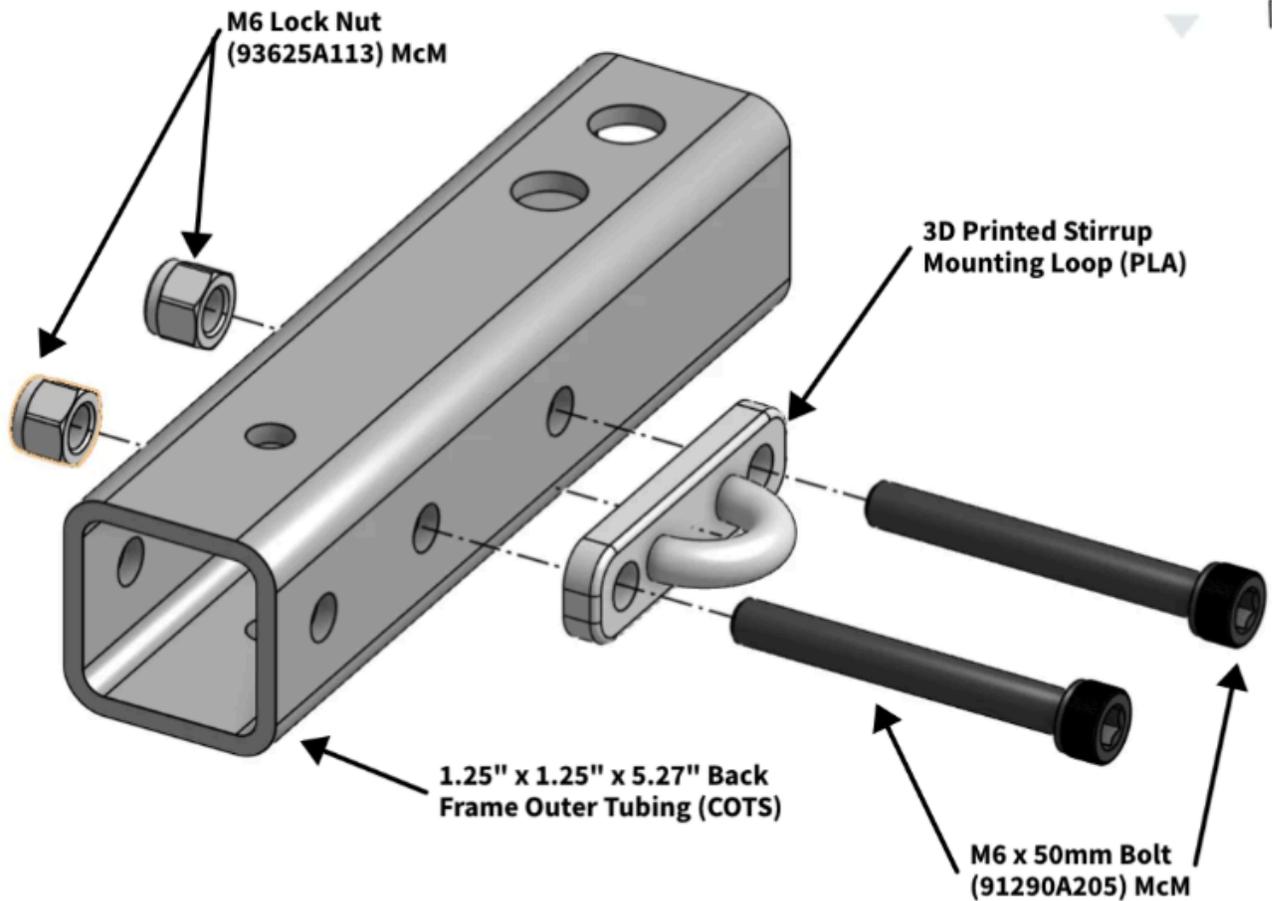


There should be two assemblies for the left and right sides like in the figure above

Stirrup Mount Attachment:

Parts Needed:

- COTS
 - 1.25" x 1.25" x 5.27" Box Tubing: x2
- McM
 - M6 x 50mm Bolt (91290A205): x4
 - M6 Lock Nut (93625A113): x4
- Fabricated Plastic
 - 3D Printed Stirrup Mounting Loop (PLA): x2



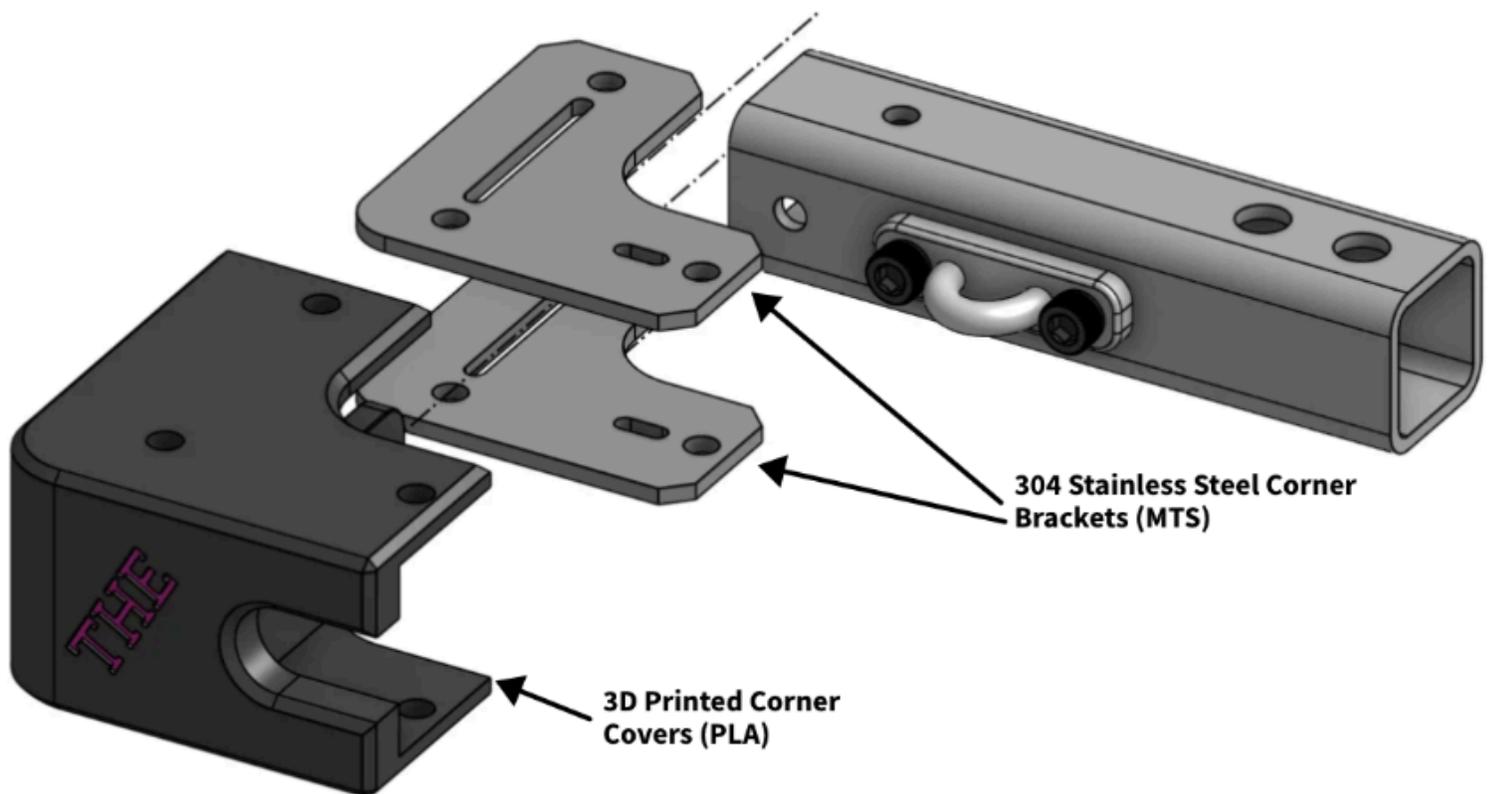
The figure above only depicts the left side of this assembly step. The right side is a mirrored version of this part

1. Screw the stirrup the mount into the box tubing using the lock nuts and bolts (the nuts are seated on the outside of the box tubing)
2. Repeat for the box tubing piece on the right

Corner Bracket Attachment (1):

Parts Needed:

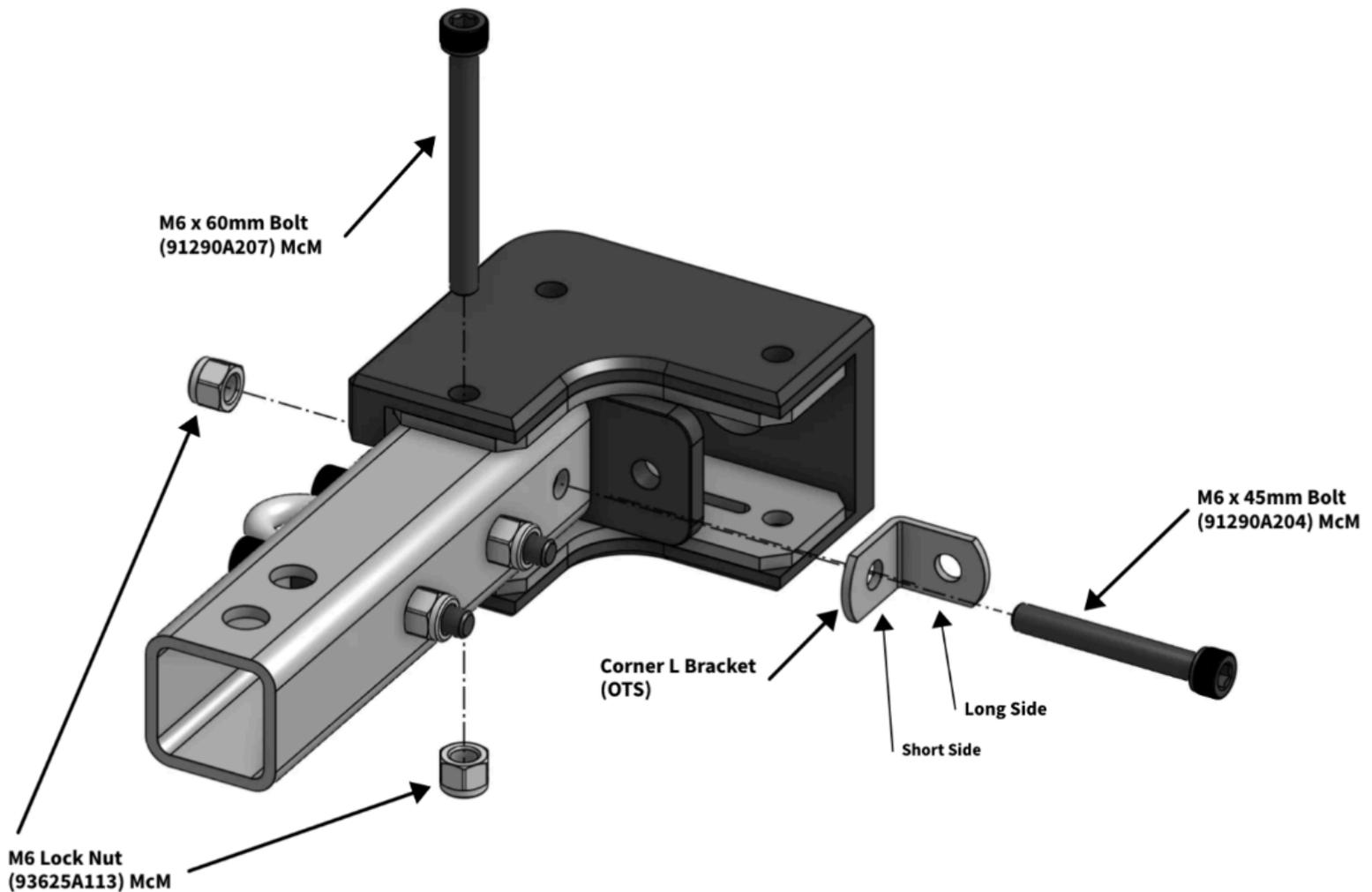
- Off the Shelf (OTS)
 - Corner L Bracket: **x2**
- McM
 - M6 Lock Nut (93625A113): **x4**
 - M6 x 60mm Bolt (91290A207): **x2**
 - M6 x 45mm Bolt (91290A204): **x2**
- Made to Specifications (MTS)
 - 304 Stainless Steel Corner Bracket: **x4**
- Fabricated Plastic
 - 3D Printed Corner Cover: **x2**



The corner covers slide over the box tubing and gets fastened on later. This figure is still a depiction of the left side

1. Slide the stainless steel corner bracket over the box tubing and line up the holes
2. Slide the 3D-printed corner cover over the steel brackets and the box tubing
 - a. There should be a relatively snug fit between all the components
3. Repeat for the right piece of box tubing

Corner Bracket Attachment (2):



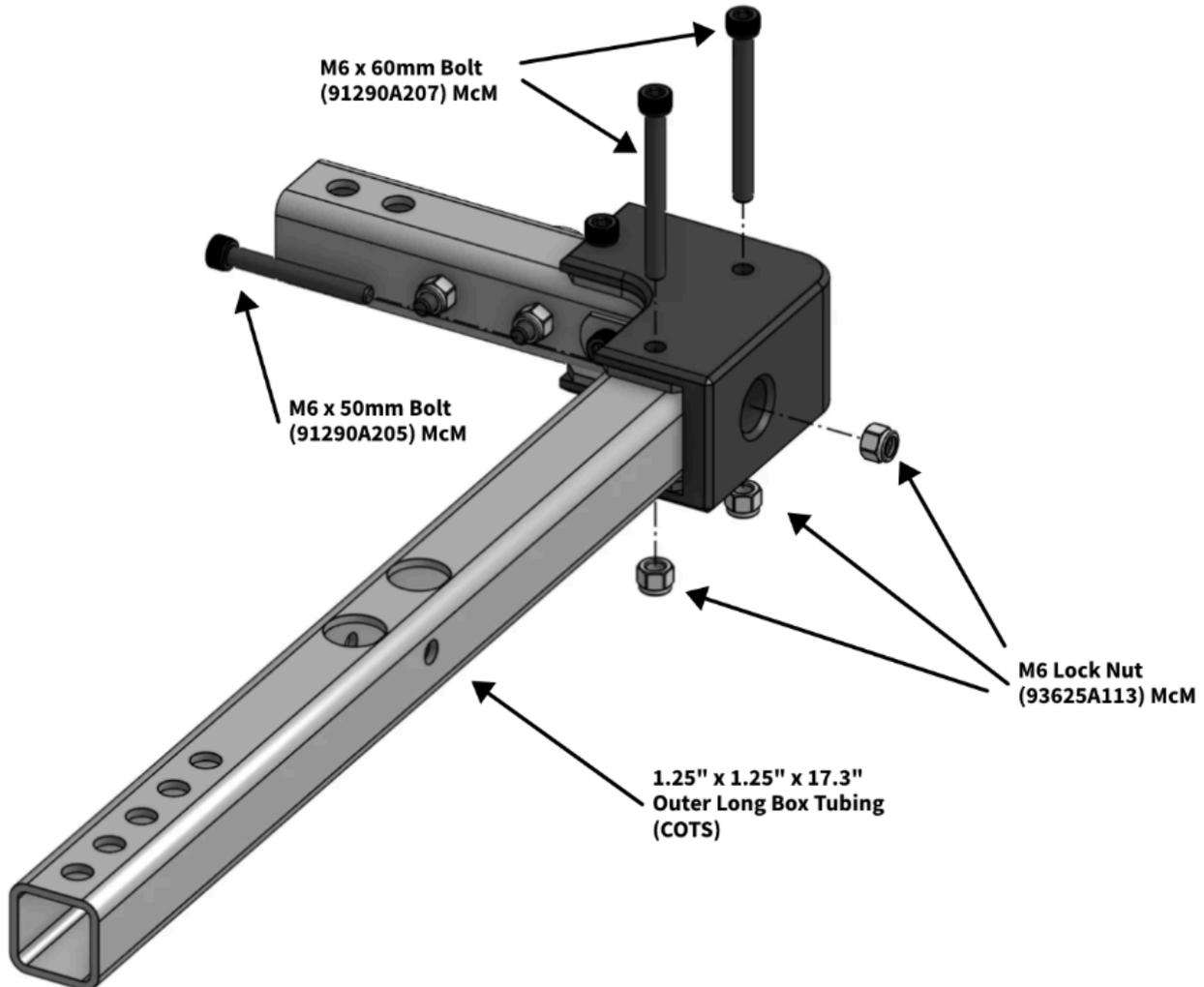
The diagram above depicts the fasteners used to assemble the corner covers and brackets. The left side only is still shown

1. Screw in the corner cover and brackets that were previously put in place using the appropriate fasteners
2. Screw in the corner L bracket also with the appropriate fastener
 - a. Make sure that the short side of the L bracket is the side being screwed in otherwise the holes won't line up
3. Repeat the above steps for the right side

Outer Long Box Tubing Connection:

Parts Needed:

- COTS
 - 1.25" x 1.25" x 17.3" Outer Long Frame Box Tubing: x2
- McM
 - M6 x 50mm Bolt (91290A205): x2
 - M6 x 60mm Bolt (91290A207): x4
 - M6 Lock Nut (93625A113): x6



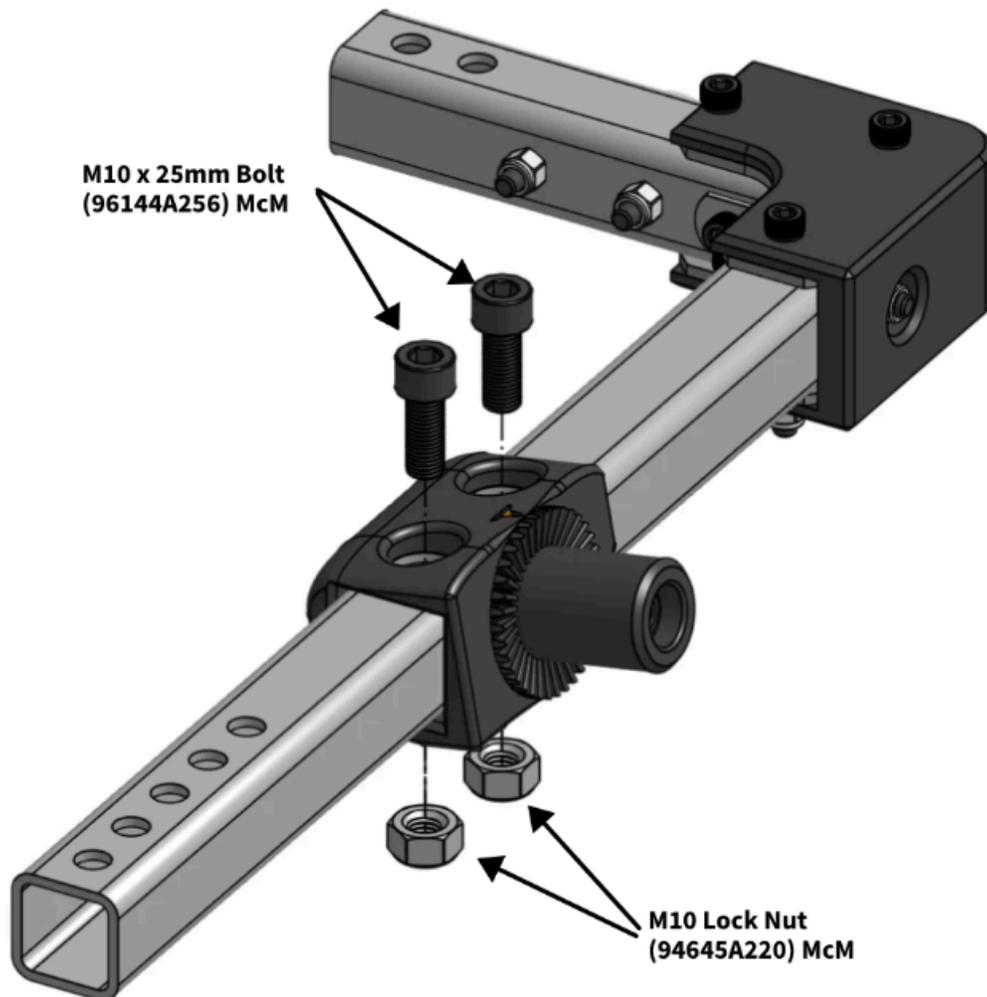
Left side of the frame depicted

1. Slide the outer box tubing into the corner bracket slot
 - a. It should slide in with some resistance to maintain a press fit
2. Screw in the box tubing with the longer fasteners
3. Screw in the other side of the corner L bracket that was not fastened in the earlier step
 - a. If the holes don't line up make sure the correct side of the corner bracket is being secured in this step the side being secured should be the long side
4. Repeat for the right side

Hirth Joint Attachment:

Parts Needed:

- McM
 - M10 x 25mm Bolt (96144A256): x4
 - M10 Lock Nut (94645A220): x4
- Fabricated Plastic
 - 3D Printed Male Hirth Joint (R&L) (Onyx): x2



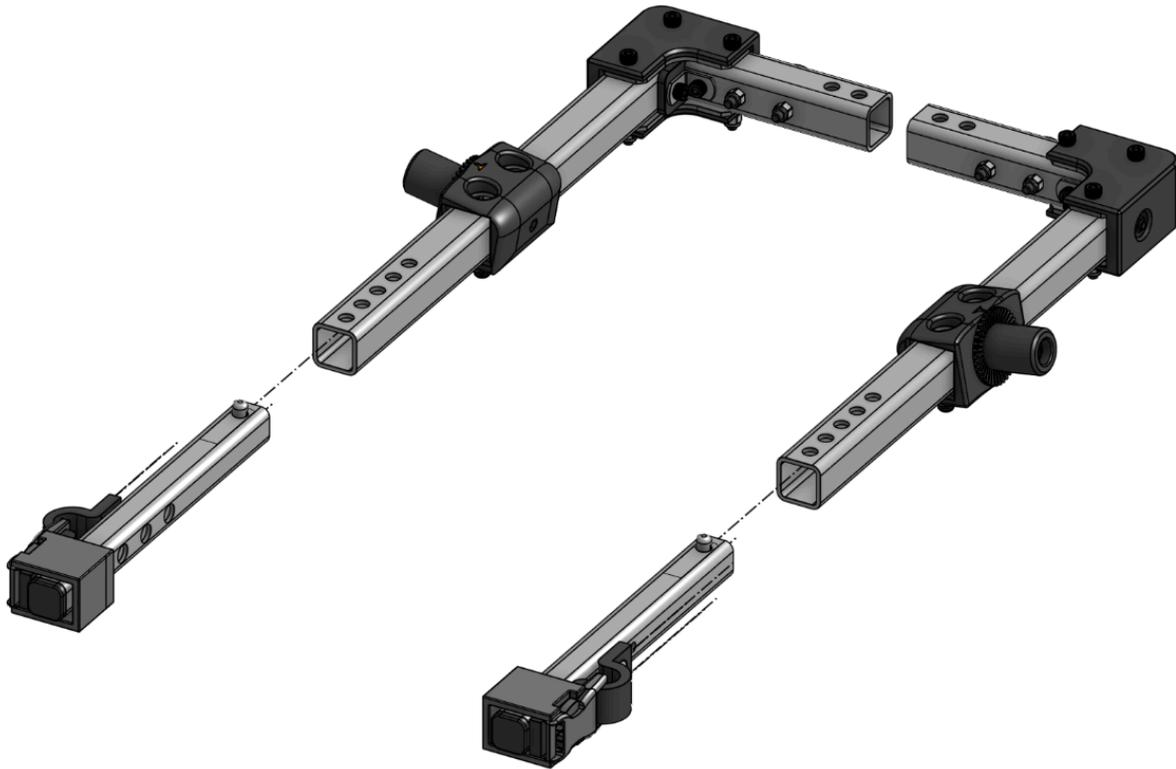
All the previous steps starting from the stirrup mounting attachment should result in the above assembly for the left side. The right side should look identical but mirrored

1. Slide the male hirth joint piece onto the box tubing until the large holes are aligned
 - a. Ensure that the left male hirth joint is being used on the left side there is a cutout on the Hirth joint (not shown) that should be facing the back of the wheelchair
2. Screw the joint in with the fasteners
 - a. Note that the bolts are seated on the inside of the box tubing
3. Repeat for the right assembly

Inner Box Tubing Connection:

Parts Needed:

- Assemblies
 - Inner Tubing With Harness Buckles Assembly: **x2**



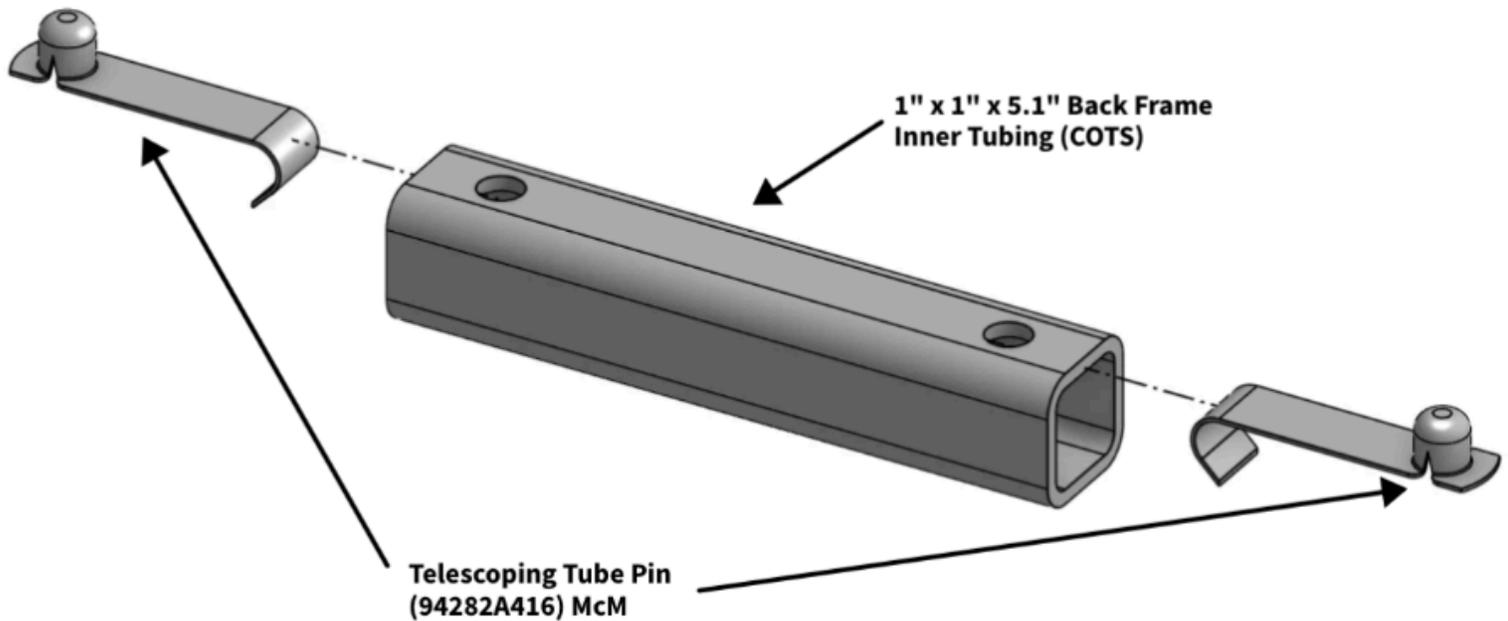
Following the above steps should result in two left and right assemblies like in the above figure

1. Slide the left and right inner tubing assemblies into the left and right outer tubing assemblies
2. By pressing down on the telescoping pin in the inner tubing it should fit into the outer tubing and lock in place when the pin springs back through the holes in the outer tubing
 - a. By pressing the pin down again the position of the inner tubing can be adjusted to change the frame length
 - b. Note that there should be two assemblies still and they are not connected yet

Back Inner Tubing Pin Insertion:

Parts Needed:

- COTS
 - 1" x 1" x 5.1" Back Frame Inner Tubing: x1
- McM
 - Telescoping Tube Pin (94282A416): x2



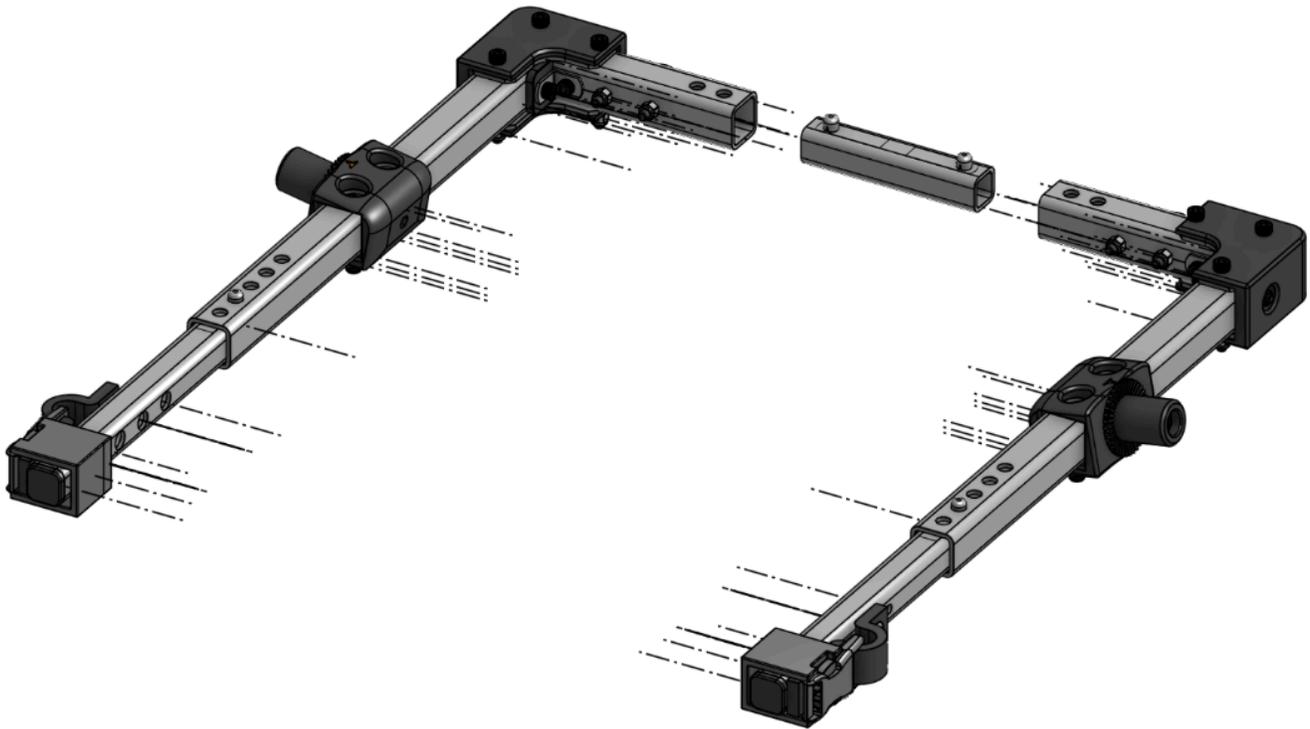
Note that there is no right and left component as this connects the right and left assemblies

1. Similar to the frame inner tubing pin insertion the pins need to be compressed so that they can be inserted into the tubing
2. They should slide in until the cylindrical pin pops out through the drilled hole in the tubing

Final Frame Assembly:

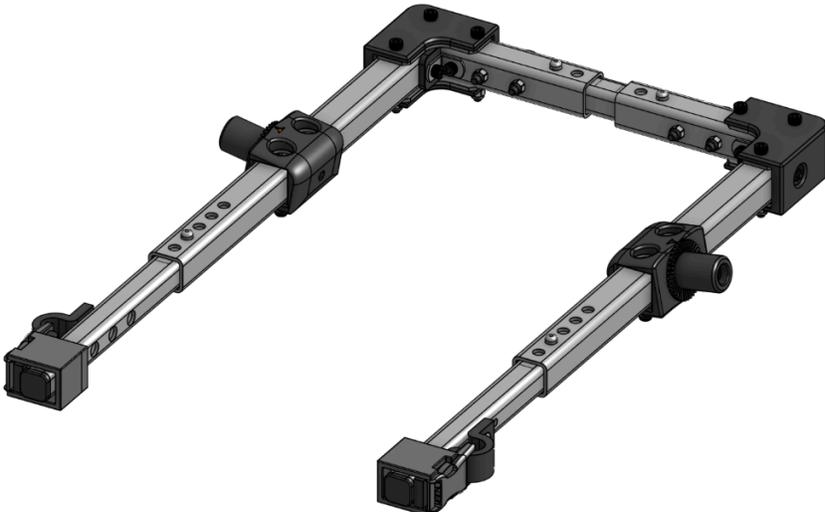
Parts Needed:

- Assemblies
 - Frame Length Assemblies (L&R): x2

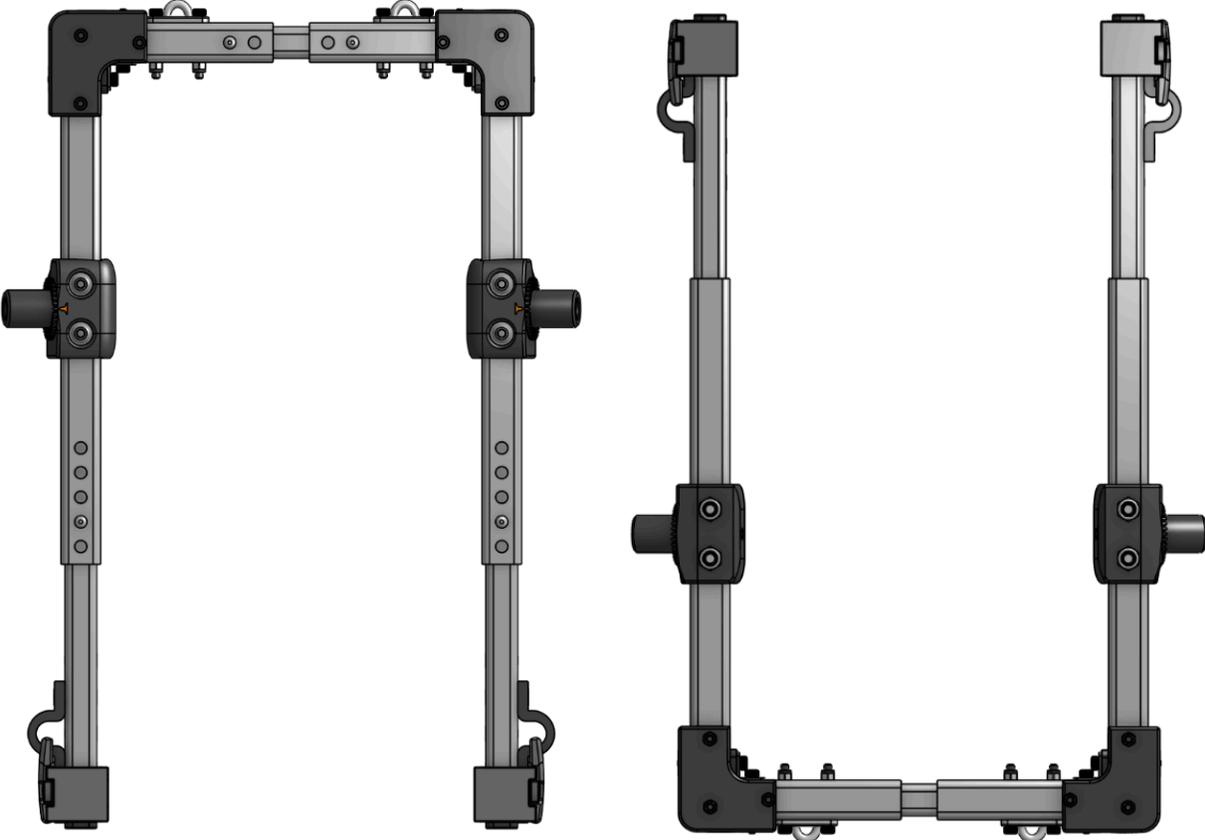


This step should complete the frame assembly

1. Slide the left and right side onto the smaller back inner tubing
2. Pressing the pin down should allow the outer tubing to slide over until the telescoping pins pop out through the holes in the outer tubing
 - a. There is also adjustability in this section so by pressing the pins down again you can adjust the frame width



The fully assembled frame should look like the figure above



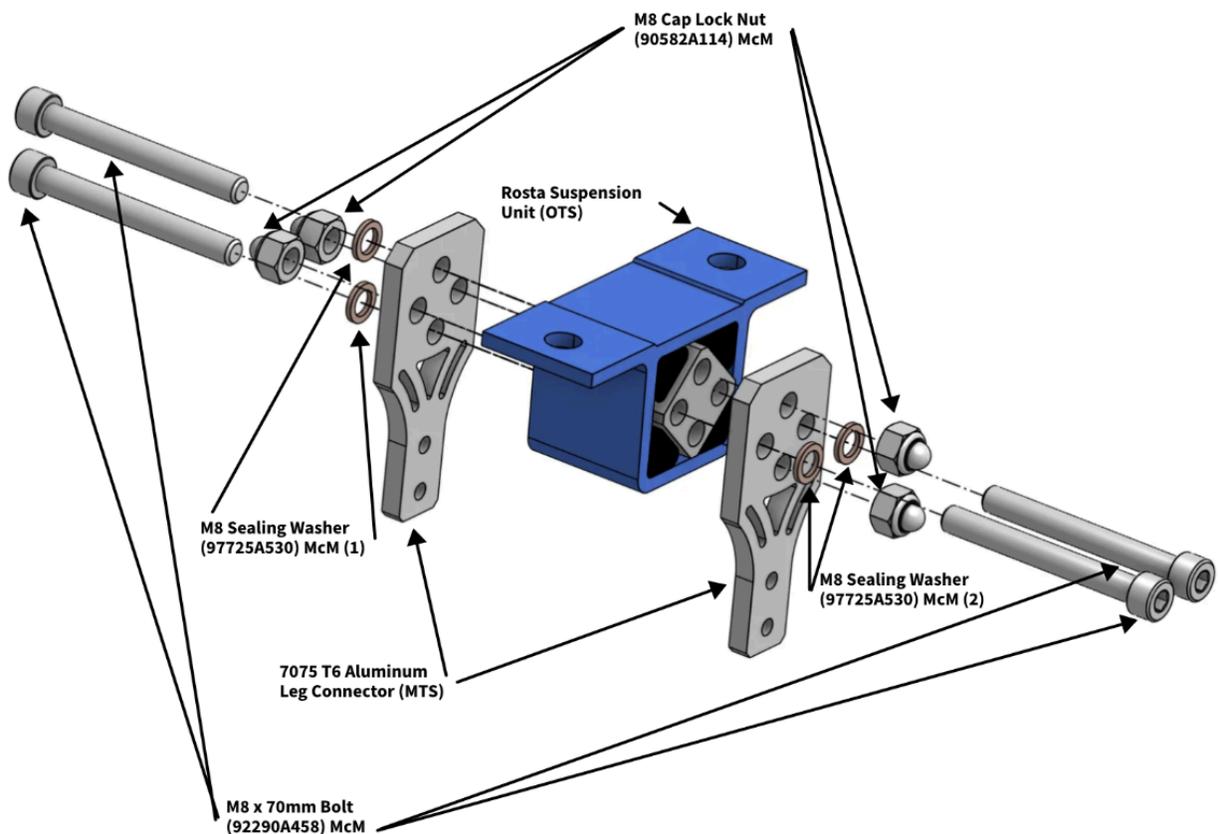
Top and bottom views of the frame depicted above

Legs:

Rosta Suspension Connector Attachment:

Parts Needed:

- OTS
 - Rosta Suspension Unit: **x2**
- McM
 - M8 x 70mm Bolt (92290A458): **x8**
 - M8 Cap Lock Nut (90582A114): **x8**
 - M8 Sealing Washer (97725A530): **x8**
- MTS
 - 7075 T6 Aluminum Leg Connector: **x4**



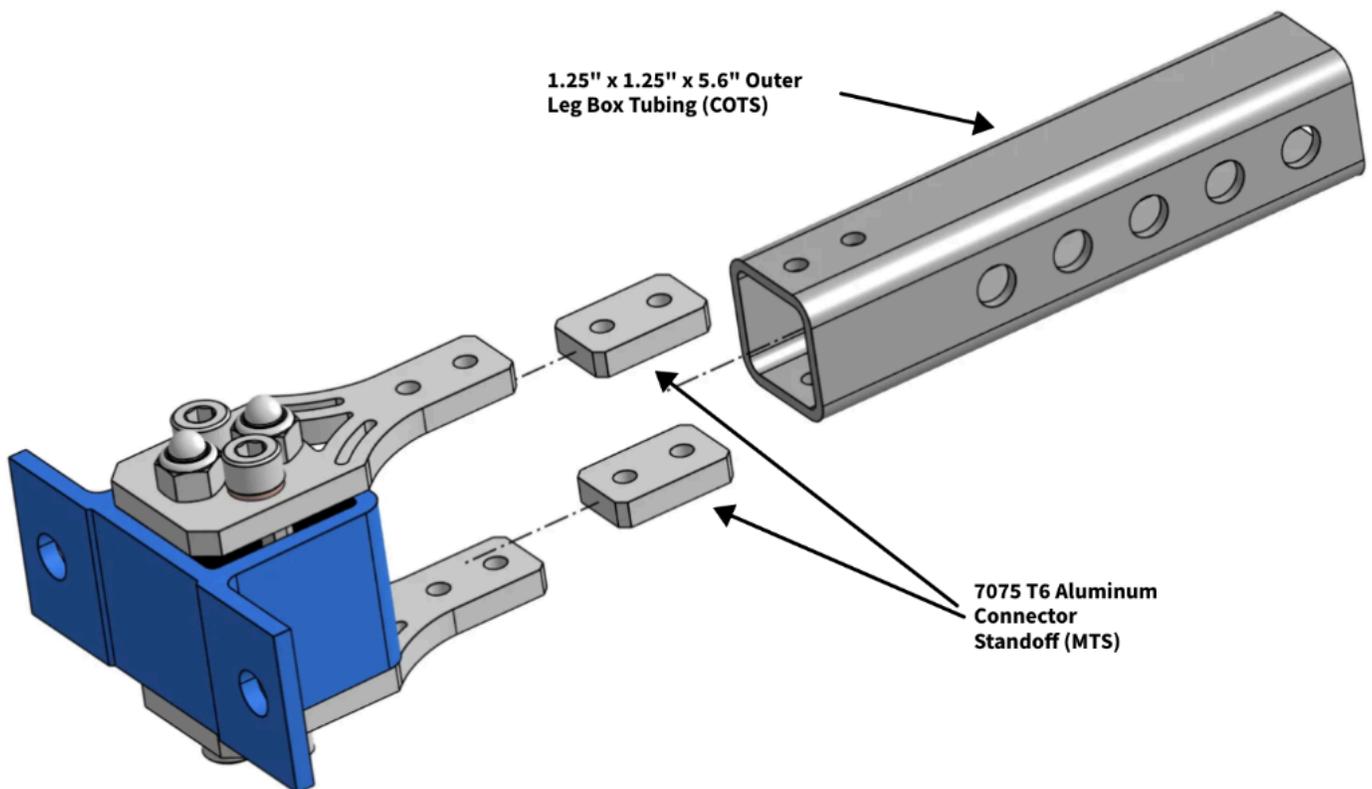
There should be two identical assemblies of the above component made to connect the left and right legs

1. Slide the washers onto the bolts and then slide the bolts through the first aluminum connector then the rosta suspension unit and then through the second aluminum connector
2. Fasten the cap lock nuts on the bolts to complete the assembly
 - a. Note that there need to be two bolt heads and two lock nuts per side of the assembly otherwise, the fasteners won't fit
3. Remake the above assembly for the opposite leg

Leg Box Tubing Attachment (1):

Parts Needed:

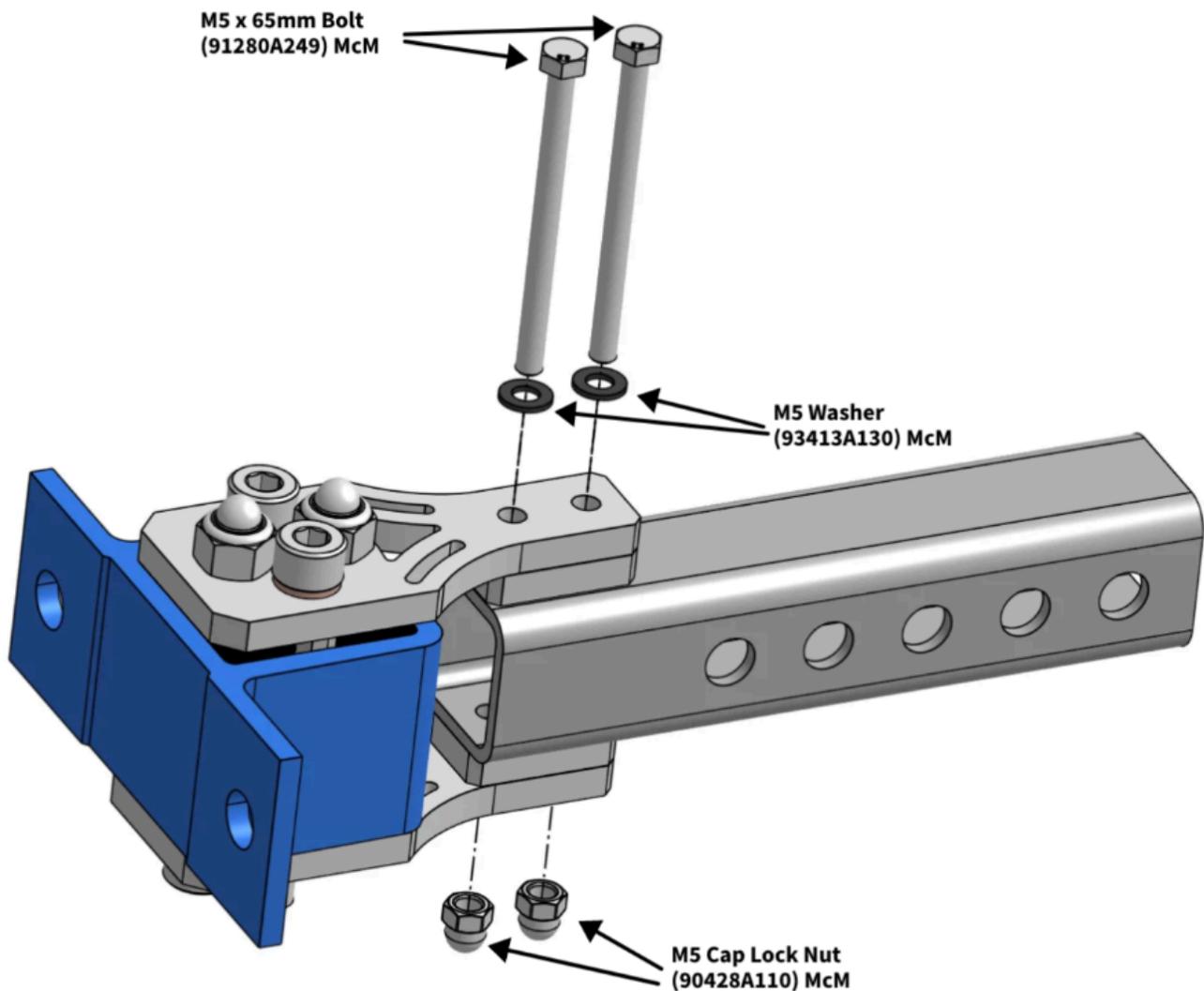
- COTS
 - 1.25" x 1.25" x 5.6" Outer Leg Box Tubing: **x2**
- McM
 - M5 x 65mm Bolt (91280A249): **x4**
 - M5 Cap Lock Nut (90428A110): **x4**
 - M5 Washer (93413A130): **x4**
- MTS
 - 7075 T6 Aluminum Connector Standoff (MTS): **x4**



The figure depicts how to line the components up the step for fastening them together next

1. Slide the spacers into place so that the holes line up with the holes on the leg connector
2. Slide the box tubing in between the spacers so that the mounting holes line up
3. Repeat for the second assembly

Leg Box Tubing Attachment (2):



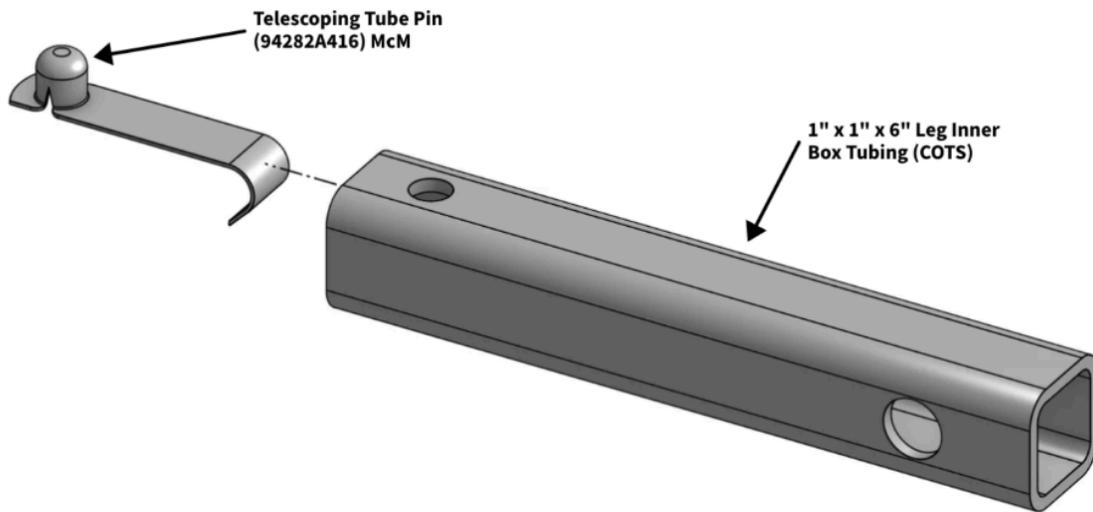
The pieces that were put in place earlier should stay held together under a press fit

1. Slide the washers onto the bolts and then push them through the leg connector, spacer, and box tubing stack
2. Fasten them together with the cap lock nuts on the other side
3. Repeat for the other assembly

Inner Leg Tubing Pin Insertion:

Parts Needed:

- COTS
 - 1" x 1" x 6" Leg Inner Box Tubing (L&R): **x2**
- McM
 - Telescoping Tube Pin (94282A416): **x2**



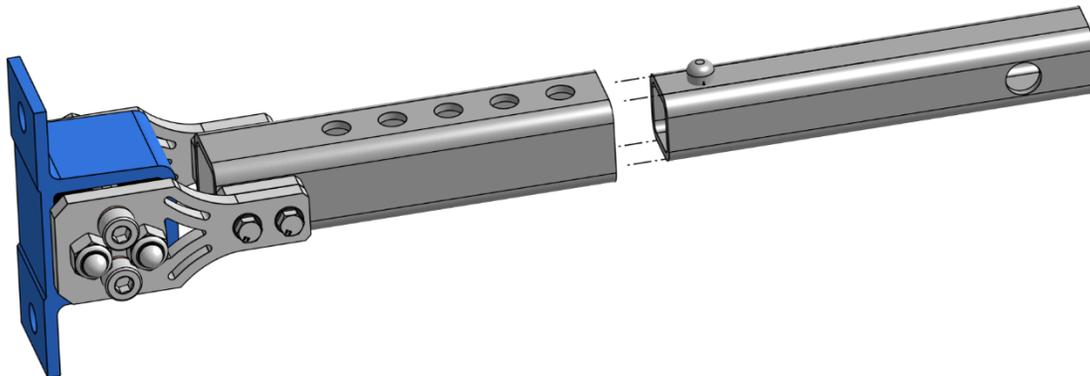
The left inner box tubing piece is identical for the right leg except the wheel gets mounted on the other side

1. Like previous instances the press the pin down and insert it into the tubing until the pin is exposed

Inner Leg Tubing Connection:

Parts Needed:

- Assemblies
 - Rosta Suspension Assembly: **x2**

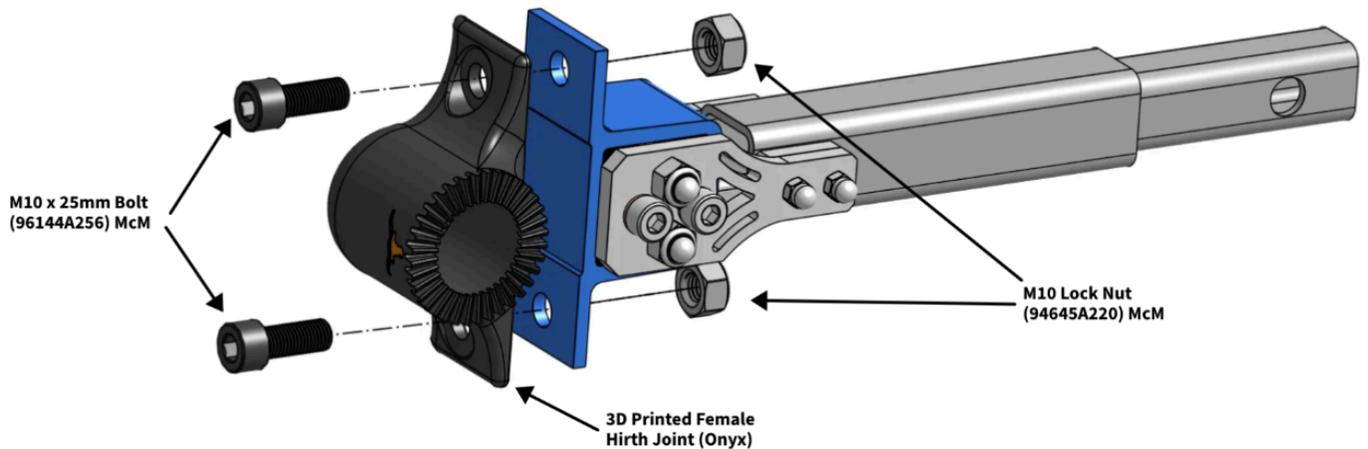


1. Slide the inner tubing into the outer tubing by pressing down on the telescoping tube pin
2. Repeat for the other assembly

Hirth Joint Connection:

Parts Needed:

- McM
 - M10 x 25mm Bolt (96144A256): **x4**
 - M10 Lock Nut (94645A220): **x4**
- Fabricated Plastic
 - 3D Printed Female Hirth Joint (R&L) (Onyx): **x2**



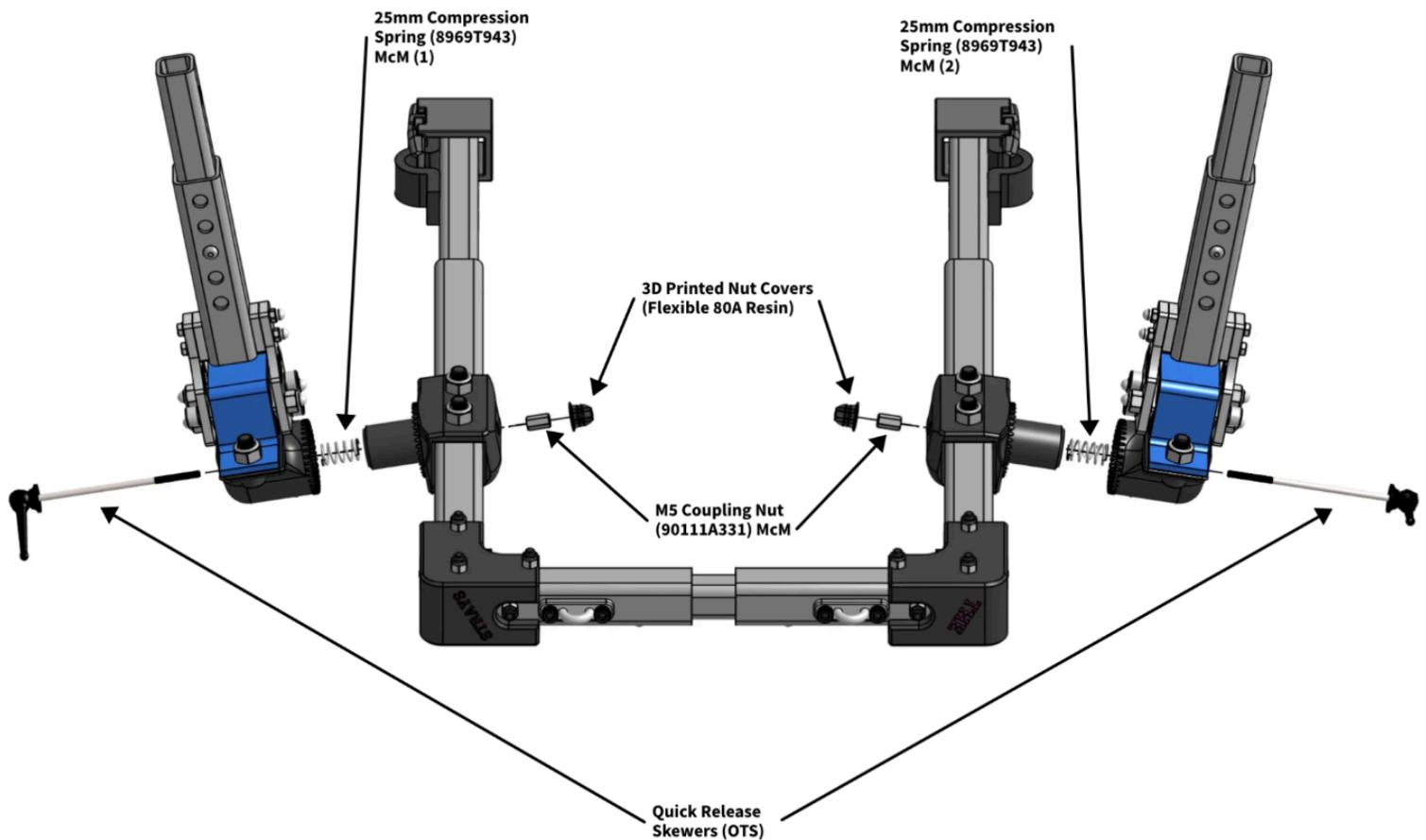
The left and right female hirth joints are identical so either can be mounted on either side

1. Slide the fasteners through the Hirth joint and ROSTA suspension mounting holes
2. Fasten on the other side with the lock nuts
3. Repeat for the other assembly
 - a. Note at this point in the assembly of the legs there should now be a distinction between the right and left legs
 - i. The left leg shown above has the telescoping holes (not shown) facing downwards so that they face towards the back of the wheelchair when assembled. Make sure that for the right leg assembly if the leg is oriented in this position the telescoping holes are facing upwards instead so that the legs are mirrored versions of each other
 - ii. **Optional:** For consistency sake the visible part of the leg connector shows two bolt heads in line with the leg and two lock nuts perpendicular to the leg. For the right leg, this bolt position can be replicated on the same side to keep the parts perfectly mirrored but it is not crucial to the actual assembly process

Attaching the Legs:

Parts Needed:

- OTS
 - Quick Release Skewers: **x2**
- McM
 - M5 Coupling Nut (90111A331): **x2**
 - 25mm Compression Spring (8969T943): **x2**
- Fabricated Plastic
 - 3D Printed Nut Covers (Flexible 80A Resin): **x2**



The figure shows both the left and right legs being attached no extra steps are needed for the opposing sides

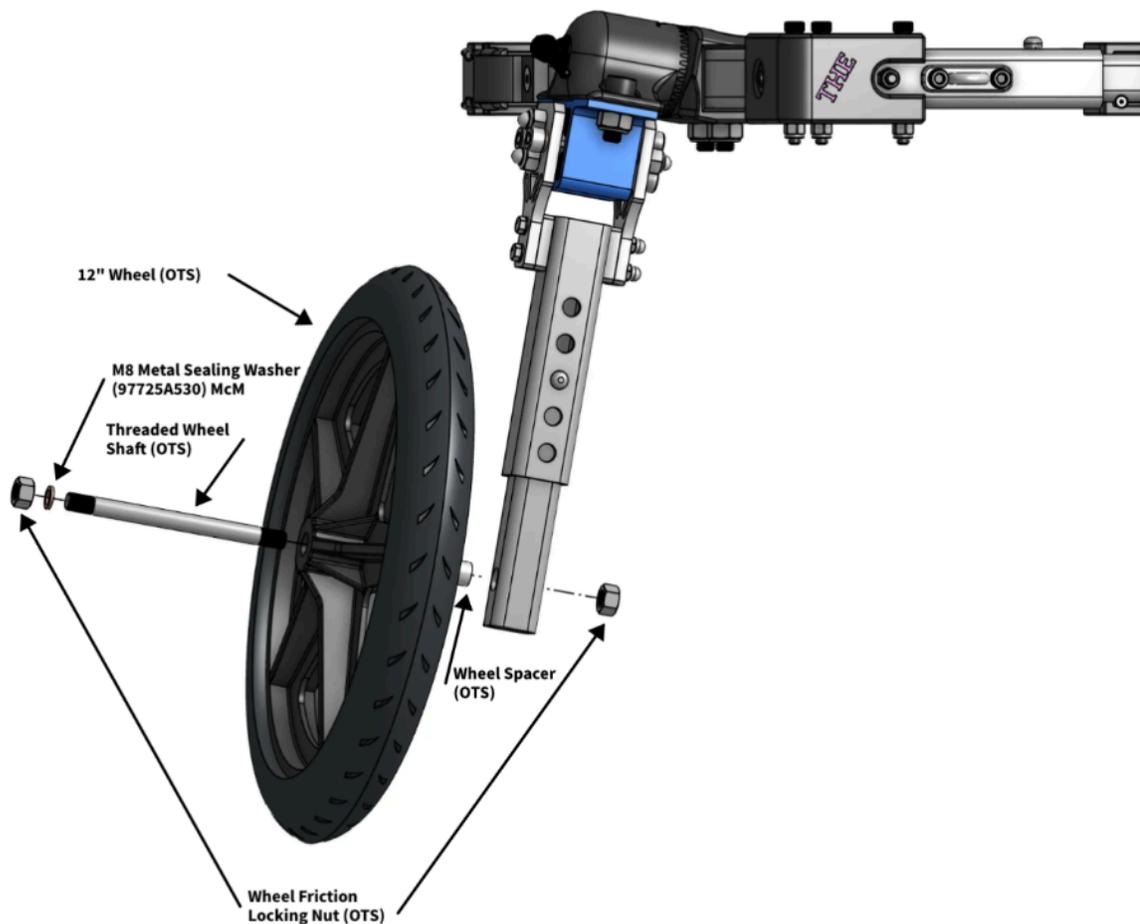
1. Slide the skewer through the back of the female hirth joint, compression spring, male hirth joint, and box tubing
2. Thread the coupling nut onto the threaded part of the skewer
 - a. There is a hexagonal divet in the back of the male hirth joint that should keep the nut from rotating and give it a place to mount to
3. Slide the flexible nut cover over the nut it should fit tightly and might require some force to connect

Wheels:

Attaching the Wheels:

Parts Needed:

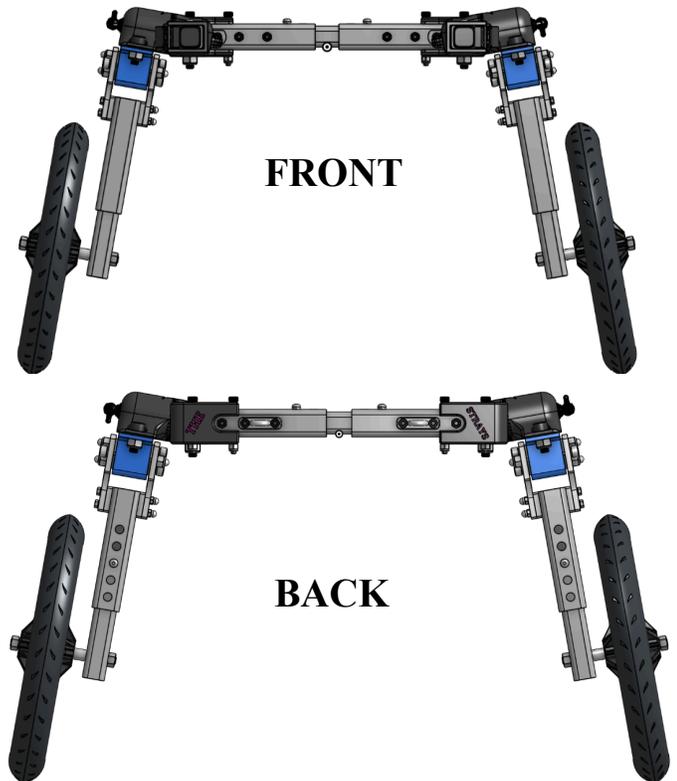
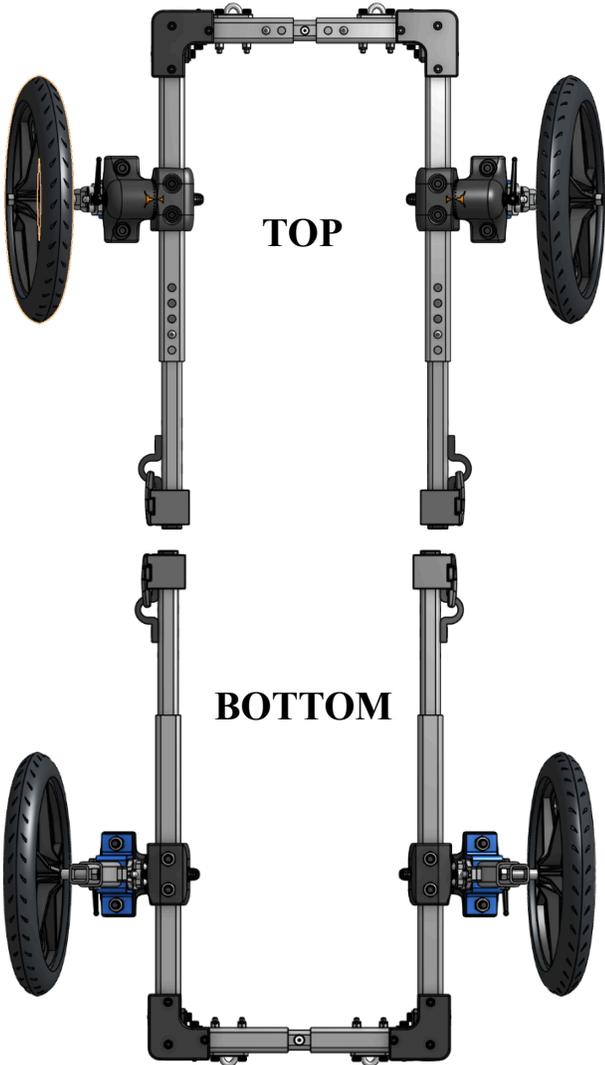
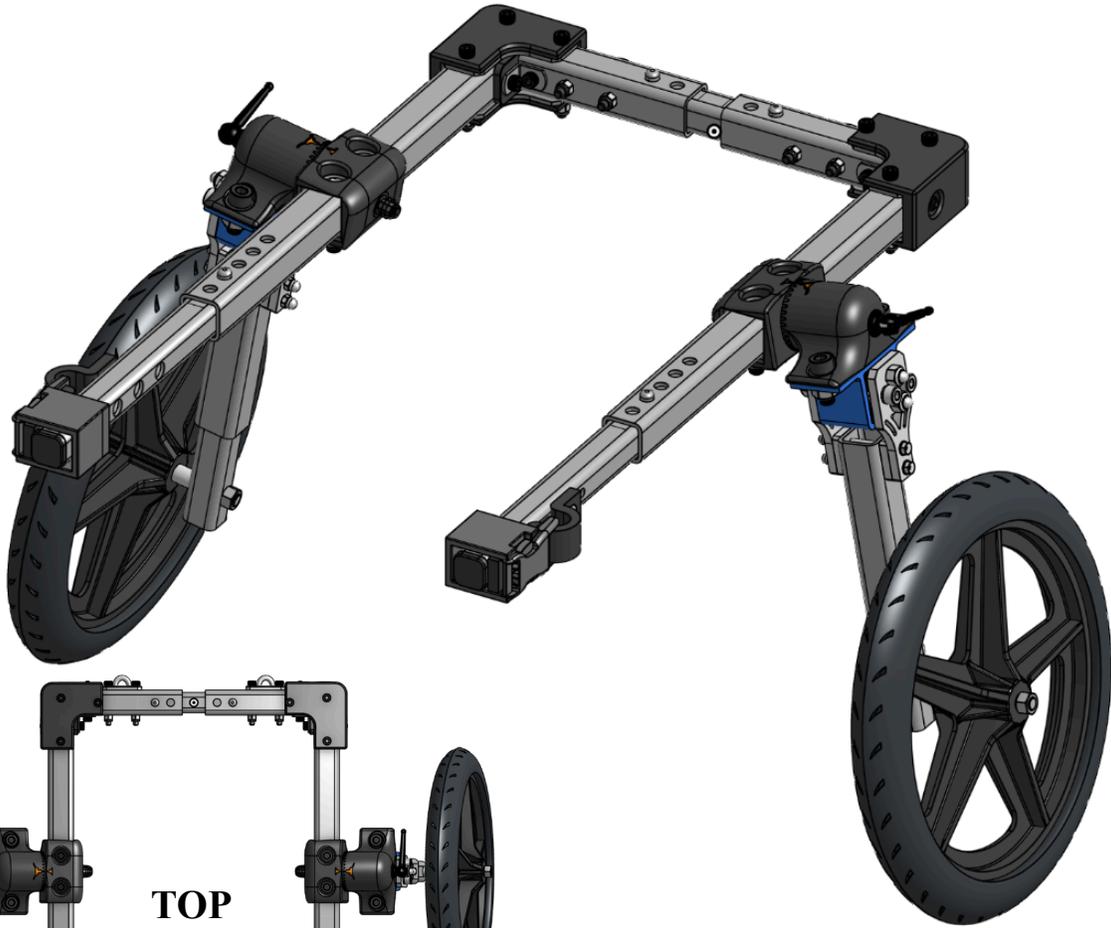
- OTS
 - 12" Bike Wheel Parts (All parts below are included in the Amazon order)
 - Threaded Wheel Shaft: **x2**
 - 12" Wheel: **x2**
 - Wheel Locking Friction Nuts: **x4**
 - Wheel Spacer: **x2**
- McM
 - M8 Sealing Washer (97724A530): **x2**



The above figure shows only the left wheel being attached (Tip: Attach wheels with the wheelchair upside down)

1. Slide the washer onto the shaft and then slide the shaft through the wheel, spacer, and box tubing
2. Fasten on both sides with the friction locking nuts
3. Repeat for the right side

Fully Assembled:



References

4 Aluminum Recycling Examples That Aren't Just Cans. Cohen. (2022, June 6).

<https://www.cohenusa.com/blog/4-aluminum-recycling-examples-that-arent-just-cans/>

Rubber suspension elements - rosta. (n.d.).

https://www.rosta.com/ro-wAssets/docs/ROSTA_Katalog_2021_EN-hi.rubber-suspension-elements.pdf

(Part 2, split for visibility)

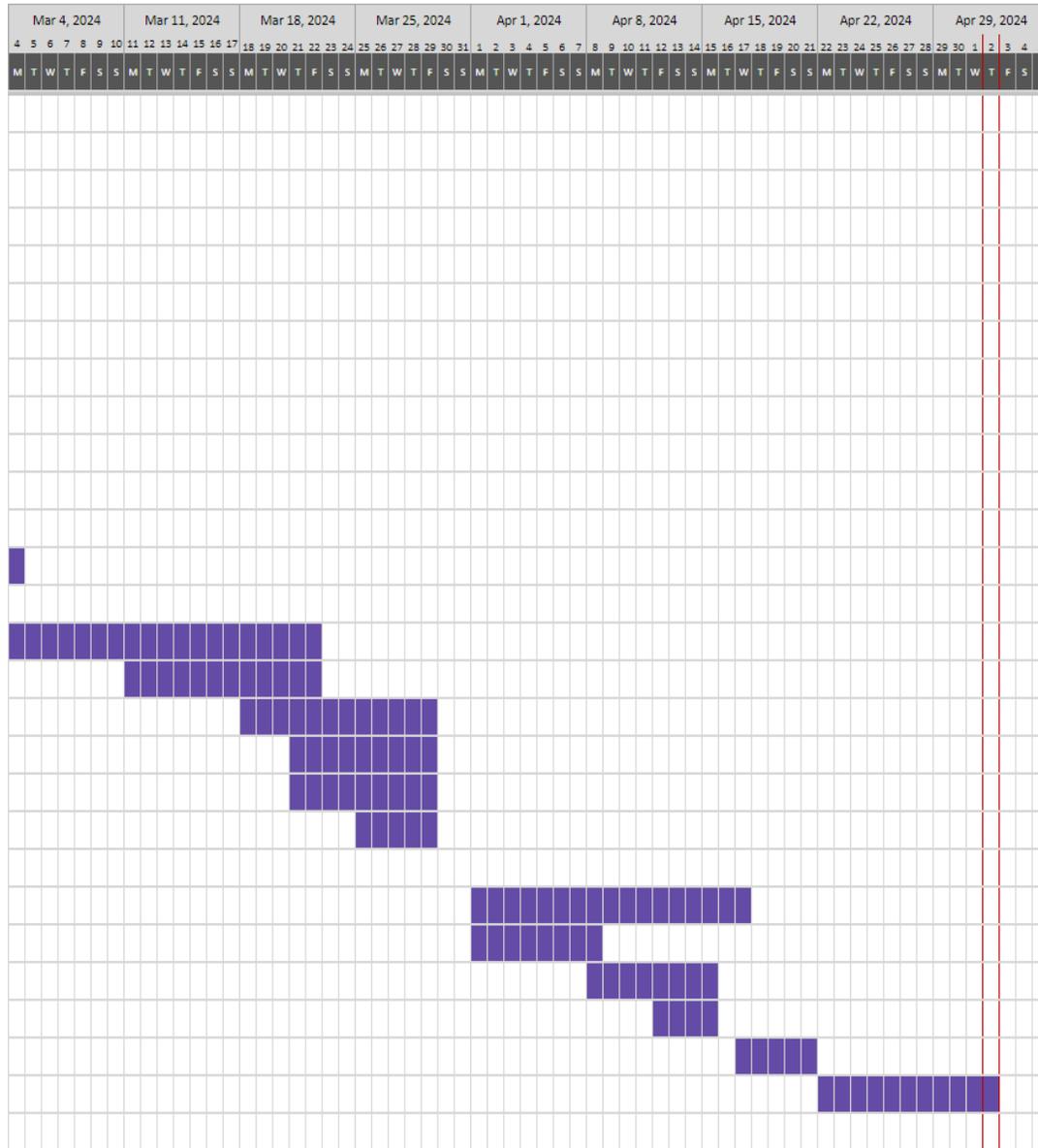


Figure 19. Task List

Task	Additional Details	Timeline
Create Gantt Chart		1/17-1/22
Gather Information on Types of Dog Wheelchairs	Conduct market research on other competitors and their design and manufacturing process of their wheelchairs. Also analyze consumer responses to their products to determine what to focus on with our design.	1/22-1/29
Gather Information on Canine Biomechanics	Study research papers and websites to analyze the mechanics of canines when in motion to better understand how to design a wheelchair that doesn't interfere with them.	1/22-1/29
Research Individuals and Companies to Potentially Interview	Conduct research into individuals or organizations who frequently use dog wheelchairs for their perspective on wheelchairs currently on the market. Also search for individuals who have experience producing dog wheelchairs and individuals with knowledge on canine biomechanics.	1/26-1/31
Reach Out to the People We Want to Interview	Draft and send out emails to chosen people asking to interview them or send them questions that we have pertaining to dog wheelchairs.	1/31-2/5
Conduct Interviews	Draft a list of questions depending on the individuals chosen to interview then either send them the questions over email, or try to meet with them over Zoom or in person to ask the questions.	2/5-2/9
Convert Interviews Into Customer Needs and Weigh them by Importance	Transcribe the conducted interviews as needed then determine the primary needs each	2/5-2/12

	customer wanted and weigh them by the importance that we believe that they have.	
Convert Weighted Needs into Engineering Specifications	Convert the weighted needs into specific engineering problems and determine metrics and testing methods with which we can determine whether the need has been resolved.	2/9-2/12
Draft Proposal	Assign responsibility to group members and draft sections of the written proposal.	2/9-2/12
Draft Preliminary Wheelchair Sketch	Choose the design criteria we are aiming to have and collaborate on a preliminary engineering sketch of it.	2/12-2/16
Finalize Proposal	Make final edits to the proposal and add any resources to the appendix.	2/14-2/16
Brainstorm Designs	Begin generating preliminary design ideas for the design of a preliminary prototype.	2/5-2/16
Decision Matrix	Create a decision matrix to narrow down ideas generated during the brainstorming process.	2/7-2/16
Materials Selection	Begin making decisions on the materials for each component and research into acquiring them	2/19-2/23
Structural Analysis	Begin performing finite element analysis on components that are most at risk of failing to determine the criteria necessary to prevent these from failing.	2/19-2/23
Design Finalization	Make final decisions about design based on materials selection and structural analysis done previously.	2/19-2/28
Initial Prototype	Begin manufacturing and	2/28-3/1

Fabrication	purchasing components for initial in class review.	
Initial Prototype Assembly	Begin assembling manufactured components for initial in class review.	3/1-3/6
Redesign Components	Redesign and alter existing design based on feedback from initial design review and observations	3/8-3/11
Materials Purchasing	Begin purchasing the required materials and components for the final prototype	3/11-3/15
Final Prototype Fabrication	Begin manufacturing the components of the final prototype	3/15-3/29
Final Prototype Assembly	Begin assembling final prototype out of fabricated and purchased components	3/22-4/12
Physical Testing	Perform physical testing and experimentation on the final components to ensure that they fulfill the required specifications	3/29-4/12
Final Adjustments	Make final adjustments to any components based on the testing done previously	4/8-4/15
Final Presentation	Create final report to display the design process and work that went into creating the final wheelchair	4/15-4/21
Final Report	Write a final report to document the design process including simulations done, physical testing done, an assembly manual, etc.	4/21-5/2

Figure 20. Preliminary FMEA

Preliminary FMEA						S	O	D	RPN
Failure Location/Component	Failure Mode	Failure Effect	Failure Cause	Suggested Remediations	Current Detection Steps	S	O	D	RPN
Frame	Deflections or Deformation	Difficulties adjusting dimensions	Stress Concentrations	Make Frame Stainless Steel	Simulation Analysis	5	2	2	20
Frame	Fatigue	Failure of frame	Fatigue	Make Frame Stainless Steel	Simulation Analysis	6	3	3	54
Frame	Fracture	Failure of frame	Stress Concentrations	Make Frame Stainless Steel	Simulation Analysis	8	2	1	16
Pins	Misalignment	Frame components detaching	Human Error	Replace with button Pins	Visual Observation	3	4	1	12
Pins	Wear	Frame components detaching	Interactions with other components	Increase Size	Material Review	5	4	3	60
Pins	Deflections or Deformation	Difficulties removing pins and adjusting frame	Stress Concentrations	Increase Size	Material Review	4	2	3	24
Pivot Joint	Fracture	Leg becomes detached from frame	Stress Concentrations	Use 3D Printed Nylon	Simulation Analysis	8	3	3	72
Pivot Joint	Wear	Leg slips and is unable to stay at consistent angle	Fatigue	Use 3D Printed Nylon	Material Review	5	4	5	100
Fasteners	Stripping	Components detach from frame	Improper Installation/Maintenance	Change to more durable material	Visual Observation	4	3	2	24
Fasteners	Vibrations	Nuts loosen and unscrew from bolts	Improper Installation/Maintenance	Use Locknuts or Loctite	Visual Observation	4	4	1	16
Fasteners	Corrosion	Fasteners become loose or fracture entirely	Corrosion	Use more corrosion resistant material	Material Review	4	2	3	24
Rosta Suspension	Deflections or Deformation	Decreases stability of the wheelchair	Stress Concentrations	Use larger size suspension	Visual Observation	6	1	6	36
Wheels	Fracture	Unable to move the wheelchair	Stress Concentrations	Use aluminum spoked wheel	Simulation Analysis	8	3	2	48
Wheels	Wear	Decreased traction and suspension	Interactions with environment	Use Rubber tires	Material Review	3	6	1	18
Wheels	Cracking	Leads to possible failure of wheels	Stress Concentrations	Use aluminum spoked wheel	Visual Observation	5	3	4	60
Wheels	Starved for Lubrication	Increased difficulty of moving	Improper Maintenance	Reduce friction at bearing	Visual Observation	4	5	2	40
Quick Release Axles	Stripping	Components detach from frame	Improper Installation/Maintenance	Use stainless steel	Visual Observation	4	5	1	20
Quick Release Axles	Vibrations	Components detach from frame	Improper Installation/Maintenance	Use Locknuts or Loctite	Visual Observation	4	5	4	80
Quick Release Axles	Deflections or Deformation	Decreases stability of the wheelchair	Stress Concentrations	Increase Diameter	Simulation Analysis	3	4	2	24
Harness	Wear	Dog detaches from wheelchair	Stress Concentrations	Use more durable material	Visual Observation	2	6	2	24
Harness	Fretting	Harness at risk of tearing	Interactions with other components	Use more durable material	Visual Observation	1	7	1	7
Harness Buckles	Fatigue	Dog detaches from wheelchair	Fatigue	Use 3D Printed Nylon	Simulation Analysis	3	3	4	36
Harness Buckles	Loosening	Dog detaches from wheelchair	Fatigue	Use 3D Printed Nylon	Visual Observation	2	6	6	72
Leg Hinge	Fatigue	Wheel detaches from the rest of the leg	Fatigue	Use stainless steel	Material Review	8	6	5	240
Leg Hinge	Buckling	Wheel detaches from the rest of the leg	Stress Concentrations	Use stainless steel	Simulation Analysis	8	5	5	200
Stirrups	Wear	Legs of dog become loose	Fatigue	Use more durable cables	Visual Observation	2	2	1	4

Figure 21. Final FMEA

Final FMEA						Updated Ratings			
Failure Location/Component	Failure Mode	Failure Effect	Failure Cause	Revisions Made	Current Detection Steps	S	O	D	RPN
Frame	Deflections or Deformation	Difficulties adjusting dimensions	Stress Concentrations	None	Simulation Analysis	5	2	2	20
Frame	Fatigue	Failure of frame	Fatigue	None	Simulation Analysis	6	3	3	54
Frame	Fracture	Failure of frame	Stress Concentrations	None	Simulation Analysis	8	2	1	16
Pins	Misalignment	Frame components detaching	Fatigue	Replaced with button Pins	Visual Observation	3	3	1	9
Pins	Wear	Frame components detaching	Interactions with other components	Used Steel	Material Review	5	3	3	45
Pins	Deflections or Deformation	Difficulties removing pins and adjusting frame	Stress Concentrations	Used Steel	Material Review	4	3	3	36
Pivot Joint	Fracture	Leg becomes detached from frame	Stress Concentrations	Used 3D Printed Nylon	Simulation Analysis	8	2	3	48
Pivot Joint	Wear	Leg slips and is unable to stay at consistent angle	Fatigue	Used 3D Printed Nylon	Material Review	5	3	5	75
Fasteners	Stripping	Components detach from frame	Improper Installation/Maintenance	None	Visual Observation	4	3	2	24
Fasteners	Vibrations	Nuts loosen and unscrew from bolts	Improper Installation/Maintenance	Used Locknuts	Visual Observation	4	2	1	8
Fasteners	Corrosion	Fasteners become loose or fracture entirely	Corrosion	None	Material Review	4	2	3	24
Rosta Suspension	Deflections or Deformation	Decreases stability of the wheelchair	Stress Concentrations	None	Visual Observation	6	1	6	36
Wheels	Fracture	Unable to move the wheelchair	Stress Concentrations	None	Simulation Analysis	8	3	2	48
Wheels	Wear	Decreased traction and suspension	Interactions with environment	None	Material Review	3	6	1	18
Wheels	Cracking	Leads to possible failure of wheels	Stress Concentrations	None	Visual Observation	5	3	4	60
Wheels	Starved for Lubrication	Increased difficulty of moving	Improper Maintenance	None	Visual Observation	4	5	2	40
Quick Release Axles	Stripping	Components detach from frame	Improper Installation/Maintenance	Added 3D Printed End Caps	Visual Observation	4	4	1	16
Quick Release Axles	Vibrations	Components detach from frame	Improper Installation/Maintenance	Added 3D Printed End Caps	Visual Observation	4	4	4	64
Quick Release Axles	Deflections or Deformation	Decreases stability of the wheelchair	Stress Concentrations	None	Simulation Analysis	3	4	2	24
Harness	Wear	Dog detaches from wheelchair	Stress Concentrations	Used more durable material	Visual Observation	2	5	2	20
Harness	Fretting	Harness at risk of tearing	Interactions with other components	Use more durable material	Visual Observation	1	6	1	6
Harness Buckles	Fatigue	Dog detaches from wheelchair	Fatigue	3D Printed Exterior Cover	Simulation Analysis	3	3	4	36
Harness Buckles	Loosening	Dog detaches from wheelchair	Fatigue	3D Printed Exterior Cover	Visual Observation	2	5	6	60
Stirrups	Wear	Legs of dog become loose	Fatigue	None	Visual Observation	2	2	1	4
Shafts	Deflections or Deformation	Wheel becomes crooked	Stress Concentrations	None	Simulation Analysis	4	2	2	16
Shafts	Loosening	Wheel comes unattached from leg	Improper Installation/Maintenance	None	Visual Observation	2	5	3	30
Shafts	Misalignment	Wheel becomes crooked	Fatigue	None	Visual Observation	3	4	3	36

Final Drawings

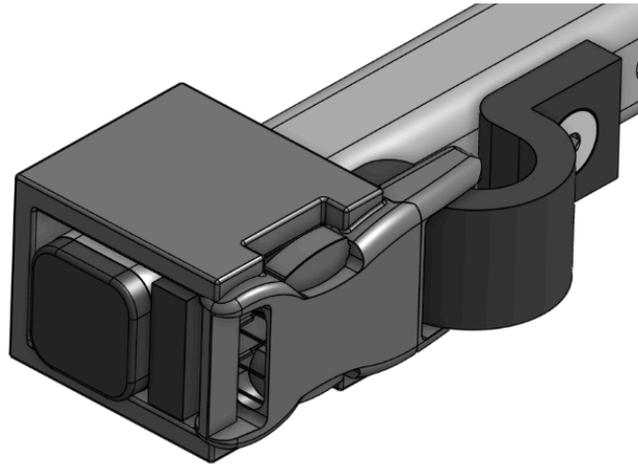


Figure 22. Front harness buckle.

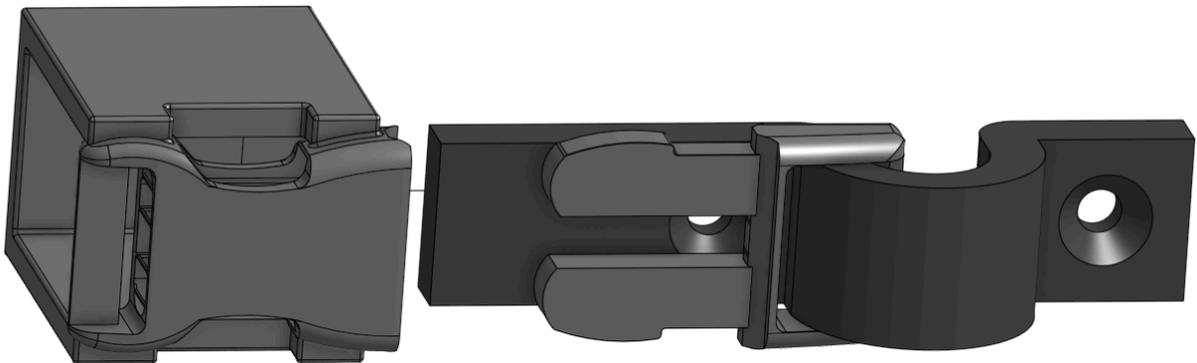


Figure 23. Front harness buckle exploded view.



Figure 24. Main wheelchair frame.



Figure 25. Wheel and shaft attachment to leg.

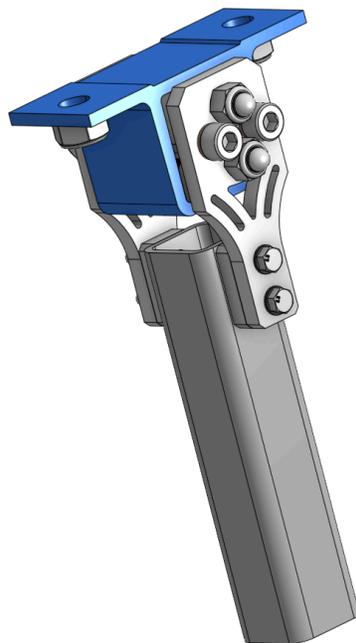


Figure 26. Leg attachment to ROSTA suspension unit.

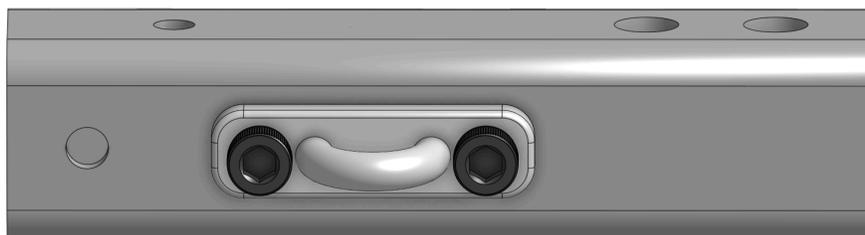


Figure 27. Stirrup attachment to wheelchair frame and fasteners.

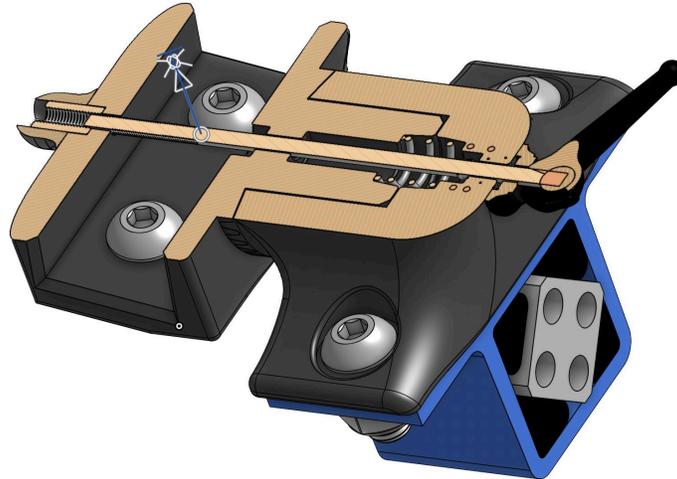


Figure 28. Pivot joint mechanism cross-sectional view.

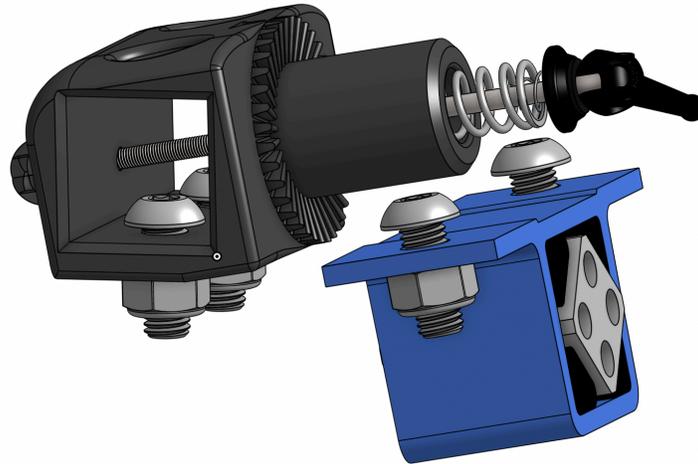


Figure 29. Pivot joint mechanism teeth view (leg joint hidden).

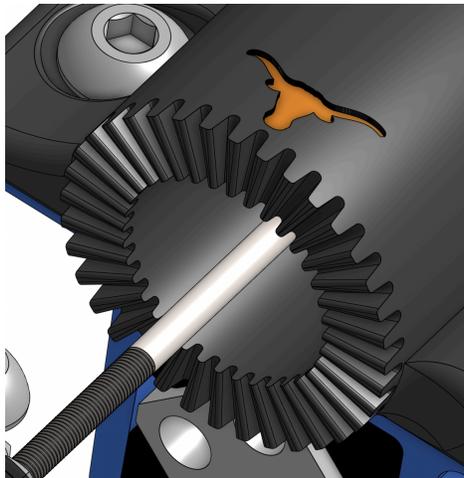


Figure 30. Pivot joint mechanism teeth view (frame joint hidden).

Figure 31. Engineering Specifications Sheet

<u>Customer Need</u>	<u>Wish/ Demand</u>	<u>Target Metric</u>	<u>Verification</u>
Durability			
Secure fasteners	Demand	No tightening needed > 2 yrs	Prototype cyclical vibration testing, customer surveying
Collision resistance	Want	Withstand 5kN of impact force	Material analysis of 6061 Aluminum, prototype impact testing, FEA stress analysis
Withstand various terrains	Demand	Can climb up or descend grades of up to +/- 70° (35° angle)	Prototype performance testing
Low maintenance	Demand	No wheelchair maintenance > 2 yrs	Customer surveying, cyclical load testing on prototype
Cleanability			
Anti-rust/Anti-corrosive	Demand	No visible rust in the average humidity of Austin (67%) for > 5 yrs	Material corrosion analysis and research
Waterproof	Demand	No corrosion for 1 year after salt water exposure and self-draining	Material analysis, experiment with prototype
Mobility			
Low Turning radius	Want	Turning radius < 20 cm or turning area < 40 cm in diameter for tight spaces	Measure turning distance/area required on prototype
Low Profile body/frame	Want	Frame width of < 35 cm	Measure prototype
Stable wheelbase	Demand	Can withstand tipping force of 130 N	Perform point-force experiments on weighted prototype
Climb stairs/curbs	Want	Can roll over stairs of up to 20 cm in height	Test prototype on 20 cm stairs

Suspension	Want	Between 30-60 mm of sprung travel	Compress prototype suspension and measure vertical distance
Comfort			
Supports body weight	Demand	Can support ≥ 535 N (double Cleopatra's weight and a safety factor of $N = 2$)	Experiment loads on prototype, FEA stress analysis
Legs don't drag on ground	Demand	A vertical leg clearance of 10 cm from ground at suspension sag	Measure distance with prototype on Cleopatra
Bathroom usability	Want	A clear drop zone of a radius > 12 cm from private parts	Measurement and prototype restroom performance testing
Able to lay down (safely)	Want	Rear supports can fold down < 10 seconds	Time feature with customer trials after brief instructions on usage
Rounded edges	Want	Fillet radius > 3 mm on edges of frame and fasteners	Measure all edges and corner radii, prototype abrasion tests
Soft harness material to prevent irritation	Demand	Harness Shore A durometer hardness of 25-30 A for comfort vs. durability	Analysis of harness materials
Support for spinal column	Demand	Spinal column deviation of < 2 cm	Measure spinal deviation once wheelchair fitted properly
Ease of Use			
Lightweight	Demand	Total weight < 67 N	Measure total weight of wheelchair system (with harness)
Compactability/portability	Want	Can be folded or packed in < 20 seconds	Time feature with customer trials after brief instructions on usage

Ease of don/doff	Demand	Can be attached or removed from dog in < 20 seconds	Time feature with customer trials after brief instructions on usage
Adjustability			
Size adjustability	Want	Harness, height, width, and length can be adjusted by at least +/- 15% of Cleopatra's measured dimensions	Experiment with and measure prototype adjustability
Different wheel per terrain	Want	2 sets of swappable wheels (indoor/outdoor) or (asphalt/off-road)	Produce 2 sets of wheels and test with terrain metrics
Easily replaceable parts	Want	> 70% of parts can be replaced by department store products	Compare compatibility specifications with common store-bought products

Figure 33. BOM & Budget

MCMaster Parts:				
Part Number	Price/Order	Order Qty	Part Description	Link:
MISC.				
94282A416	\$6.94	2	5x Spring Steel Button Pins for Telescoping Tubing Zinc-Plated, Single, 11/16" to 1-3/8" ID, 3/8" Button Diameter	LINK
1556A24	\$0.93	2	1x Zinc-Plated Steel Corner Bracket, 7/8" x 7/8" x 5/8"	LINK
8969T943	\$4.71	2	1x 316 Stainless Steel Corrosion-Resistant Compression Springs, 25 mm Long, 15.010 mm OD, 11.810 mm ID	LINK
92290A458	\$14.81	2	5x M8 x 1.25mm Super-Corrosion-Resistant 316 Stainless Steel Socket Head Screw	LINK
93413A130	\$9.48	1	10x M5 Black Corrosion-Resistant Coated Steel Washer	LINK
97725A530	\$15.73	1	25x M8 Metal Sealing Washer	LINK
Nuts				
93625a113	\$6.88	1	25x 18-8 Stainless Steel Nylon-Insert Locknut, M6 x 1 mm Thread, 10 mm Wide, 8 mm High	LINK
23595T17	\$4.75	2	1x Zinc plated steel wheel axle, 1/2" diameter, 3 1/4" length, 1/2"-20 thread size with hex nut	LINK
97135A414	\$5.08	1	25x High-Strength Steel Nylon-Insert Locknut, Black-Oxide, 1/4"-20 Thread Size	LINK
90582A114	\$15.72	1	25x M8 x 1.25mm Nylon-Insert Cap Locknut	LINK
90428A110	\$9.20	1	5x M5 18-8 Stainless Steel Vibration-Resistant Cap Locknut	LINK
Bolts				
91290A204	\$5.17	1	10x Alloy Steel Socket Head Screw, Black-Oxide, M6 x 1 mm Thread, 45 mm Long, Fully Threaded	LINK
91290A205	\$5.86	1	10x Alloy Steel Socket Head Screw, Black-Oxide, M6 x 1 mm Thread, 50 mm Long, Fully Threaded	LINK
91290A207	\$5.52	2	5x Alloy Steel Socket Head Screw, Black-Oxide, M6 x 1 mm Thread, 60 mm Long, Fully Threaded	LINK
91253A540	\$10.69	1	50x Black-Oxide Alloy Steel Hex Drive Flat Head Screw, 1/4"-20 Thread Size, 3/4" Long	LINK
90111A331	\$1.20	3	1x 316 Stainless Steel Coupling Nut, Super-Corrosion-Resistant, M5 x 0.8 mm Thread	LINK
91280A249	\$13.87	1	25x M5 x 0.8mm Medium-Strength Class 8.8 Steel Hex Head Screw	LINK
Customized Parts:				
Part	Price/Order	Order Qty	Part Description	Link:
Wheels	\$30.99	1	1 Pair 11 inch Balance Bike Replacement Non Inflatable	LINK
Front Harness	\$35.99	1	Front Harness	LINK
Strirrups	\$9.95	1	Walkin' Pets Strirrups	LINK
Rear Harness	\$21.99	1	ROZKITCH Dog Lift Harness, Pet Rear Support Aid Veterinarian Approved Sling for Old K9 Help with Poor Stabilit	LINK
2x ROSTA untis	\$137.99	1	01 101 022 TENSIONER RUBBER SUSPENSION UNIT TYPE DW-A 27X 40	LINK
2x 100x5 Skewer	\$15.14	1	2x M-Wave Aluminum Front Hub Quick Release Skewer, Silver	LINK
Frame Tubing	\$90.11	1	1.25"/1.00"x.110" 6005A16 Square Telescoping Tubing	LINK