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Design of an Off-Road Manual Wheelchair

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Abstract

The objective of this project is to design and test a wheelchair that can traverse off-road terrain. The design has four main subsystems: a supporting frame that is broken up into an upper and lower frame, a drivetrain to power the wheelchair's motion, a braking system to ensure that it stops when desired, and a suspension system to absorb impacts from off-road obstacles. The team modified an existing Silver Sport 2 wheelchair by breaking it into two parts: an upper frame and a lower frame. The upper frame consists of steel tubing for the armrests, leg supports, seat attachments, and brackets. The lower frame consists of steel tubing for attaching wheels and brackets. The brackets are used for mounting the other subsystems. We evaluated the performance of the frame using Finite Element Analysis based on the forces from the user and the other subsystems. For stopping the wheelchair, our design replaces the existing parking brake lever mechanisms with a caliper braking system used on bicycles. In addition, dynamic analysis was conducted to find the appropriate size brake pads based on various stopping distances. The drivetrain sub-system uses chains and sprockets similar to those seen on mountain bikes to propel the wheelchair. Lever bars have been added to create a mechanical advantage that allows for easier propulsion. Finally, the suspension system includes four springs and dampers mounted between the upper frame and the lower frame to minimize impacts on the upper frame and provide a comfortable ride for the user. All sub-systems have been designed to satisfy the given requirements for the project. Further physical testing with the fully assembled prototype would confirm the sub-system designs are satisfactory.

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Variables	Term	Values and Units
m_{sys}	Mass of the system	$9.3168\ (\frac{lb*s^2}{ft})$
a_{sys}	Deceleration of the system	$5\frac{ft}{s^2}$
v_{sys}	Assumed Velocity of the system	$15\frac{ft}{s}$
W_{total}	Total weight of the system. Includes the weight of the person and wheelchair	$300\ lbs$
μ_T	Coefficient friction at the tire-road contact patch	• Asphalt (0.8) • Wet Asphalt (0.6) Others (0.7)
μ_R	Coefficient of friction the radius of the rotor	0.4-0.6
$h = y_4 + y_3$	Height from the ground to the center of mass	$28\ in$
$d_1 = x_2$	Distance from point A to center of mass	$5\ in$
$d_2 = x_1$	Distance from point B to center of mass	$16\ in$
$L = x_1 + x_2$	Distance between the center of both large and front caster wheel	$21\ in$
f_1	Friction force at A	$Unknown$
f_2	Friction force at B	$Unknown$
N_1	Normal force acting at A	$Unknown$
N_2	Normal force acting on B	$Unknown$
r_R	Radial length of rim	$13\ in$

r_{wheel}	Radial length of large diameter wheels	$15.5\ in$
$F_{f,r1}$	Force of friction acting on large diameter inner wheel	$Unknown$
T_{cable}	Pressure in cable	$280\ psi$
$F_{applied}$	Applied force on the handles	$70\ lbs$
n	Number of pistons acting on the large tire	$2\ per\ wheel$
F_{cable}	Force of cable acting on the large tires	$Unknown$
KE	Kinetic energy	$Unknown$
ω	Angular velocity	$Unknown$
F_{clamp}	The force of the clamp on the caliper	$Unknown$
$F_{friction}$	Friction Force created from brake pads	$Unknown$
τ_r	Braking torque	$Unknown$
$R_{effecient}$	Distance used to find torque	$3.54\ in$
θ	Angle through which disc rotated during brake period	$Unknown$
t	Time it would take for wheelchair to stop	$Unknown$
x_{stop}	Distance it would take for the wheelchair to stop	$Unknown$
k	Stiffness of the spring	$300\frac{lbs}{in}$
W	Weight of the user	$300\ lbs$
$W_{applied}$	Weight applied on the rear suspensions for testing	$230\ lbs$

ζ	Damping ratio of the suspension system	0.321
δ	Logarithmic decrement variable	2.126
c	Damping constant	Type equation here.
F_d	Force from damper	N/A
F_s	Force from spring	
ω_n	Natural frequency	
T	Period of oscillation	

1.0 Introduction

The following will focus on the design of an Off-Road Manual Wheelchair. The reason this project focuses on designing an Off-Road Manual Wheelchair is to allow those with disabilities to have more access outdoors. This design specifically wants to give the user the ability to explore the outdoors to their comfort, especially if they wish to travel through hiking trails.

To do so, a proper brake system needed to be incorporated. It might not be known, but most standard wheelchairs just contain a parking brake. This parking brake requires the wheelchair to be in a static position, otherwise activating the parking brake while the wheelchair is in motion would put the user in danger **[2]**. Therefore, since the Off-Road Manual Wheelchair will be subjected to outdoor terrains with steep inclinations. The user should have control in stopping the wheelchair to their comfort without feeling that they are in danger. Now the brake system will be tested by collecting the stopping distance, stopping time, and deceleration that will be used to compare to the theoretical values. This will help ensure the proper brake will stop the system as expected.

To ensure the propulsion mechanism will work, the gear ratio will be analyzed later in the report. The propulsion mechanism was added since it will be used to put the wheelchair in motion. The propulsion mechanism discussed in more detail will use a chain and sprocket mechanism similar to those on mountain bikes. This propulsion mechanism will have a gear ratio that will allow it to drive through any type of terrain. The propulsion mechanism was added to give the user the ability to move without any assistance **[1]**.

The suspension was added to create a smooth ride for the user since the wheelchair will be subjected to tough, inclined terrains. The suspension will be tested by finding the damping ratio which will be discussed later in the report. This will ensure that the suspension will create a smooth ride for the user **[18]**.

Lastly, the results obtained for each subsystem will be discussed. This will help determine whether the wheelchair subsystems will do their job. It will discuss the lessons learned from this project. It will also include looking into future work and a disposal plan for the project. Then it will conclude with the final product of the wheelchair.

1.1 Objective Statement

The objective of this project is:

Design and test an Off-Road Manual Wheelchair that allows wheelchair users to access outdoor terrains.

1.2 Deliverables

The deliverables for the project are as follows:

- A SolidWorks assembly of the Off-Road Manual Wheelchair
- Documentation of engineering calculations and design
- Physical prototype of the design

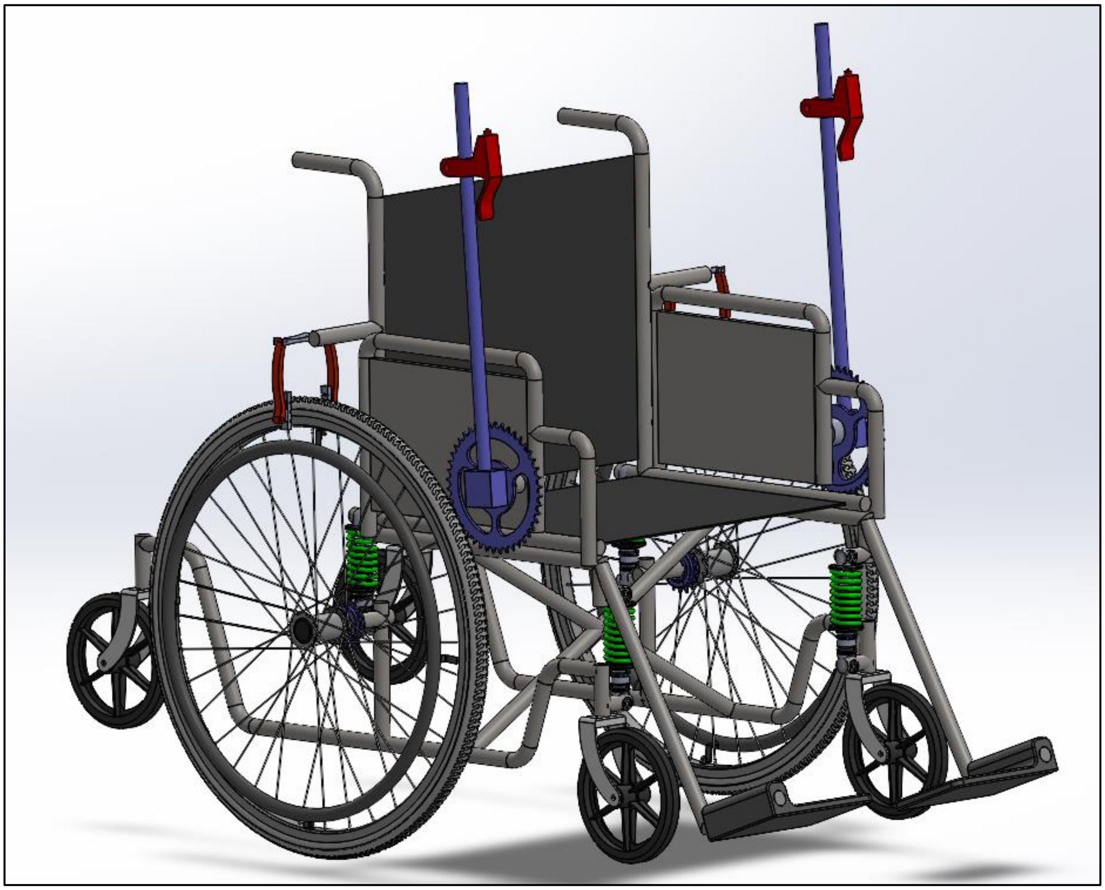

Figure 1. Isometric View of the Off-Road Manual Wheelchair SolidWorks Model

2.0 Background

2.1 Motivation

When hearing about a wheelchair, what comes to mind is the use of them in a hospital setting. If not in a hospital setting, the next in mind are those around the world with disabilities who are not able to move around due to medical conditions from birth. The idea behind the Off-Road Manual Wheelchair is that those with disabilities should have the same opportunities to enjoy life as everyone else. They should have the opportunity to travel and hike if they please, or even simply use the wheelchair for outdoor recreational purposes without the need to be assisted.

2.1.1 Current Wheelchair Use

Now there are already wheelchairs that are designed for outdoor use. For example, in the Paralympics, those who enjoy basketball have wheelchairs with cambered tires to prevent the user from falling over in a fast-paced sport. There are also wheelchairs that allow the user to move around without assistance both with and without electrical components. For the non-electric wheelchairs, the user tends to use the hand rim to move themselves forward as shown in Figure 2 **[12]**. How it works is when the user wants to move forward, they have to use the rims that are provided on the wheels **[2]**. Once having a good grip, the user's next step is to attempt rotating the wheel by exerting a force that will get the tire rotating and moving forward **[2]**. They would then repeat this same procedure until they get to their desired destination **[2]**. Although the user can use the hand rims to get the wheelchair moving forward, the assistance handlebars that are included on the back of the wheelchair are used more to prevent the user from fatiguing their body **[2]**. Note that with the assistance handles it would require having another person push them to their desired destination **[2]**. Therefore, the goal of the wheelchair in this project is to give the user the ability to travel outdoors without needing constant assistance.

Figure 2. This demonstrates how the user brakes using their hands ***[2]***

Now the hand-rim method is not the only way for those with disabilities, there are existing wheelchairs that are electrically powered. These electric-powered wheelchairs allow the user to move without needing as much assistance as those using hand-rimmed powered wheelchairs. Although the electric power allows the user to move around freely, there is extra weight added to the wheelchair from the electrical components. Aside from extra weight being added for electric-powered wheelchairs, the transportation of these wheelchairs is difficult to deal with when traveling as opposed to the hand-rim wheelchairs. A big reason it is difficult to transport is that the wheelchair cannot be folded like the hand-rim wheelchairs instead, the electrical-powered wheelchairs require using a large vehicle **[2]**. The electrical-powered wheelchair also requires an understanding of electrical components. Therefore, rather than messing with electrical components, this project will use a lever-arm propulsion mechanism that will move the wheelchair. This lever-arm propulsion pro will be discussed later on in the report.

The braking system will also be discussed later in the report. A reason that this project focuses on adding a brake system is because, from the literature, most standard wheelchairs use just a parking brake. This parking brake requires the user to be in a static position, meaning the wheelchair must be in a stopped position **[2]**. For example, hand-rim-powered wheelchairs require the user to use their hands and attempt to hold the rim to stop the wheelchair from moving. Using their hands creates friction that slows down the wheelchair and when they are not moving can they then apply the parking brake to not worry about the wheelchair rolling off. The hand rim is that when the user wants to slow down if they were to use it for hiking purposes, their hands could be severely damaged due to not having a proper brake system **[2]**. This is why adding a braking system to the off-road wheelchair would prevent the user from harming their hands to stop the wheelchair. As mentioned earlier, cambered wheels are used for recreational sports to prevent the user from tipping, but this project will focus on it being outdoors for hiking purposes. Therefore, adding cambered wheels with a lever-arm propulsion mechanism would be difficult to incorporate. Instead, the project will add a tipping component to the back of the wheelchair discussed later in the report.

2.1.2 Off-Road Manual Wheelchair

The Off-Road Manual Wheelchair is different from standard wheelchair due to the subsystems that are implemented namely: the propulsion system, the braking system, and the suspension system. For propulsion, the offroad wheelchair uses lever handles to which are attached chains and sprockets instead of traditional hand on rims. This allows for a different method of propulsion, potentially offering more power (mechanical advantage) and control compared to the hand rim propulsion of a standard manual wheelchair. The offroad wheelchair is also equipped with caliper brakes, which are commonly found in bicycles. These brakes provide more stopping power and precision compared to the standard push-to-lock or scissor brakes found in manual wheelchairs or the user just gripping the wheels to stop the wheelchair which would have been impossible in an offroad setting. The presence of a suspension ensures that shocks and vibrations will effectively dissipate while navigating over offroad terrains. And lastly, due to the bicycle tires used, the pneumatic front casters used, and the back support casters, the offroad manual wheelchair is equipped to traverse terrains that standard manual wheelchairs would not afford to traverse as they are designed much more for indoor use and smooth terrains.

2.2 Similar Projects and Designs

2.2.1 Leverage Freedom Chair

The first similar design for an off-roading wheelchair was developed by Massachusetts Institute of Technology to create a suitable wheelchair for rural areas in Africa. An article from MIT states, the Leverage Freedom Chair is an off-road wheelchair that was designed for rural countries in Africa. The wheelchair is manually driven with a dual-lever propulsion system. The dual levers are designed to generate more mechanical power than other manual propulsion systems and it allows the user to maneuver the direction of the wheelchair by making the two levers independent from one another. The mechanical advantage was 3:1. The wheelchair also utilizes a bicycle gear system to translate the input motion of the hand-lever system toward the output motion of turning the wheels **[2]**. Figure 3 below shows a person using one of the proposed designs of the LFC wheelchair.

Figure 3. LFC Wheelchair [2]

The LFC design proves to be an adequate base for developing a lever propulsion system for this project's off-road wheelchair design. Using a duel-levered propulsion system with independent lever bars will help produce enough power and maneuverability for a user to drive the wheelchair on rocky and dirt terrains. Also, the front guiding caster wheel proves to be an essential part in maneuvering over large objects. An engineering report from MIT states, the front guiding caster wheel provides greater stability and better maneuverability over large objects. Calculations were conducted by MIT to investigate the benefit of the front guiding wheel and the sized objects that it can maneuver over **[3]**. The biggest issue with the LFC wheelchair is that there is no anti-tipping analysis or measures performed to see if the wheelchair will tip backwards on a specific percent slope.

2.2.2 Gölem Project Hiking Wheelchair

The Gölem Project is a design for an off-road wheelchair for hiking purposes. The goal is to design and create a wheelchair that can traverse rough and mountainous terrain. The design consists of using a suspension system that prioritizes traversing on very rocky terrain. The unique design It allows the user to travel in very unstable environments without the risk of tipping. The design also highlights the use of bicycle parts and tubular frames as the materials used for the construction. This is incorporated to diminish special machining needs for wheelchair design and construction. The Gölem Project proves that their design can traverse very mountainous and rocky terrain with its unique seat and wheel suspension system while also incorporating a hand brake system. The downside is that it doesn't show any specifications on how a user can manually propel the wheelchair on their own. It only specifies an assistive force guiding system **[4]**. Figure 4 shows the overall design of the Gölem wheelchair. The Gölem Project also fails to include a braking system that the rider can access for themselves **[1]**. Figure 4 does show that there are handles on the back of the wheelchair for braking but it requires having someone that is assisting using them rather than the user **[1]**.

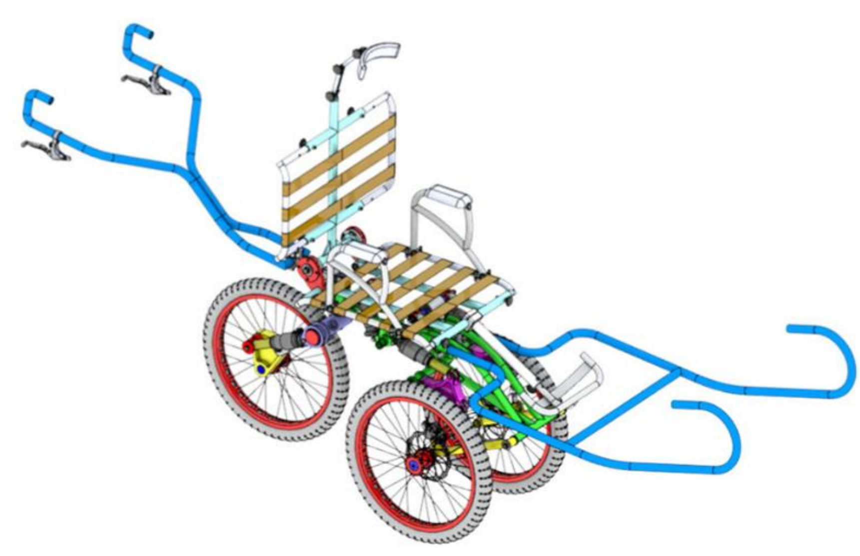

Figure 4. Gölem Project Final Design [4]

Figure 4 above highlights the suspension system in yellow. Each drive wheel include a independent suspension system that optimizes for lateral balance maneuverability of the wheelchair **[1].**

2.2.3 Motivation Rough Terrain Wheelchair

In a research article from Informa Healthcare, a United Kingdom off-road hand-rim propelled wheelchair was designed specifically for individuals who lived in low-resourced or less fortunate areas in the world. The rough terrain it was designed for was specifically for dirt paths, grass, and gravel **[5].** The design incorporated a long wheelbase and large-diameter wheels and a centered guiding wheel in the design. The guide wheel was smaller in diameter and had a thicker wheel width which provided sufficient maneuverability through rough terrain. The "tricycle-like" design ultimately allowed the wheelchair to be versatile on multiple terrains. Unfortunately, the hand-rim propulsion system caused the user to have sore hands when using the wheelchair in tests. The hand rims used for the propulsion of the wheelchair were too close to the two base wheels, and it was cumbersome for the user to navigate and change direction on rough terrain with this propulsion system **[5]**. Figure 5 below shows the assembled Motivation Rough Terrain Wheelchair.

Figure 5. Motivation Rough Terrain Wheelchair [5]

2.3 Requirements

The Offroad Manual Wheelchair shall…

- Support a weight of 300 lb.
  - Per the Americans with Disabilities Act (ADA) **[6]**
- Include a lever-arm propulsion mechanism.
- Move up a 25% slope.
  - ADA requires a 15% slope **[6]**
- Include a manual braking system.
- Include a suspension system.
- Weigh less than 60 lb.

The requirement to support a weight of 300 lb. comes from the ADA. The requirements for including a lever-arm propulsion mechanism, a manual braking system, and a suspension system come from the team's desire to add said systems. The requirement of moving up a 25% slope comes from the ADA standard of moving up a 15% slope, the team increased this requirement by 10% as the wheelchair will be in the outdoors subjected to steeper slopes. The final requirement of weighing less than 60lb. is a typical manual wheelchair weight.

3.0 Concept Selection

3.1 Concept Design 1

The focus of the first concept design was to replace the standard wheelchair rubber tire with a tank tread tire. Figure 6 shows the tank tread wheelchair through a front view and side view. The idea of including tread wheels rather than the standard rubber tire is that the tank tread tires should allow the user to move through any type of terrain. The tank tread tire requires gears, these gears driven by a motor allow for the wheelchair to move through most of its obstacles. The flat design and grooves being evenly spaced out on the tank tread tire allow it to move through any terrain **[22]**. The reason for the grooves being evenly spaced out allows for the edges to act as hooks that create better traction through any terrain **[22]**. The flexibility of the tank tread tire is another feature that allows for easy mobility through any terrain **[22]**. That is because by keeping a thin tire, the tire itself can bend, essentially adapting to its surroundings **[22]**. With the original rubber tires, the user would be limited to where they can and cannot go due to mobility restrictions **[22]**. An example of this is if the user wished to go on a hike with their friend, with the original tires, the user would struggle to move through a possible rough landscape. Now if they were to have the tank tread tires, their mobility through the hike would not be a hassle as the tread wheels tend to adapt to any terrain. That is because as mentioned before, the tank tread tire can adapt since they can bend to adapt to the terrain and maneuver through it.

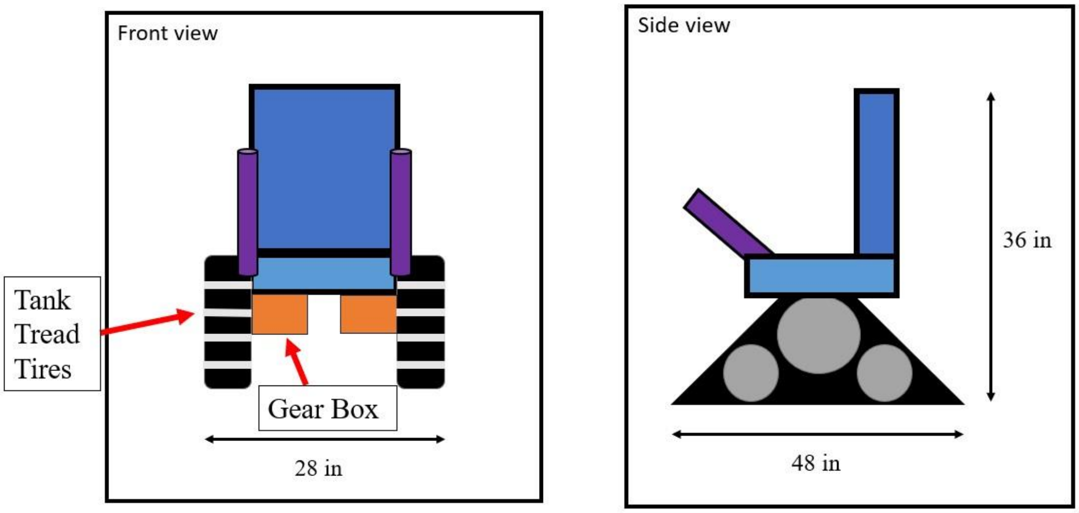

Figure 6. The image on the left shows the Front View of the Tank Tread Tire Wheelchair and the image to the right is a Side View of the Tank Tread Tire Wheelchair

It should also be noted that tank tread tires have been used in combat as shown in Figure 7 **[22]**. Tanks in combat use the same concept of tank tread wheels, that is because the tanks used need to be able to move through the roughest landscape **[22]**. Now to get the tread wheel attached to the wheelchair, it would require using many gears to get the tread wheels moving as mentioned before **[22]**. Not only that, but a gearbox would also need to be designed to protect the gears from deteriorating at a faster rate than anticipated. Therefore, despite the idea that using a tread wheel would be nice to integrate, it would be a much better option to just keep the original tires of the wheelchair **[22]**.

*Figure 7. Tank with Tread Tires being Tested **[22]**.*

As mentioned in the previous paragraph, the idea of integrating a tread wheel into the wheelchair would require using gears. These gears as described previously mesh with each other with a motor allowing for it to move **[22]**. That is why adding a lever-propelled mechanism would have been a feasible feature to add. It is feasible because the lever-propelled mechanism will also use gears. The lever-propel mechanism will include using a chain and sprocket mechanism. The idea is similar to the mechanism used in mountain bikes; the chain will be stretched out in tension at two ends **[2]**. One end will have the sprocket and the other the shaft on which the levers are connected to drive the wheelchair forward **[2]**. The shaft being connected to the levers would allow for the user to push on the levers creating a propulsion motion that would drive them forward **[2]**. That is because the chain is in tension and connected to the sprocket at the bottom of the wheelchair frame allowing the gear sprocket to drive the wheelchair into motion **[2]**. The discussion of the propulsion mechanism will be in more detail later in this report. For now, a rough idea of where the lever for the propulsion mechanism would be positioned is to the sides of the armrests of the wheelchair frame roughly shown in Figure 6. The lever arms would be long enough for the user to use without having to reach out to activate the lever arm propulsion mechanism. The problem once again, is that since this concept uses several gears, creating a gearbox would be needed. Therefore, for simplicity purposes, this concept was scrapped. It was decided to keep the standard wheelchair frame and add the subsystems to it. Even then, this concept does not include a brake system that would stop the wheelchair, nor does it include a suspension. Without a brake system, the user would have no way to stop to their comfort when going on hike trails. Without a suspension system, the user would have a bumpy ride. Both of these put the user in danger if they are not included when on hiking trails. The biggest issue yet is that if the user were to tip back, there is nothing that will prevent the user from falling backward. This is why this concept was not the final concept, but it helped structure the other designs that will be discussed.

3.2 Concept Design 2

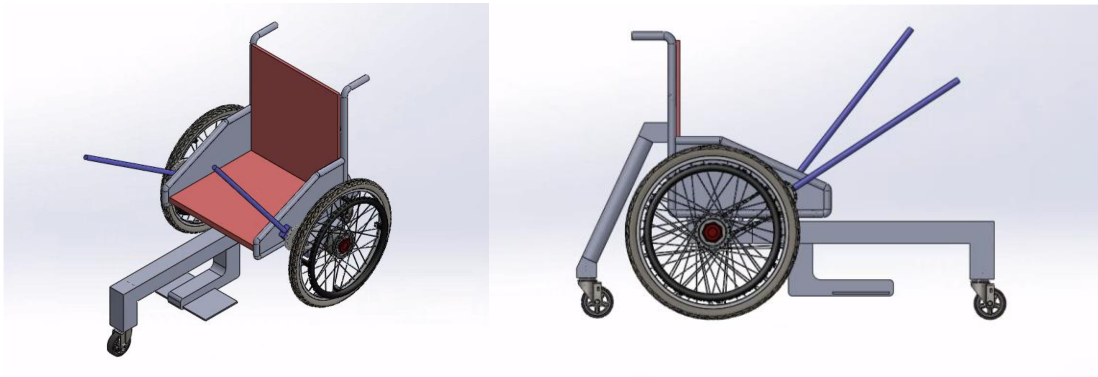

Figure 8. The image on the left is the Isometric View of the Second Concept Design and the image on the right is the Side View of the Second Concept Design with an Anti-Tipping Mechanism

The second concept design, the idea of the lever arm-propelled mechanism was kept as discussed in the previous concept design. Figure 8 shows the location in which the lever arm propulsion mechanism will be attached. The idea of using a chain and sprocket system as discussed is intended for this second concept design. Figure 8 shows additional components that were added, one of those is an extension for the front caster wheel. The idea behind this extension is that it would help the user maneuver over any terrain, in this case, it would help the user move up a hiking trail if needed. However, the problem with extending the front is that keeping the caster wheel the same size as that of a standard wheelchair would throw the idea of it moving easily through any terrain. That is because if the caster wheel comes across any small bump, rather than moving over it with ease. Therefore, a bigger tire would be needed for it to work. Another component that was added to this concept design is the mountain bike tires. This was intended to allow for the wheelchair to drive through any terrain easily. These wheels also have rims that would allow the user to move the wheelchair forward if the propulsion mechanism were to fail. The assistive handles on the back of the wheelchair frame were also added to this concept design. It was done to provide additional assistance to the user if needed on the bike trails. Figure 8 also shows another component that was added to the back of the wheelchair. That back component is an anti-tipping mechanism that would prevent the user from tipping backward and falling completely on their back. This idea came about because the wheelchair will be subjected to steeper slopes than typical wheelchairs. How it works is that as the wheelchair starts to tip, the anti-tipping mechanism with the caster wheel rolls out and locks out after a certain length. That length would be found doing a tipping analysis. This in return would keep the user from completely falling on their back and causing harm to the user.

As mentioned previously, the issue with extending the front caster wheel is that the caster wheel is too small to drive over any object that the user would come across in hike trails. For it to work ideally, the front caster wheel size would need to increase. By increasing the size of the front caster wheel, if the user were to come across a speed bump on the hiking trail, they would move over it easily. The other issue with this concept design is that a brake system was not added nor was a suspension system. Which are crucial as described in the previous concept design. Without them, the user would be at risk. The anti-tipping mechanism was also room for concern, although it would prevent the user from falling completely on their back. It would still leave the user in a very uncomfortable position on their back with no way of being back in their original position. Therefore, this concept was scrapped but helped set the following concept design with the components that were added to this concept design.

3.3 Concept Design 3

Taking into consideration the aspects discussed in the previous concept designs, the third and decided-upon concept is shown in Figure 9. This concept design includes a lever-driven propulsion mechanism that will drive the wheelchair forward as in previous concepts. It also includes a caliper braking system that will allow the user to stop the wheelchair to their comfort. A suspension system was added to smoothen the ride for the user. This design also includes wheels on the back of the wheelchair as the anti-tipping mechanism of the wheelchair that the team was keen on implementing. This concept design also includes the wheels as discussed in the previous concept design. These wheels include rims that allow the user to drive the wheelchair forward in case the propulsion mechanism fails. Also, the caster wheels are of a larger size that will allow the user to move through any terrain despite the speed bumps it may encounter. Justification for the design of this Off-Road Manual Wheelchair will be discussed in each sub-system design portion of this report.

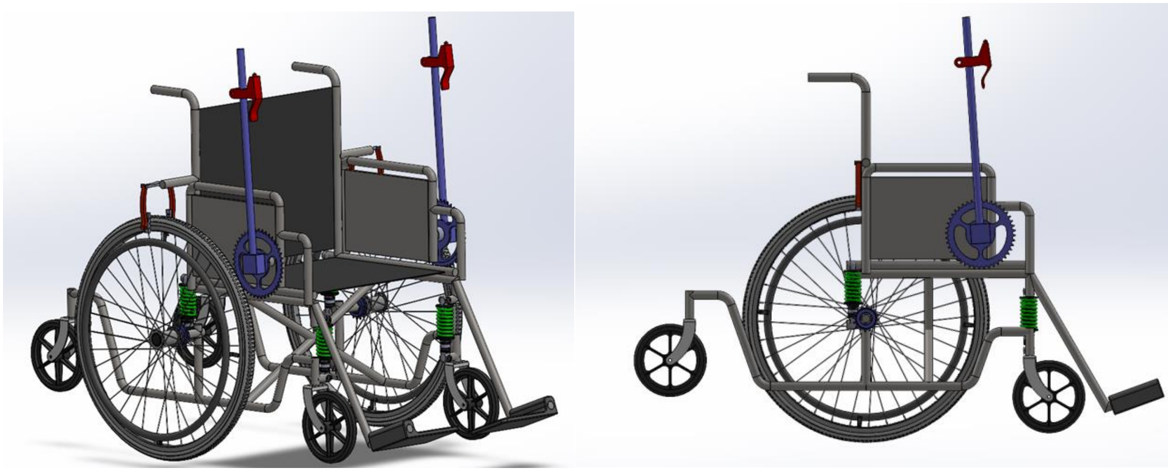

Figure 9. SolidWorks Drawing on the left is the Isometric View of the Third Concept Design, and the right is the Side View of the Third Concept Design with brakes

4.0 Final Design and Analysis

This section describes the final design and analysis of each sub-system. The sub-systems are ordered in the following order frame, propulsion system, braking system, and suspension. Each sub-section will discuss in detail the designs and analysis of each sub-system and its components.

4.1 System Overview

The sub-system hierarchy of the project which includes the frame and mechanical sections can be seen below in Figure 10. The frame is broken down into an upper and lower frame. While the mechanical section includes the other sub-systems, namely the propulsion system, the braking system, and the suspension system. Appendices A through E show the sub-system hierarchy breakdowns of the Off-Road Manual Wheelchair.

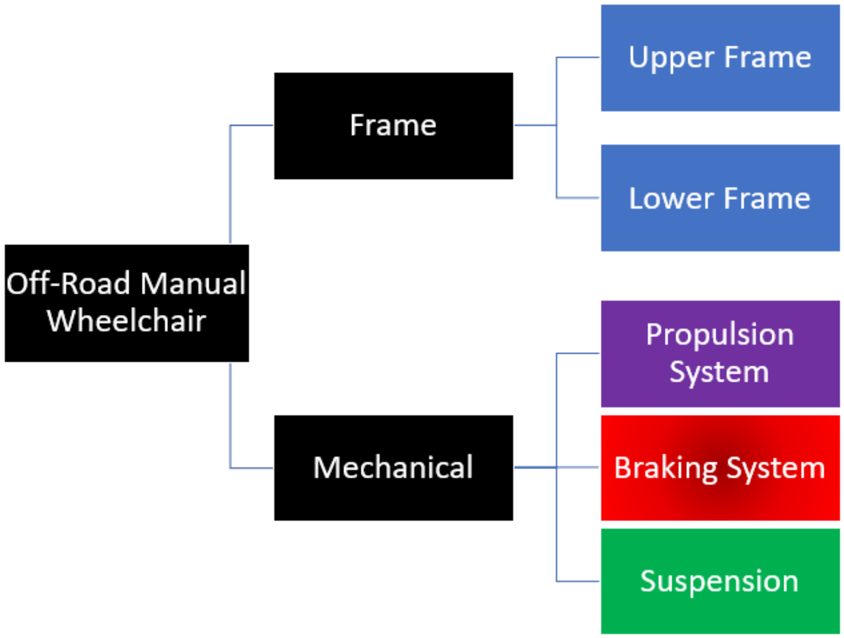

Figure 10. Sub-System Hierarchy Breakdown

4.2 Subsystem 1 – Frame

A standard wheelchair, "Silver Sport 2" **[25]**, was donated to the team to modify into a prototype of the Off-Road Manual Wheelchair. The team decided to model the wheelchair in SolidWorks and then update that model with the Off-Road Manual wheelchair design. Figure 11 shows the donated wheelchair before any modifications.

Figure 11. Donated Silver Sport 2 Wheelchair [25]

Figure 12 highlights which areas were designed by the team with red boxes. The components added to the frame include footrests, anti-tipping wheel supports, and the mounting brackets for the other subsystems. The addition of the suspension sub-system divided the frame into an "Upper" and "Lower" frame. Appendix B shows a more detailed sub-system hierarchy breakdown of the frame, the anti-tipping wheel supports fall in the wheel supports section of the lower frame.

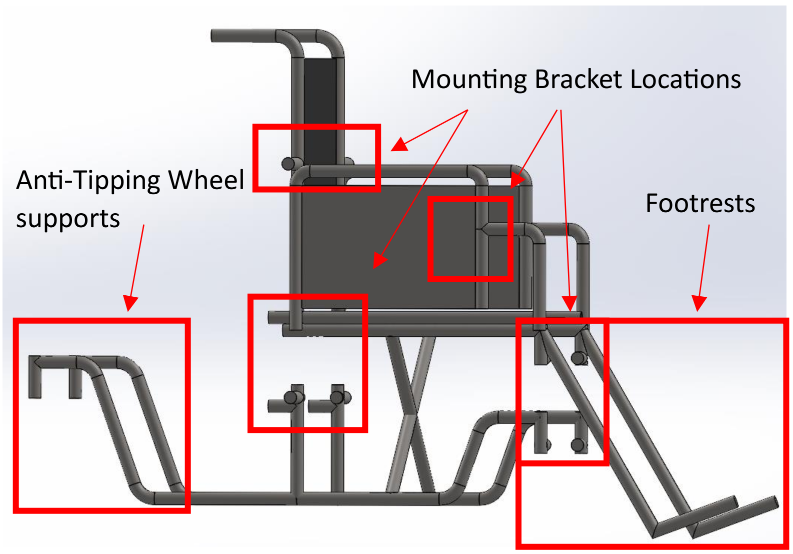

Figure 12. Designed Frame Components

4.2.1 Frame Requirements and Material Selection

The requirements for the frame are listed below. These requirements help achieve the overall wheelchair requirements. The first comes from the ADA standards of supporting a user that weighs 300 lb. **[6]**. The second requirement comes from the need to add the other sub-systems.

Requirements for the frame:

- Support a weight of 300lb.
- Include mounting brackets for the other subsystems.

The donated Silver Sport 2 wheelchair frame is constructed from 7/8 in. diameter by 1/16 in. thick steel tubing that the manufacturer calls "Powder-coated silver vein steel" **[25]**. We modeled the Off-Road Manual Wheelchair in SolidWorks using the provided plain carbon steel material. Plain carbon steel was used as the material of the model because no information could be found on the specifics of the "Powder-coated silver vein steel". Table 1 shows the material properties of SolidWorks plain carbon steel.

Table 1. SolidWorks Plain Carbon Steel Material Properties

Property	Value	Units
Tensile Strength	57989.86	psi
Yield Strength	31994.45	psi

4.2.2 Designed Components

4.2.2.1 Footrests

The footrests were designed using ADA standards provided for wheelchair footrests **[6]**, which states the toe height of the user cannot exceed 8 inches from the ground and the footpads must be 6 inches long and 8 inches wide. The footrest supports are angled thirty degrees away from the front caster wheels to keep the user's legs away from the front casters and front suspension, this can be seen in Figure 13. The footpads, Figure 14, are six inches long and eight inches wide which fulfill the ADA standards. Figure 15 shows the footrest supports and footpads together to complete the footrests. The top of the footpads is where the toe height is located according to the ADA, with the top of the footpads reaching 6.5 inches from the ground this fulfills the ADA requirement of having the toe height less than 8 inches above the ground **[6]**.

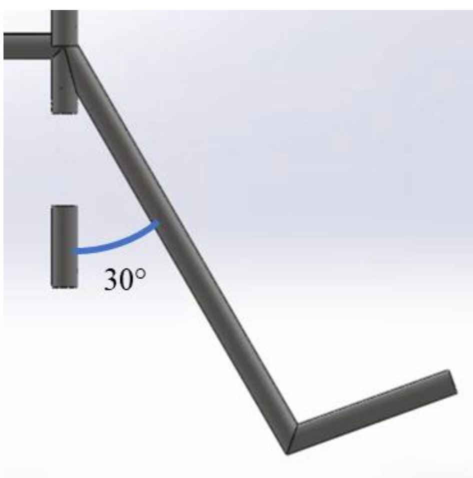

Figure 13. Footrest Support

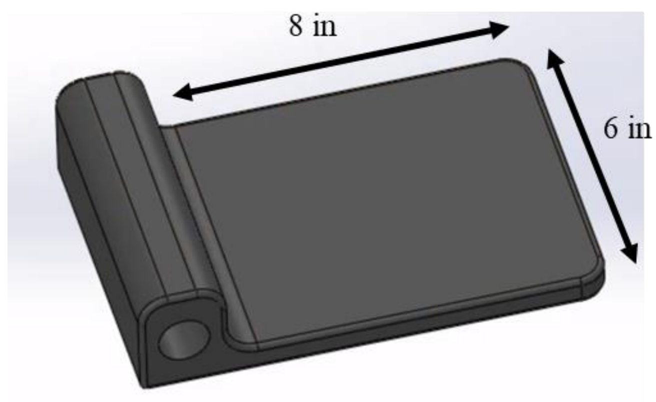

Figure 14. Footpad

Figure 15. Footrests

4.2.2.2 Anti-Tipping Wheel Supports

The team wanted to add an anti-tipping component to the Off-Road Manual Wheelchair as it is designed to go up steeper slopes than a conventional wheelchair. Anti-tipping wheels were decided on and supports for those wheels were designed to keep the user from reaching the critical point of tipping. The anti-tipping wheels will catch the user then allow them to keep moving as they are wheels.

A tipping analysis was conducted to find the tipping angle and tipping height of the Off-Road Manual Wheelchair without any anti-tipping components. To do this, the center of gravity, CG, of an average user was found using anthropometric data **[7]** and measurements of teammates as a bases on where the average user data would be located on the wheelchair. The team considered the user an upper body point mass and a lower body point mass. Each being located at the center of gravity of those portions of the body. This can be seen in Figure 16 below.

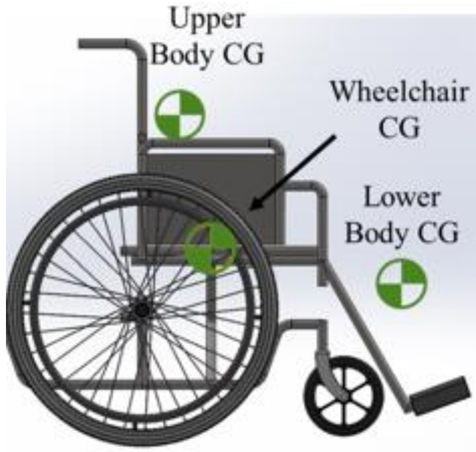

Figure 16. Upper body, wheelchair without user, and lower body Center of Gravities

The anthropometric data **[7]** had the team assume the upper body to be 65% of the total weight of a user and the lower body to be 35% of the total weight of a user. Assuming a user weight of 300 lb., the requirement weight, Equations (1-2) below show the calculated weights and center of gravity locations.

$$Upper\ Body\ Weight = 300lb(0.65) = 195lb \quad (1)$$

$$Lower\ Body\ Weight = 300lb(0.35) = 105lb \quad (2)$$

$$Upper\ Body\ CG\ location\ (x, y) = (5in, 19.25in)$$

$$Lower\ Body\ CG\ location\ (x, y) = (18in, 9in)$$

The center of gravity of the wheelchair with no user was found using SolidWorks. Assuming the weight of the wheelchair to be 60lb, the requirement weight, Equations (3-4) show the location of the wheelchair center of gravity and the overall center of gravity of the wheelchair with the user.

$$Wheelchair\ CG\ location\ (x, y) = (7.3in, 12.67in)$$

$$Overall\ CG_x = \frac{\sum w_i(x_i)}{\sum w_i} \quad (3)$$

$$Overall\ CG_y = \frac{\sum w_i(y_i)}{\sum w_i} \quad (4)$$

$$Overall\ CG\ (x, y) = (9.173in, 15.164in)$$

Using the overall center of gravity, the tipping analysis was completed to find the critical point of tipping. The critical point of tipping occurs when the center of gravity is directly above the point of contact the wheels make with the ground, as can be seen in Figures 17 and 18. The critical point of tipping makes the users stability unstable where they could fall backward. The tipping angle is the angle the wheelchair is at when at the critical point of tipping. The tipping height is the height the front caster wheel is at when the wheelchair is at the critical point of tipping. Using the variables from Figure 17, Equations (5-8) below show how the tipping angle and tipping height were calculated.

$$\tan\theta_{tip} = \frac{A}{B} \tag{5}$$

$$\theta_{tip} = arctan\frac{A}{B} \tag{6}$$

$$\theta_{tip} = 18°$$

$$\sin\theta_{tip} = \frac{h_{tip}}{d} \tag{7}$$

$$h_{tip} = d * sin\theta_{tip} \tag{8}$$

$$h_{tip} = 5.87\ in$$

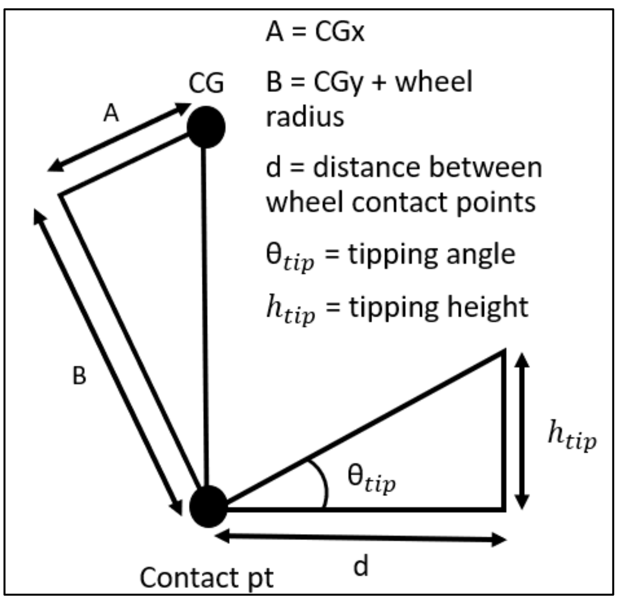

Figure 17. FBD of Tipping Analysis

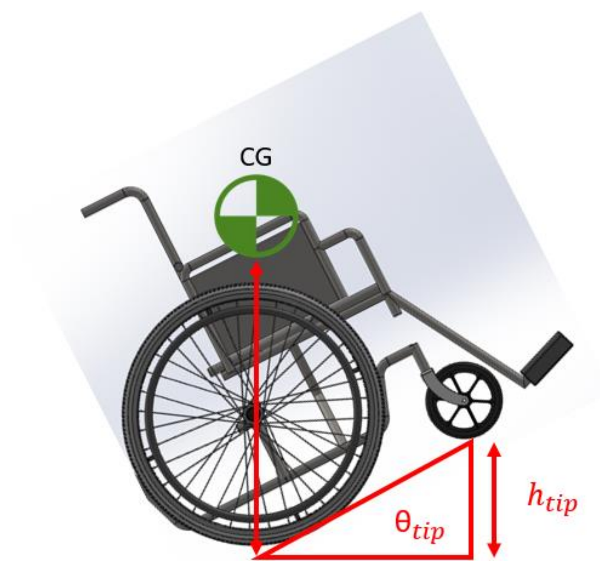

Figure 18. Simplified FBD of Tipping Analysis

As the tipping height is calculated to be 5.87 inches above the ground, the team decided to design the anti-tipping wheels to stop the user before reaching this height. The decided upon height that the user would be caught before tipping is four inches. With the four inch catch height in mind, the anti-tipping wheel supports were designed to be equidistant from the center of the wheel to the front caster wheels in the x-direction so that they move the same distance in the y-direction. This is demonstrated in Figures 19 and 20 below.

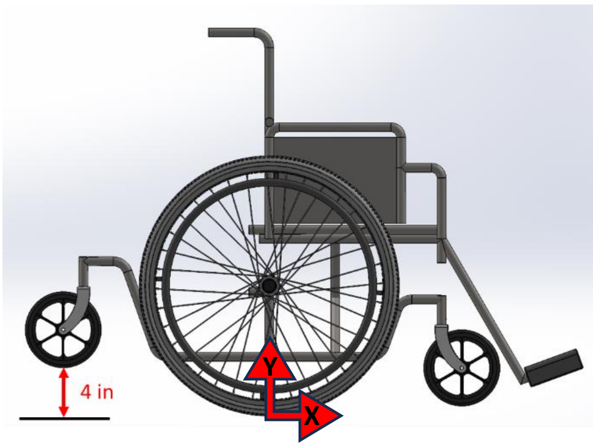

Figure 19. Wheelchair with no tipping

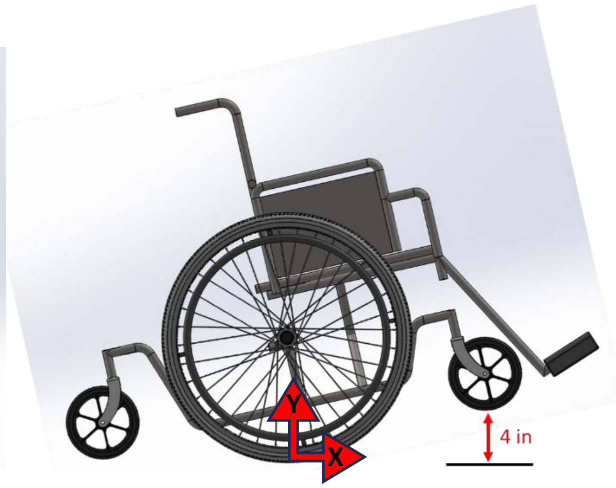

Figure 20. Wheelchair tipping backward

4.2.2.3 Propulsion System Mounting Brackets

The propulsion system mounting brackets are positioned so that the chain and sprocket system are aligned properly. The supports are 2 inches long protruding away from the center of the wheelchair to allow room for the propulsion system. The supports are connected to the frame and then connected to the drive sprockets. The supports are boxed below in Figure 21, where they protrude away from the user.

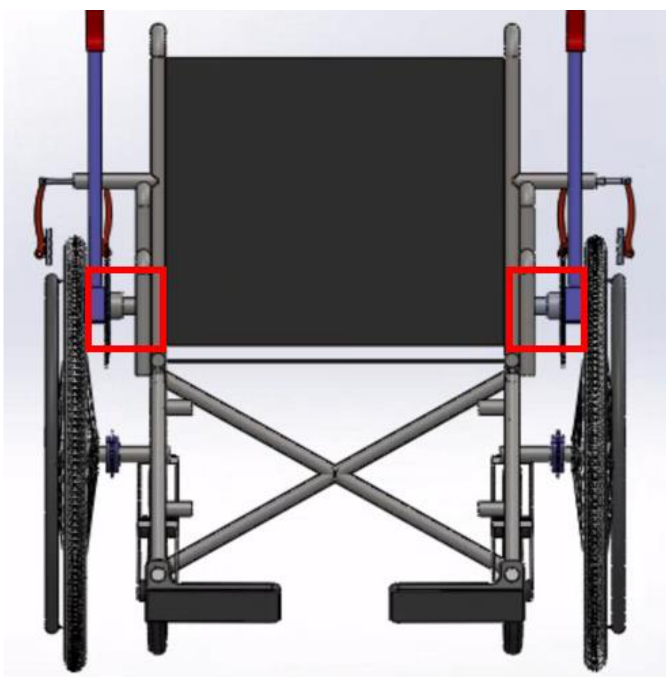

Figure 21. Front view showing propulsion supports

4.2.2.4 Braking System Mounting Brackets

The braking system mounting brackets are positioned just above the wheels to allow the calipers to activate on the top of the tires of the drive wheels. These supports are 6 inches long and protrude away from the user as seen in Figure 22. The free ends of the supports will have the calipers connected to them with a bolt.

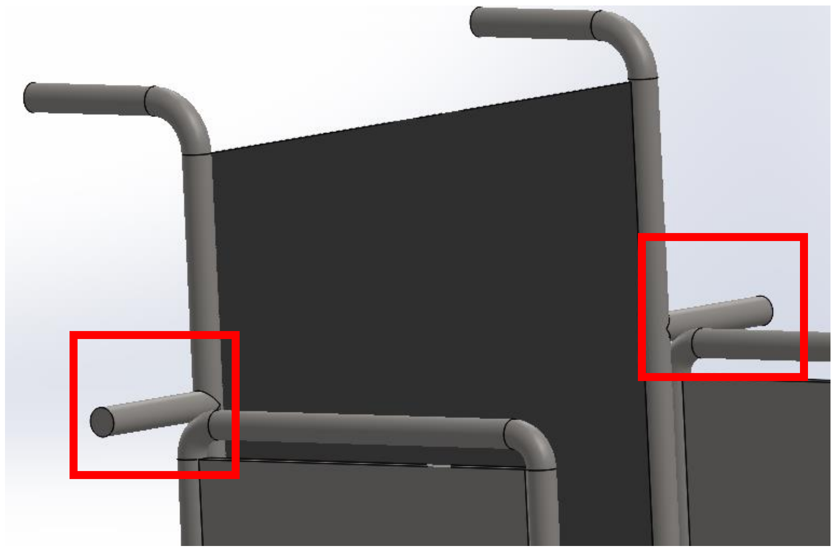

Figure 22. Brake System Brackets

4.2.2.5 Suspension System Mounting Brackets

The mounting brackets for the suspension are located above the driving wheels and front caster wheels. The drive wheel brackets protrude two inches towards the back of the wheelchair, Figure 23, this is to allow adequate space for the installation of the suspension. The front castor brackets protrude inward two inches towards the center of the wheelchair, which can be seen in Figure 24. Material had to be removed from the donated wheelchair frame to allow the installation of the suspension system, the supports are boxed in Figure 23 and Figure 24 below.

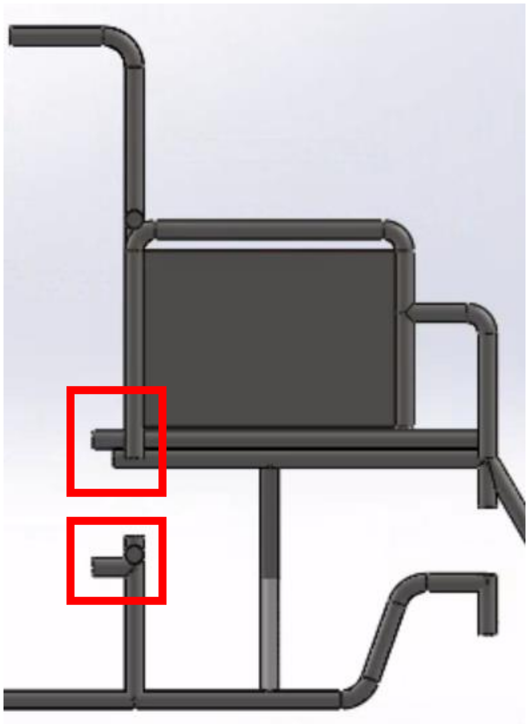

Figure 23. Side view of Suspension Brackets

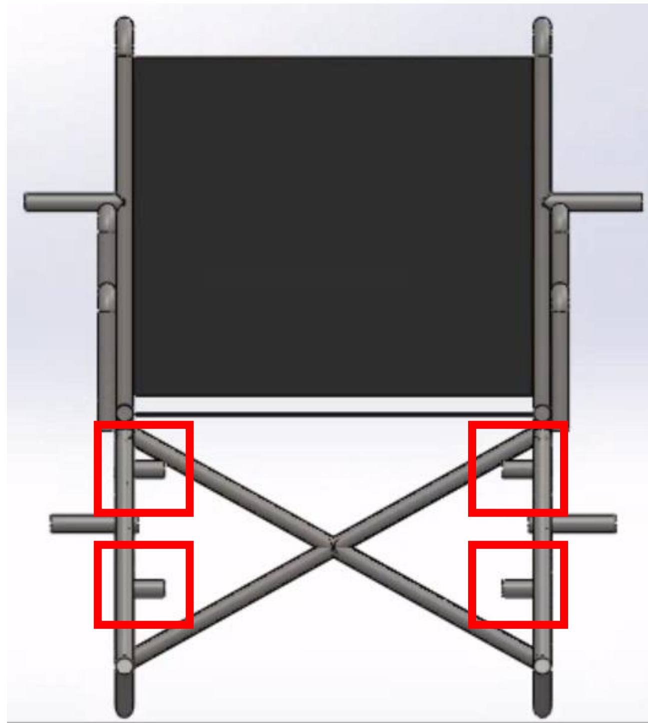

Figure 24. Front view of Suspension Brackets

4.2.3 Finite Element Analysis (FEA)

Using SolidWorks Simulation, Finite Element Analysis (FEA) was conducted on the mounting brackets and the anti-tipping wheel supports. This was conducted to find the factor of safety (SF) of the components. The factor of safety is the ratio of the material strength to the expected stress acting on the component. Therefore, if the expected stress is higher than or equal to the material strength then the factor of safety would be less than or equal to 1 and failure would occur. All simulations used the highest expected static loads as the team wanted to simulate each component in the worst-case scenario to ensure they would not fail. None of the components had a SF equal to or below 1, meaning no components failed the simulation. The results of the FEA are discussed below.

4.2.3.1 Anti-tipping Wheel Supports

The anti-tipping wheel supports were simulated assuming the user weight of 351 lb. was acting on the supports. This is simulated as the full weight of the user and the wheelchair on the supports, to act as if the full system is being held by the anti-tipping wheels. Figure 25 shows the simulated stresses and direction of the load applied on the component. The SF equals 1.5 for the anti-tipping wheel supports when modeled with the full weight of the user and wheelchair acting on them.

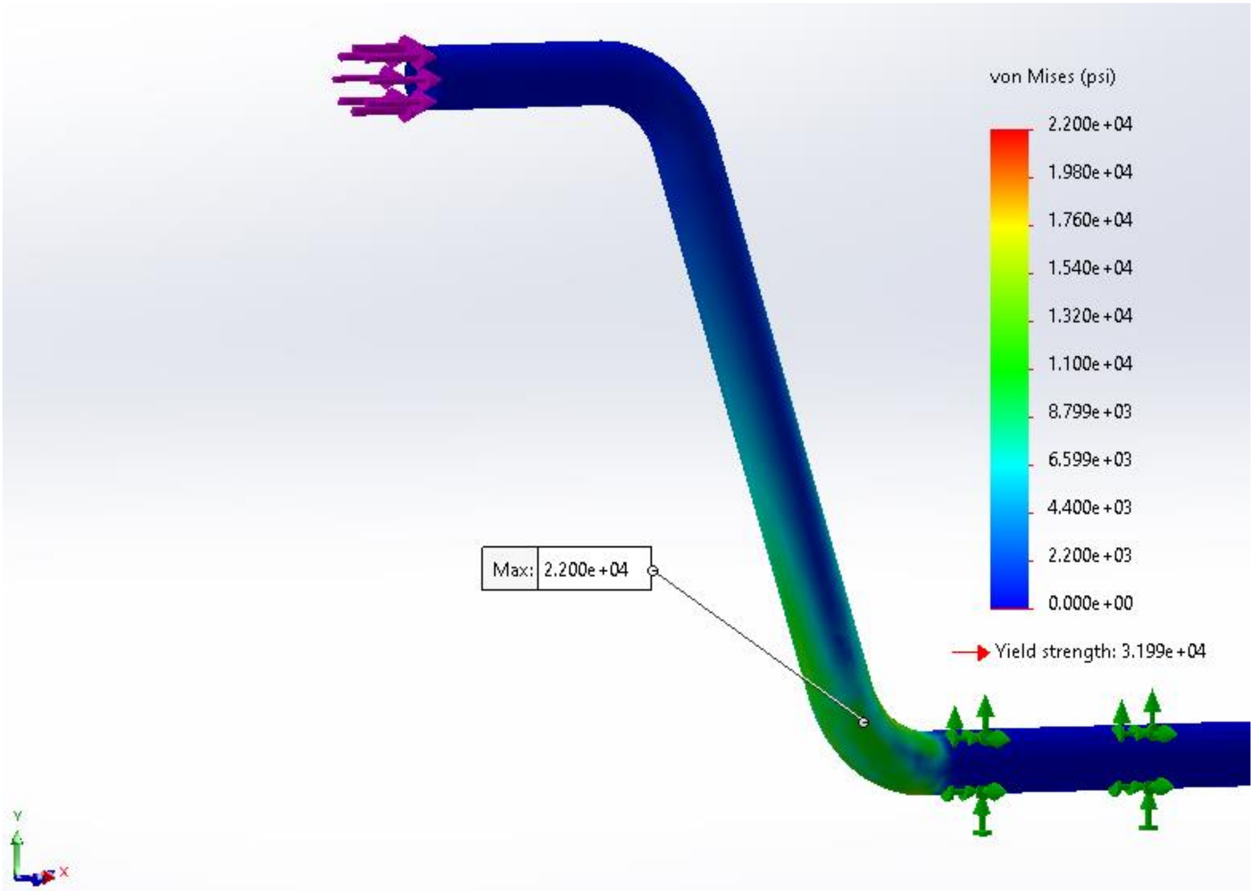

Figure 25. FEA results for anti-tipping wheel supports

4.2.3.2 Propulsion System Mounting Brackets

The propulsion system mounting support was simulated with a load of 100 lb., which comes from the maximum force applied by a user's hands on the lever arm discussed in the propulsion system section of this report. The larger diameter section of the support will be surrounded by a bearing as it is the section connecting the lever-arm and sprocket. The simulated load was applied in one direction because the area is surrounded by a bearing which makes the torque applied by the user instead act as a force. Figure 26 shows the direction the force was applied and the resulting stresses. The SF of the propulsion system support equals 17, which is well above 1, so the support will not fail.

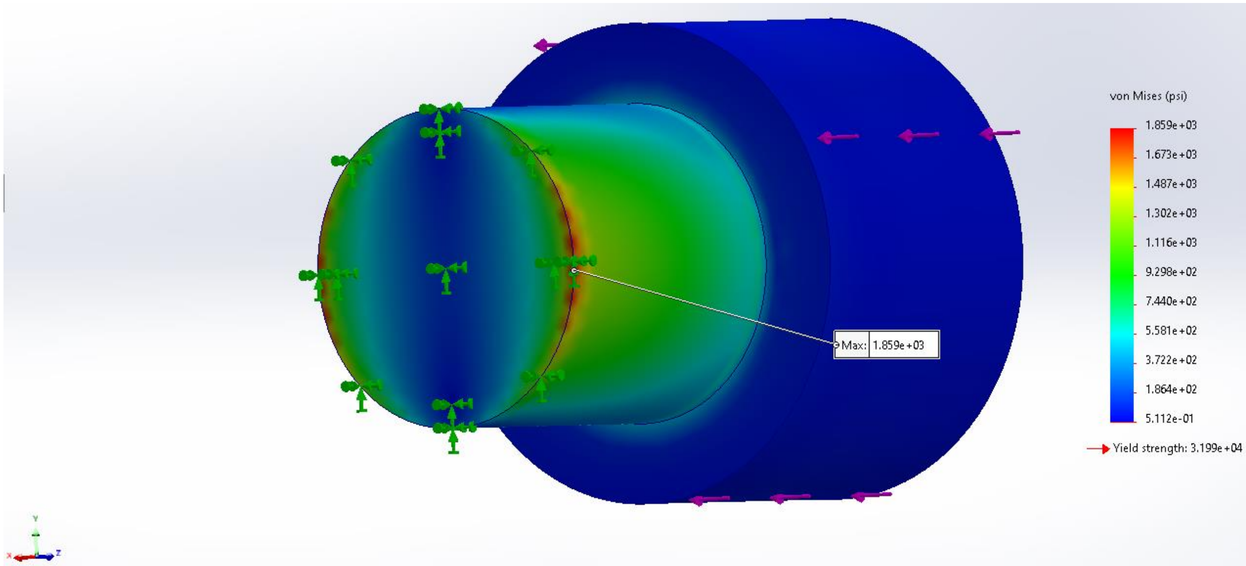

Figure 26. FEA results for propulsion system support

4.2.3.3 Brake System Mounting Brackets

The brake system supports applied a load of 210 lbs. horizontally to the bolt hole where the calipers connect to the support. This load comes from the calculated force of friction discussed in the braking system section of the report. The load was applied horizontally as that is the direction of the force acting. Figure 27 shows how the load was applied and the simulated stresses. The braking system supports resulted in a SF of 1.5.

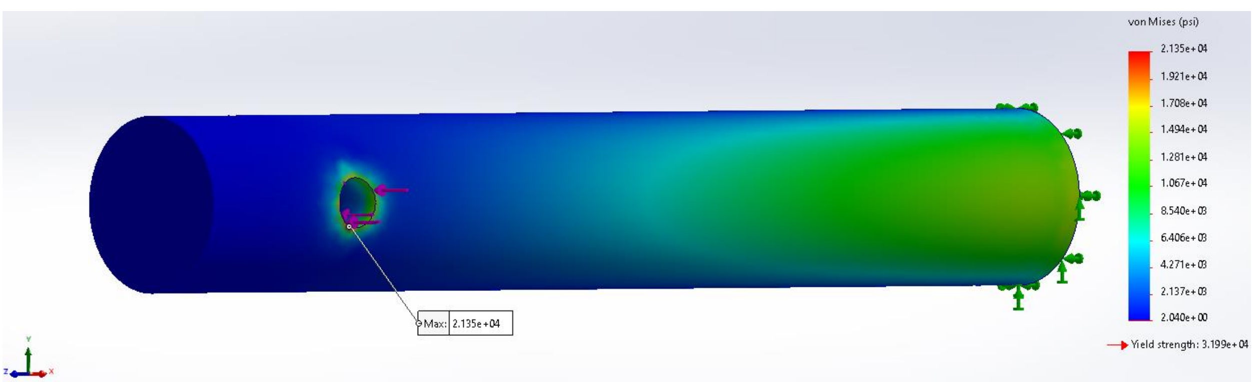

Figure 27. FEA results for braking system support

4.2.3.4 Suspension System Mounting Brackets

Assuming the user is 300 lb., the expected load on the front suspension supports would be 105 lb. and the expected load on the rear suspension supports would be 195lb. based on the calculations using the anthropometric data **[7]**. However, the load applied on each support in the simulation was 300lb. as the team wanted to simulate as if the full weight of the user was acting on the supports. The front suspension supports resulted in a SF of 2.5, Figure 28 shows the stresses simulated on the front supports. The rear suspension supports resulted in a SF of 2.2, Figure 29 shows the stresses simulated on the rear supports.

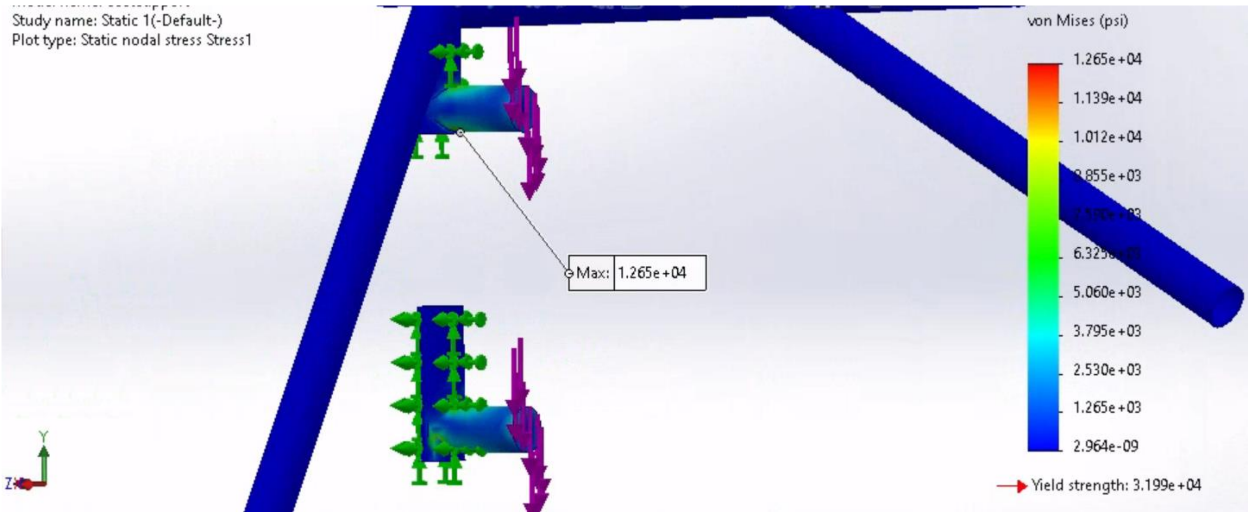

Figure 28. Stress simulation results for front suspension supports

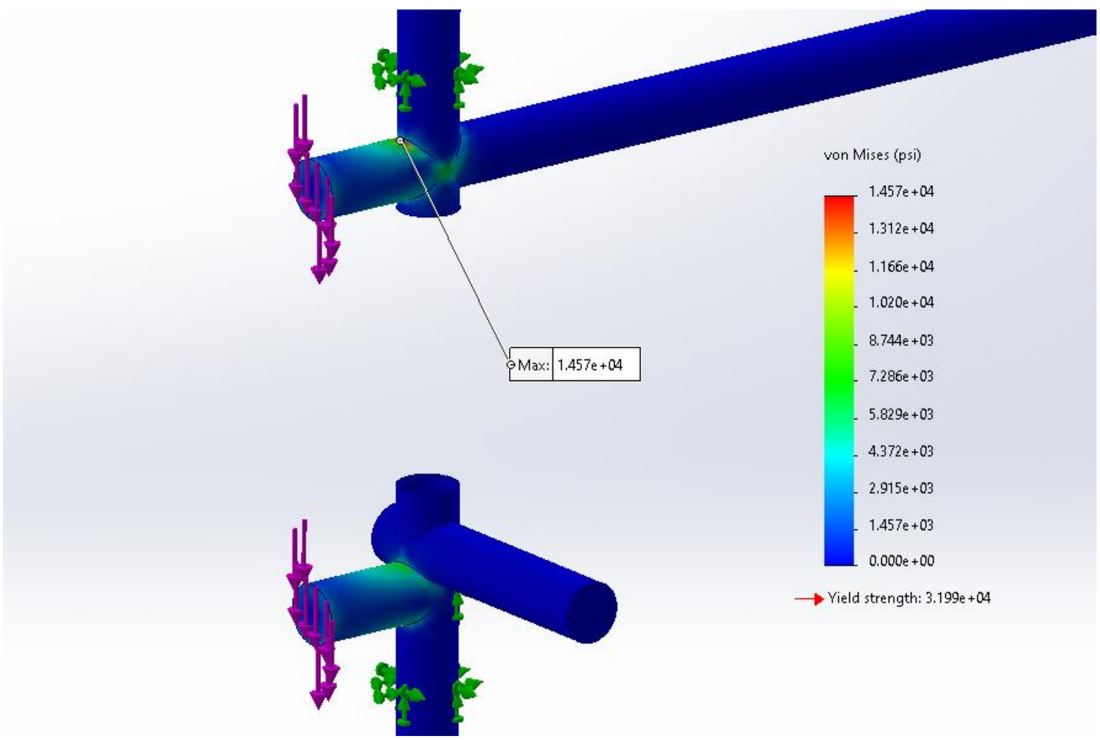

Figure 29. Stress simulation results for rear suspension supports

4.3 Subsystem 2 – Propulsion System

4.3.1 Propulsion System Overview

The propulsion system is a key factor in allowing the wheelchair user to propel forward and turn adequately. With the requirement of having the wheelchair move up a 25% grade slope and including a lever-propulsion system, the Off-Road Manual Wheelchair would need to have components to meet these requirements. After careful literature review, the team decided to make the manual propulsion system a lever-arm operated chain and sprocket gear system. The effectiveness and simplicity of this propulsion system design will be ideal for meeting the wheelchair requirements and functioning alongside the other sub-systems. Figure 30 below shows the design of the said propulsion system.

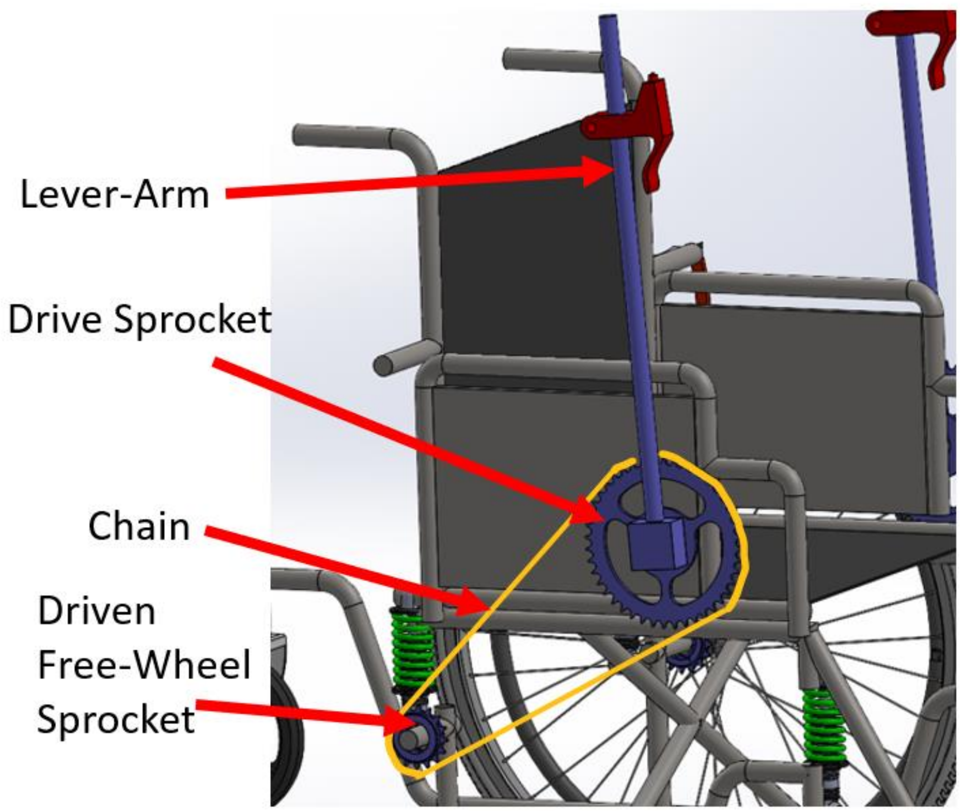

Figure 30. Propulsion System Overview

4.3.2 Functionality of the Propulsion System

Moving forward, the manual aspect of the propulsion system and Off-Road Manual Wheelchair refers to the lever and gear-driven design as viewed in Figure 30. The design was inspired by the LFC Wheelchair design [8]. Our design includes a lever-arm positioned on both sides of the wheelchair allowing the wheelchair user to use both hands to activate the chain and sprocket gear system.

To propel the wheelchair, the user must place both hands on the lever-arms while gripping the caliper brake handle. They must then push the lever-arm forward or in the positive x-direction as shown in Figure 31. The force on the lever-arm will create a subsequent torque on the drive sprocket, and ultimately activating the chain and sprocket gear assembly. There will then be a subsequent torque created by the gear ratio design and the drive torque on the driven free-wheel sprocket. Gear ratios, which will be further explained later on in the report, will ensure the chain and sprocket design is ideal for the Off-Road Manual Wheelchair requirements. The driven free-wheel sprocket, being connected to the drive wheel hub, translates the corresponding torque on the drive wheel. The torque produced on the driven sprocket ultimately turns the drive wheel in the forward direction and causes the Off-Road Manual Wheelchair to propel in a desired direction. Figure 31 below shows the functional use of the propulsion system.

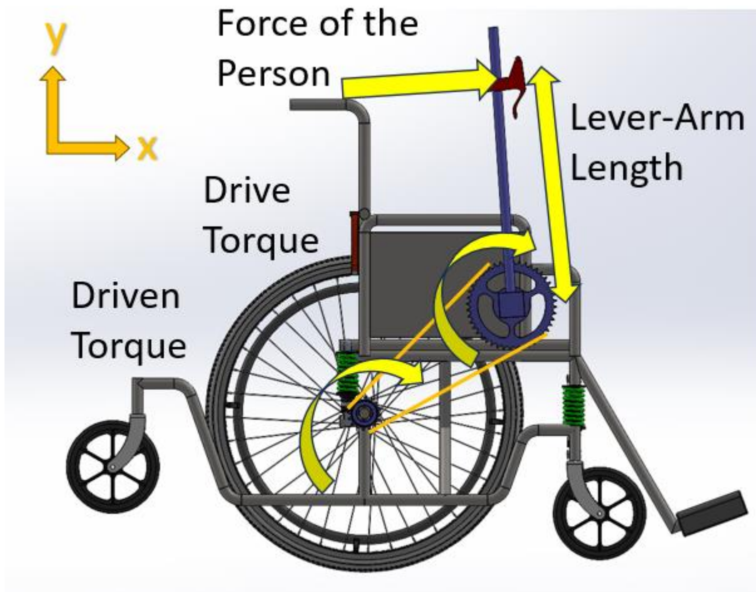

Figure 31. Functional Diagram of the Propulsion System

There will be two lever-arms and chain and sprockets on either side of the wheelchair. Each chain and sprocket gear system will only interact with the lever-arm and drive wheel on that side of the off-road wheelchair. The purpose of this design choice is to allow the user to turn the Off-Road Manual Wheelchair like they would with a typical hand-rim propelled wheelchair. If the user desires to turn towards their right, they will only need to push the left lever-arm with their left-hand. This action will only allow the user's left side drive wheel to propel forward and allow the wheelchair to rotate around the center point created by the right drive wheel. Figure 32 below demonstrates how the wheelchair will turn to the user's right.

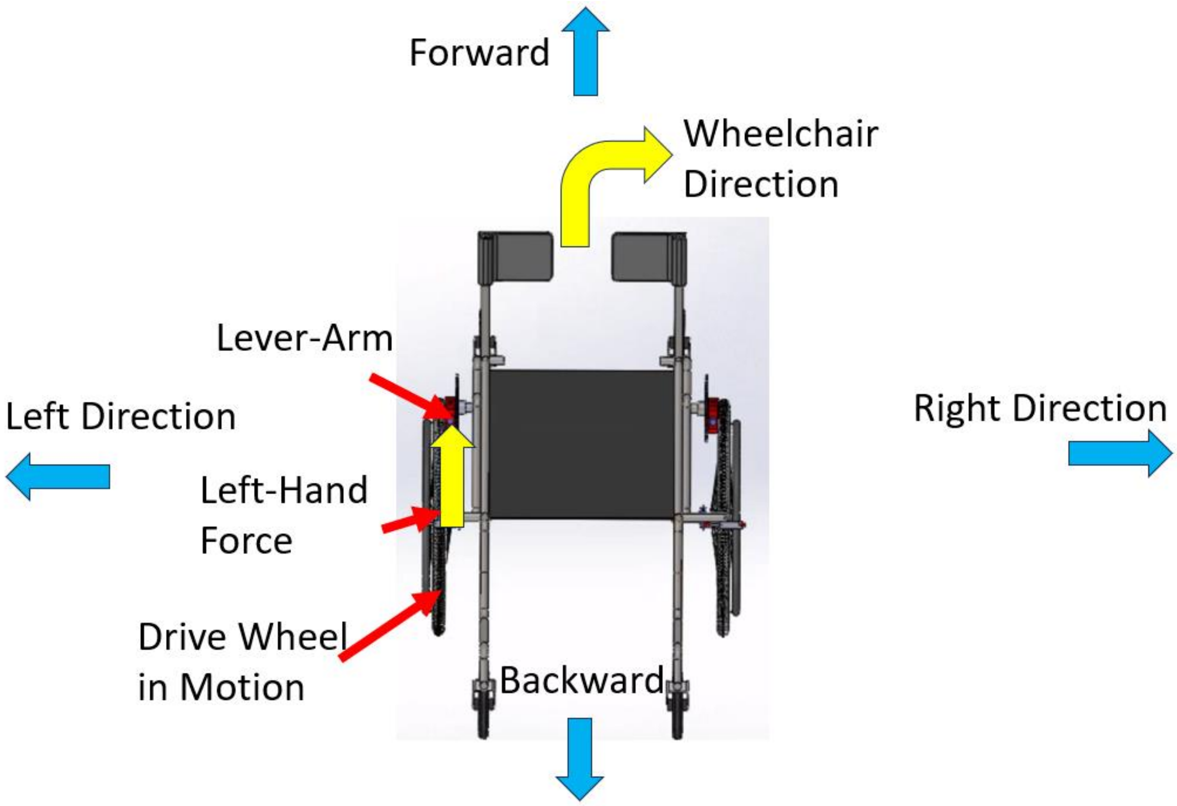

Figure 32. Top View of the Wheelchair Turning to the Right

The user can use a similar methodology to turn the Off-Road Manual Wheelchair to their left. This time the user must only use their right hand to push their right-most lever-arm forward. This action will only allow the user right drive wheel to propel forward and radially turn to the user's right. Once again, only pushing one lever-arm will only activate the corresponding chain and sprocket gear system and propel the corresponding drive wheel forward. This allows the Off-Road Manual Wheelchair to have a similar functionality to a typical hand-rim propelled wheelchair, and ultimately allows the user to easily maneuver the wheelchair. Figure 33 below shows the functionality of turning the wheelchair to the user's left.

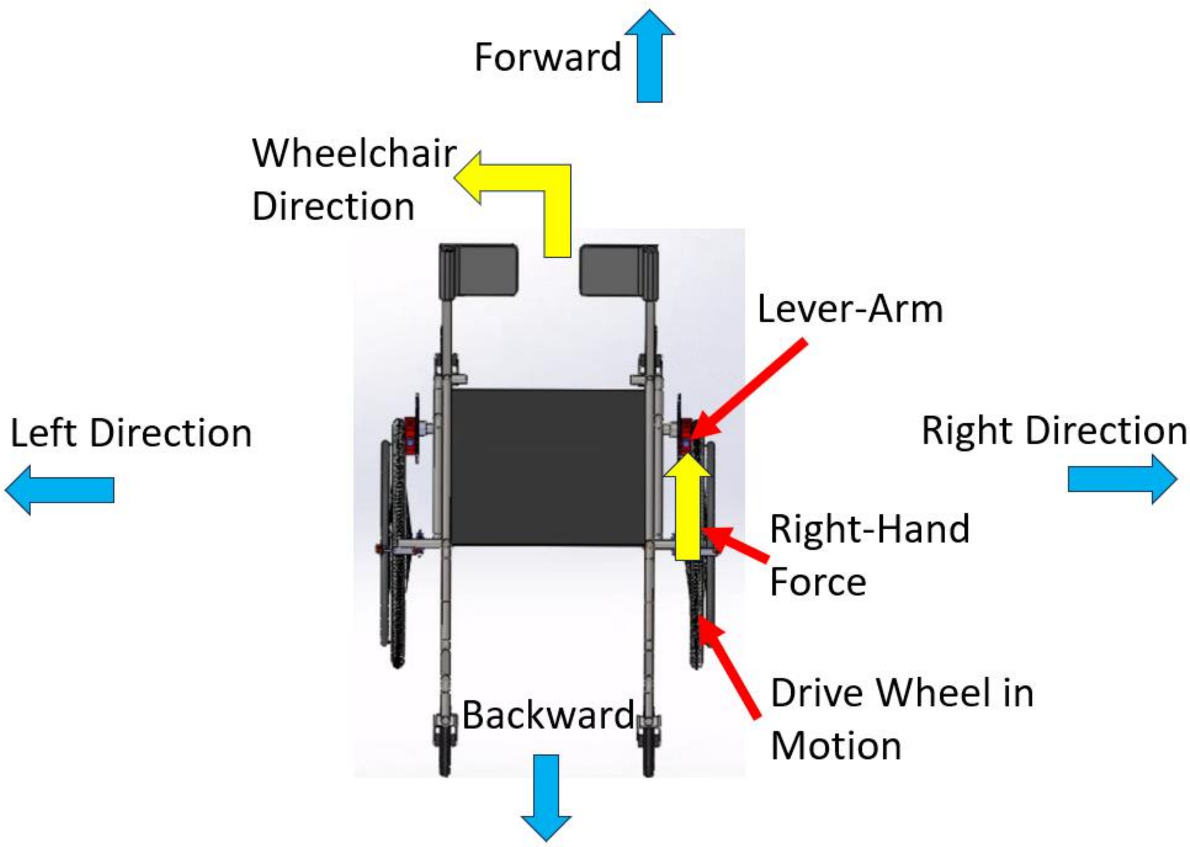

Figure 33. Top View of the Wheelchair Turning to the Left

For propelling the Off-Road Manual Wheelchair forward, the user will need push both lever-arms in their forward direction. This action activates both gear systems and both drive wheels. It will allow the user to propel in the direction parallel to the drive wheel's position. As said previously, the Off-Road Manual Wheelchair's functionality is very similar to that of a typical hand-rim propelled wheelchair. How the Off-Road Manual Wheelchair differs is the fact that it is not designed to move backward with the lever-arm gear system. The reason for this design choice is due to the chain and sprocket gear system utilizing a free-wheel sprocket and hub. A ratchet and pawl mechanism within the driven free-wheel sprockets only allow the drive wheel to propel in the forward direction and not backward. Further explanation of the free-wheel sprocket can be found on page #. With that said, the user is still able to turn backward by radially turning 180° with only one lever-arm and gear system. This is the same methodology when turning left and right. The user can also use the hand-rims located on the outside of the drive wheels if they need to move directly backwards. Lastly, the wheelchair is also able to move forward or backward with the assistance of another individual. The assistive handles allow someone to guide the wheelchair in any direction, and this method will have no effect on the gear system due to the free-wheel design. Figure 34 below represents the wheelchair user propelling the wheelchair forward.

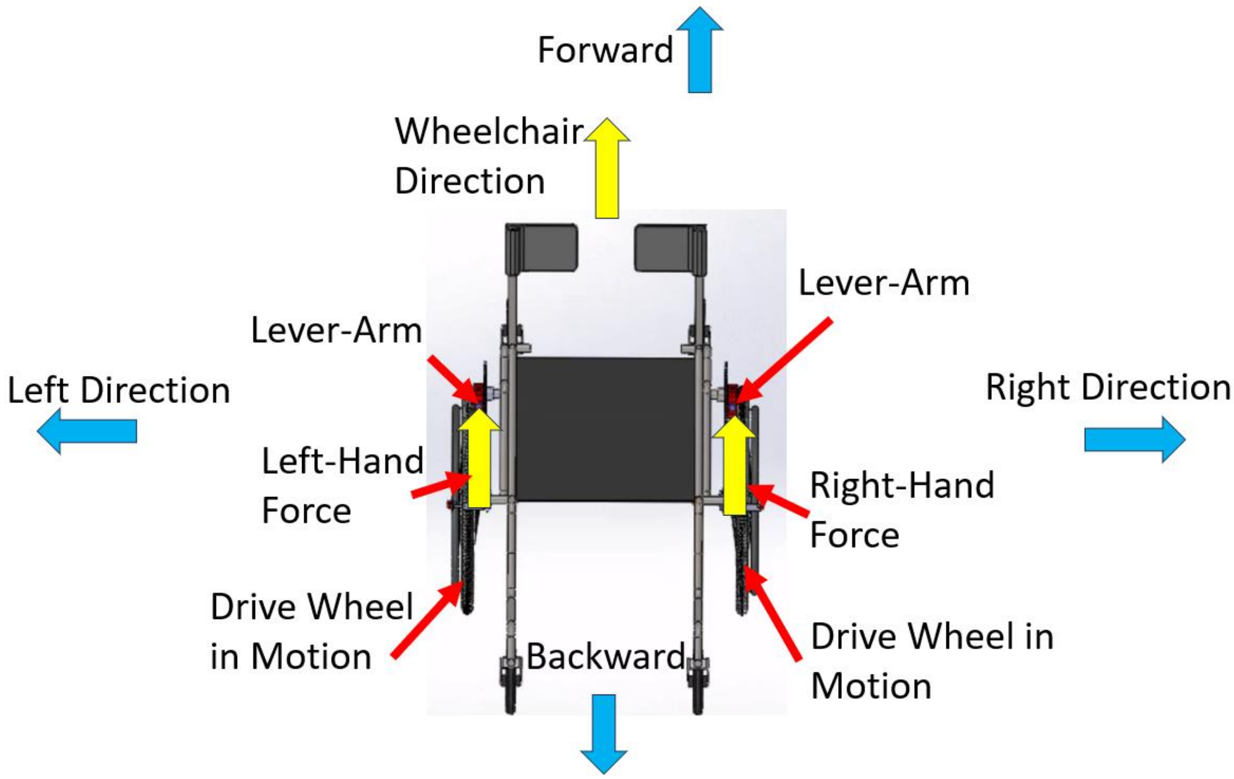

Figure 34. Top View of the Wheelchair Propelling Forward

4.3.3 Engineering Design of the Propulsion System

The engineering design of the propulsion system was heavily determined by how it would with the other sub-systems of the Off-Road Manual Wheelchair. The propulsion system interacts with the upper frame, the brake system, and the suspension. It is crucial that the propulsion system properly mounts or allows mounting with all the other sub-systems as well as not interfering with the other sub-systems' functionality. An important connection between the propulsion system and the braking system is the caliper brakes attached to the lever-arms.

The lever-arms can be described as the main interaction between the wheelchair user and the Off-Road Manual Wheelchair. The user is able to propel the wheelchair to their desired direction due to the lever-arms, but it is also essential that the user is able to access the braking system The lever-arm is designed to fit through the caliper brake's connection clamp. Essentially the caliper brake handles have a cylindrical fitting that allows the caliper to slide up and down the lever-arm. This gives the user freedom to place the caliper brake at their desirable location on the lever-arm. A screw and nut connection on caliper brake allows the circular opening to clamp on the lever-arm and form an unmovable connection. The brake cable connected to the brake handle will flow down along the lever-arm and then connect to the calipers. It is important that there is at least 28 inches of cable on each caliper brake system. This allows the propulsion system to operate without concern of the cable breaking loose. Figure 35 below shows the design of this connection.

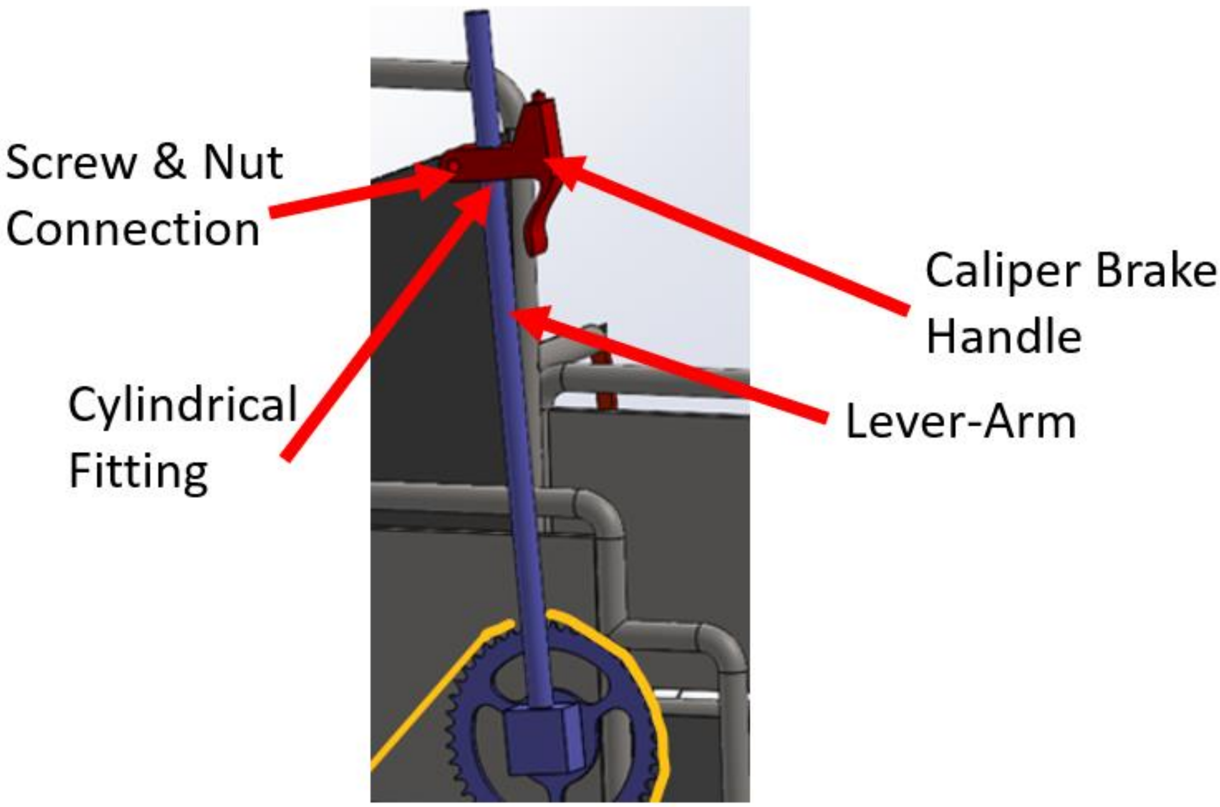

Figure 35. Lever-Arm and Caliper Brake Handle Connection

For the connection of the propulsion system to the upper frame, a steel frame connection and bottom bracket bearing was designed. Figure 36 below represents the connection of the propulsion system to the upper frame.

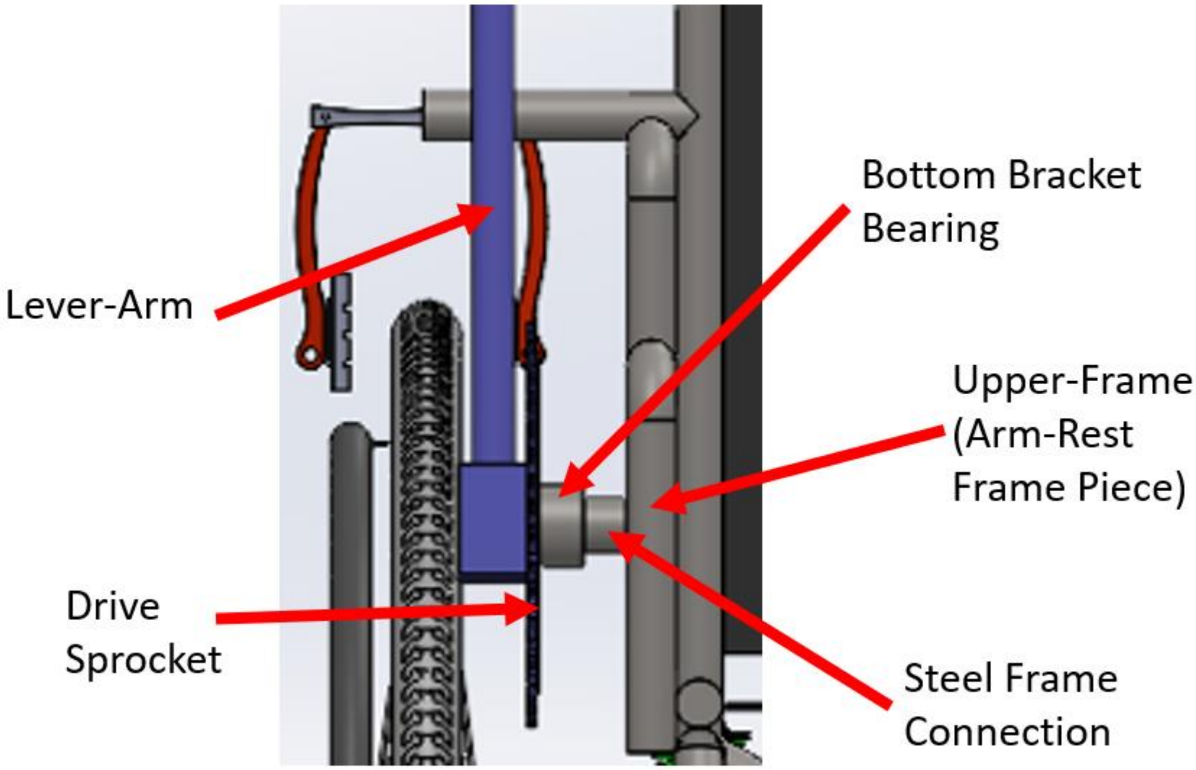

Figure 36. Propulsion System Connection to the Upper Frame

The key component to the connection with the upper frame is the bottom bracket bearing. This bottom bracket bearing is a component typically used on mountain bikes as a bearing connection on a pedal crank mechanism. The bottom bracket bearing is fitted tightly on the steel frame connection which is also used in a mountain bike pedal crank. The bottom bracket bearing component is designed to rotate along the steel frame connection without causing any torque on the connection component. This allowed the team to design the steel frame connection to be welded on the upper frame arm rest piece without any risk of the component interfering with the drive wheel. Figure 37 below shows the design concept of this connection.

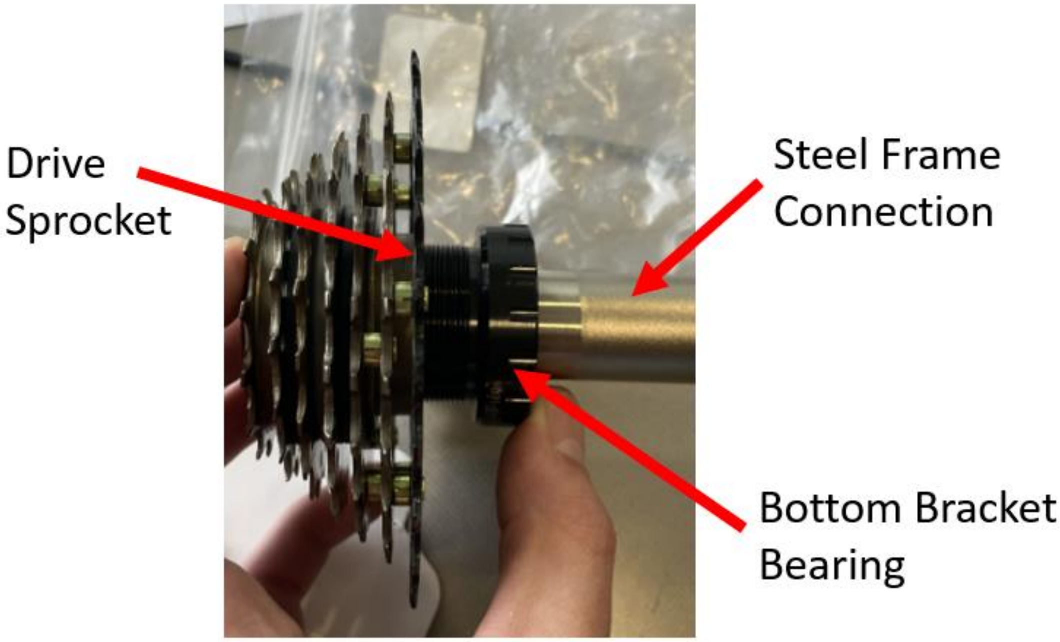

Figure 37. Bottom Bracket and Steel Frame Connection Visual

When attaching the drive sprocket to the bottom bracket bearing, a free wheel sprocket could be used to thread the sprocket on the bottom bracket threads. This can be seen above in Figure 37. In the case of the overall design, a single 28-tooth drive sprocket without a free wheel mechanism was prioritized. Further details on a free wheel sprocket will be explained for the drive wheel and free wheel sprocket connection. The reason for using the single 28-tooth drive sprocket was due to minimize weight and volume when compared to a free wheel sprocket. Figure 38 below shows the 28-tooth free wheel sprocket.

Figure 38. 28-Tooth Drive Sprocket

The 28- tooth drive sprocket is designed to mesh correctly with the desired 1/2” by 1/8” bicycle chain. This chain size fits on the 28-tooth drive sprocket and the 18-tooth driven free-wheel sprocket. This bicycle chain specification is most common for mountain bikes and most bicycles in general. It is easily obtained and can withstand the harsh offroad environments. Figure 39 below shows a visual of a 1/2” by 1/8” bike chain.

Figure 39. 1/2” X 1/8” Bike Chain

The bike chain is a key piece of the chain and sprocket gear system. It creates a connection between the drive sprocket and driven free wheel sprocket transferring the torque created by the lever-arm and drive sprocket connection to the driven free wheel sprocket. This leads to the discussion of the driven free wheel sprocket. A free wheel sprocket is a typical bicycle sprocket that encases a ratchet and pawl mechanism within the sprocket. A ratchet and pawl mechanism allows continuous rotary motion in only one direction. In the case of the Off-Road Manual Wheelchair, this mechanism only allows the drive wheels to travel in the forward direction when the lever-arm gear system is activated. Otherwise, the user can only use the hand-rims to turn the drive wheels backwards. The free wheel sprocket can also thread onto a free wheel mountain bike hub and allow the drive wheel to propel in one direction. Figure 40 below is a visual of a free wheel sprocket.

Figure 40. 18-Tooth Driven Free Wheel Sprocket

The driven free wheel sprocket designed for the Off-Road Manual Wheelchair has 18 teeth and connects the propulsion system to the suspension. Since the drive wheel is considered within the suspension sub-system, the threaded connection of the drive wheels free wheel hub and 18 tooth free wheel sprocket. As stated previously, the ratchet and pawl mechanism within the free wheel sprocket only allows the sprocket to propel the drive wheel in one direction. This design is ideal whenever the user pulls the lever-arm backward to gain leverage. The functionality depends on the drive propelling in the forward direction and the free wheel sprocket design prevents the drive wheel to go backward. Figure 41 below is a internal visual of a free wheel sprocket with the ratchet and pawl mechanism.

Figure 41. Free Wheel Ratchet and Pawl

4.3.4 Sprocket Gear Ratio Calculations and Justification

The chain and sprocket gear system are a key mechanism in transferring torque created by the force of the user and the lever-arm. Fortunately, engineering knowledge obtained from dynamics of machinery helps determine adequate gear ratios for specific design choices. Dynamics of machinery is a mechanical engineering course that prioritizes the motion of machinery and the forces acting within it. After reviewing Norton's *Design of Machinery,* gear ratios were calculated by the specified number of teeth on the sprockets. The textbook details that specified gear ratios could be determined by dividing the number of teeth of the driven sprocket by the number of teeth of the driver sprocket. This formula can be seen in Equation 9 below [11].

$$[11] Gear\ Ratio = \frac{\#\ of\ Driven\ Sprocket\ Teeth}{\#\ of\ Driving\ Sprocket\ Teeth} \tag{9}$$

For the Off-Road Manual Wheelchair, the specified gear teeth used for the driven sprocket and the drive sprocket are 18 teeth and 28 teeth respectively. These specified number of teeth were determined by reviewing literature based on off-road wheelchairs, bikes and specific requirements of the Off-Road Manual Wheelchair. The specific requirement in mention is to ensure that the Off-Road Manual Wheelchair can propel up a 25% grade slope. With slope being a critical design point for the propulsion system design, a study by the University of Amsterdam was conducted to see the effects of differing gear ratios had on lever-armed powered wheelchairs. According to *Mechanical Advantage in Wheelchair Lever Propulsion,* gear ratios ranging from 0.28 to 0.56 were analyzed and tested to see which performed more efficient on higher slope grades. Identical lever-arms and wheelchair frames were considered for the ranging gear ratios. Tests were completed on 1-3% grade slopes five varying gear ratios. The results showed that higher gear ratios were preferable for faster accelerations and steep inclination. In this case, the 0.56 gear ratio outperformed the 0.28 gear ratio when it came to steep inclination [8].

We designed a similar gear ratio to that of 0.56 gear ratio rather than a typical mountain bike and other off-road wheelchair gear ratios of 0.33. This 0.33 gear ratio idealizes better mechanical efficiency and faster speeds rather than for steeper inclination. Using typical sprocket tooth counts, a 28-tooth drive sprocket and a 18-tooth sprocket were selected. With the use of Equation #, the gear ratio for the Off-Road Wheelchair was found to be 0.64. Below are the calculations for solving the gear ratio [11].

$$[11] Gear\ Ratio = \frac{\#\ of\ Driven\ Sprocket\ Teeth}{\#\ of\ Driving\ Sprocket\ Teeth} \tag{9}$$

$$Gear\ Ratio = \frac{18\ Teeth}{28\ Teeth}$$

$$Gear\ Ratio = \frac{9}{14}$$

$$Gear\ Ratio = 0.64$$

The gear ratio selected proves to be designed specifically for steep inclinations. In theory, the Off-Road Manual Wheelchair will exceed the limits of other off-road wheelchairs on steep slopes due to the higher gear ratio design for the sprockets. Testing on a prototype is needed still to ensure that the Off-Road Manual Wheelchair can move up the 25% slope as described in the requirements. The propulsion has been designed to move up steeper slopes while also containing lever propulsion mechanism.

4.4 Subsystem 3 – Braking System

Including a brake system involves a thought process of external factors that will come into play. Therefore, before diving into the analysis conducted on the wheels of the wheelchair, it should be explained why a hydraulic brake was not used. For this design, there is a propulsion system. This propulsion system uses a chain and sprocket mechanism with the same functions as that on a mountain bike. If a hydraulic brake were to be implemented in this design, it would mean considering the propulsion system. That is, it would need to be considered how it would be attached to the wheelchair without messing with the chain nor gears that make the propulsion system. That is why rather than flustering about how the hydraulic braking system will be implemented into the wheelchair, it was decided to use a caliper brake system. Caliper Brakes are other alternatives to that of hydraulic brakes, it serves the same purpose as a hydraulic brake. That is to stop the motion of a moving object. With the caliper brake, the area size of the pad will need to be found in order to stop this wheelchair.

Therefore, an analysis of the wheels on the wheelchair was conducted to find the area size of the pad, a stopping time, and a stopping distance. All of which will be discussed in the few paragraphs. To begin Figure 42 is a free-body diagram that will help understand the procedure that was conducted to find the normal forces of the wheels on the wheelchair. Figure 43 is a free-body diagram that focuses on the rear wheel of the wheelchair, that is due to the caliper being positioned at the top of the rear wheel. The red rectangle demonstrates where the brake is positioned.

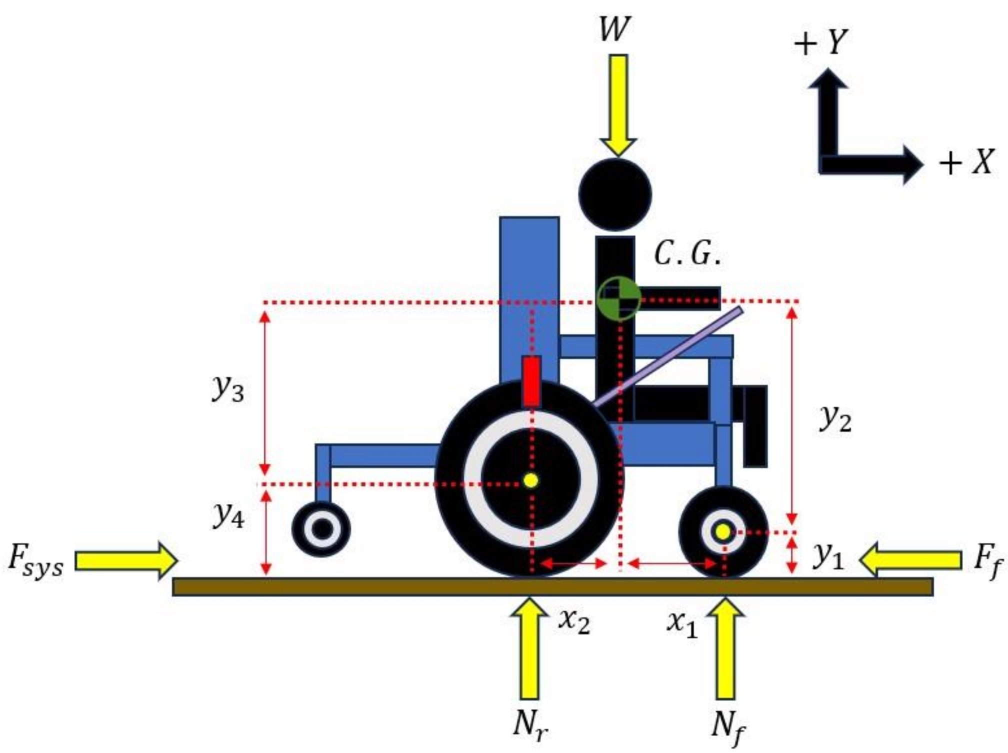

Figure 42. Free-Body Diagram of Wheelchair for Analysis of Tires

This section will go into detail about the design of the brake system for the wheelchair that is manually propelled. To begin, the purpose of the back caster wheel being added is to prevent the user from tipping and falling backward. It should be noted that the back caster wheel is not considered in the analysis since it is not in contact with the ground. Therefore, unless the wheelchair is tipping, the back caster wheel would need to be considered in the analysis. The first step in finding the ideal braking system was finding the appropriate force that the specific aluminum cable would need to act on the calipers that would clamp to the rim of the wheel of the wheelchair. To find this force, the following equations were derived as follows, a more detailed derivation can be found in Appendix F.

$$\sum F_x = 0$$

$$F_f = (ma)_{sys} \tag{10}$$

$$\sum F_y = 0$$

$$N_r + N_f = W_{total} \tag{11}$$

$$\sum M_G = 0$$

$$-(x_2)W_{total} + (x_1 + x_2)N_2 = -(y_4 + y_3)(ma)_{sys} \tag{12}$$

$$F_f = \mu_T N$$

$$(ma)_{sys} = \mu_T(N_r + N_f) \tag{13}$$

Through a summation in the horizontal and vertical directions, the normal forces acting on the rear and front wheel of the wheelchair were able to be found. A more detailed breakdown of this can be found in Appendix F. A moment at point G, as shown in Figure 43, was done in order to help find the normal forces and friction force. This can also be found in Appendix F. The values found for the terms $F_f, N_r, and\ N_f$ were obtained to be $F_f = 210\ lbs,\ N_r = 508.57\ lbs,$ $N_f = -208.57\ lbs$. Having these values will then help to find the force of the cable that is needed to design the appropriate sizes for brake pads. If the appropriate pad size is not found, then it would lead to failure in the brakes. Failure in the brakes would mean putting the user in danger. That is why the following equation for the force of the aluminum cable acting on the caliper was derived from the free-body diagram shown in Figure 43, a more detailed derivation is found in Appendix F. It will show how the equation below were found:

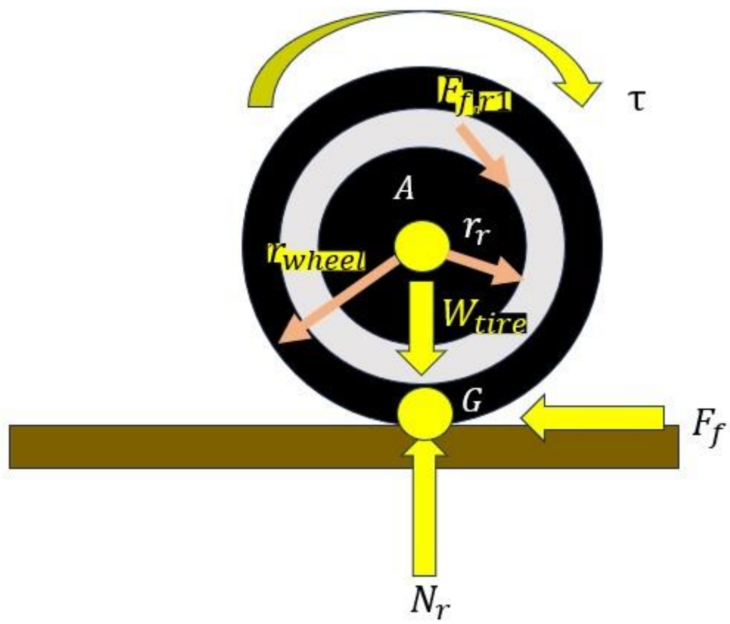

Figure 43. Free-Body Diagram of Rear, Drive Wheel

$$F_{cable} = \frac{r_{wheel} N_r \mu_T}{r_R \mu_R n} \tag{14}$$

Once deriving the equation for the force of the aluminum cable, as shown in equation (14), the next step is plugging in the values that are known, those being $r_{wheel} = 15.5\ in,\ N_r = 508.57\ lbs,\ u_T = 0.7,\ r_r = 13\ in,\ u_r = 0.5,\ n = 2$. These coefficients of friction are assuming the toughest terrain that the tires could travel through. As for the r_r and r_{wheel}, it was known that the diameter of the tire is $23\ in$. Therefore, the radius of the rear wheel $r_r = 13\ in$ is used to find the force of the aluminum cable which results in $F_{cable} = 298.58\ lbs$. Once the value of the force of the aluminum cable was found, the next step was to use the value found for the aluminum cable to find the area of the brake pad that would match this tension force from the aluminum cable. The equation to find the area size of the brake pad was derived as follows:

$$F_{caliper} = T_{cable} * A_{brakePad} \qquad (15)$$

Now the value found using equation (15) for the force of the caliper was $F_{caliper} = 298.58\ lbs$. The assumption for the tension of the aluminum cable was $T_{cable} = 280\ psi$, as that is the maximum tension that an aluminum cable is able to withstand for this case. The aluminum cable in this instance is connected to the caliper and to the handle. How it works is that the user being in the wheelchair will squeeze the plastic handles, creating tension in the aluminum cables. Once the aluminum cable is in tension, the calipers squeeze towards each other with the rim of the tire being in between the caliper. That is why the next step, having the force of the caliper and tension of the aluminum cable, is to find the area of the brake pad. Therefore, rearranging the equation (15) and using the values that have been found, the area size of the brake pad was found with the equation below:

$$\boldsymbol{A_{brakePad}} = \frac{F_{caliper}}{T_{cable}} = \frac{298.58\ lbs}{280\ psi} = \mathbf{1.07\ in^2} \qquad (15)$$

Therefore, the ideal area size for the brake pad is $1.07\ in^2$. Which from the literature, the area for the brake pad would be of a rectangular shape. The value for the tension in the cable is given as well as the force that is required to be applied on the handles. Those values being $T_{cable} = 280\ psi$ as found in the readings. Having the values of the brake pad size, the next step was to find the time it would take for the wheelchair to fully stop. Finding that time was done is fully shown in Appendix F, it should be mentioned that these values are given in the list of symbols table. The first of the many equations is using the Kinetic Energy which would then help find the angular speed produced from the wheelchair, assuming that the maximum initial velocity of the wheelchair will be 15 $\left(\frac{ft}{s}\right)$. By doing so $KE = 1048.14\ lbs * ft = 12577.68\ lbs * in$ and finding the angular velocity to be $\omega = 13.8 \frac{rad}{s}$.

Once the angular velocity was found, the next step was to find the force of the clamp as using equation (18). Now note that the force of the caliper was found earlier and that the brake system will need to have two sets of caliper brakes and handles, that is why the force of the clamp will need to account for two in equation (18). The force of the clamp came out to $597.16\ lbs$, the work for equation (18) can be found in Appendix F. After finding the clamping force, the force of friction can be found since the wheelchair is now in motion and not static. Note that equation (19) in Appendix F focuses solely on the rear wheel and not the whole wheelchair, that is because the caliper is positioned directly above the rear wheel. Therefore, the value for the force of friction came out to $298.58\ lbs$.

Having the force of friction, the next step is finding a torque that acts on the rear wheel given that diameter of the rear wheel is 26 in. Then using the torque value, the displacement can be found, as shown in equation (20) in Appendix F. The value of the torque comes out to $3881.54\ lbs * in$, and since it was mentioned previously, having the torque the next step is to find the displacement of the wheelchair. The displacement value comes out to 3.24 rads. Having the displacement, the next step is finding the stopping time for the wheelchair. By looking at equation (22) in Appendix F, the stopping time came out to $0.47\ s$.

Having the time, it would take for the wheelchair to come to a stop, the stopping distance is the next variable to find. This is found through equation (23) in Appendix F. The stopping distance comes out being $3.53\ ft$. In summary the need for solving to find the brake pad size was crucial to determine the time it would take the wheelchair to come to a stop. It also helped in determining the distance and the time it would take for the wheelchair to completely stop.

4.5 Subsystem 4 – Suspension

A suspension system was added to the wheelchair. This section of the report discusses:

- The motivation and need for a suspension on the offroad manual wheelchair.
- The overview and functionality of the suspension system.
- The requirements for the suspension system.
- The weight distribution on the wheelchair and the selection of the suspensions.
- The placement of the suspensions.

4.5.1 Suspension System- Motivation and Need

While most wheelchair models do not include a suspension system, it remains the most effective way to ensure comfort, control, and safety for the user whenever the wheelchair meets an obstacle. The need for a suspension system in an offroad wheelchair arises from the challenging terrain and conditions that these wheelchairs are designed to navigate. Offroad wheelchairs are meant to provide mobility and independence to individuals who enjoy outdoor activities such as hiking, camping, and exploring rough terrains.

The motivation behind incorporating a suspension system in the offroad wheelchair is to ensure a smooth and comfortable ride for the user. Offroad terrains often consist of uneven surfaces, gravel, rocks, tree roots, and other obstacles that can cause jarring and uncomfortable vibrations for the wheelchair user. Without a suspension system, these vibrations can be transmitted directly to the user's body, leading to discomfort, pain, potential injuries, and even breaking the wheelchair.

A suspension system in the offroad wheelchair helps to mitigate the impact of these uneven surfaces by absorbing shocks and vibrations. It consists of springs and dampers that allow the wheelchair to flex and absorb the energy from bumps and obstacles.

The suspension system also enhances the wheelchair's traction on uneven terrains. By allowing the wheelchair's wheels to maintain contact with the ground, the suspension system helps to improve the wheelchair's grip and prevent wheel slippage. This is made possible by the spring absorbing the impacts and the damper dissipating the vibrations on the other end.

4.5.2 Suspension System Overview and Functionality

Our team decided to incorporate subsystems commonly used in mountain bikes, and as a result, we have chosen to implement a suspension system specifically designed for this purpose. The team selected the TYYT, Model GS-121A mountain bike shock absorber shown in the first image in Figure 44 to the left. It is made of a spring and damper.

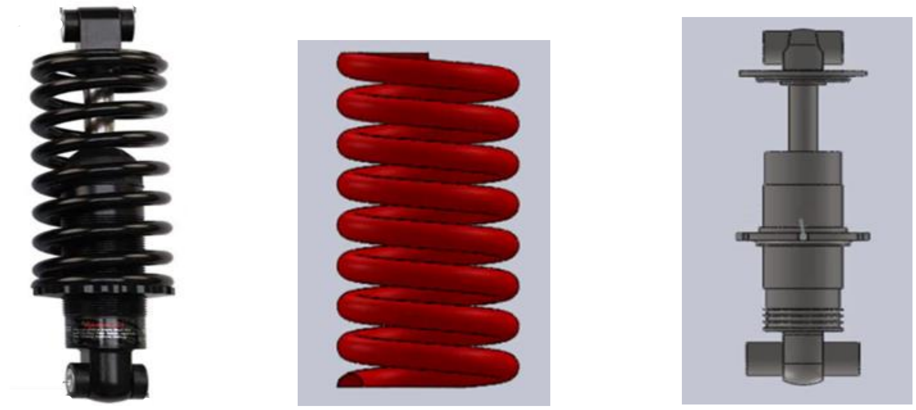

Figure 44. The First Image to the Left shows the TYYT, Model GS-121A Mountain Bike Shock Absorber, The Middle Image is the Spring Model that is used, and the Last Image to the Right is the Damper Model that is Used.

The spring shown in the second image in figure 44 is the component that is designed to provide resistance to movement and help absorb shocks and vibrations. It is an important component of the suspension system, as it helps to provide a smoother and more controlled response to external excitations. By absorbing shocks and vibrations, it can help to reduce the impact of sudden movements and provide a more comfortable and stable ride **[18].**

The damper depicted in the third image to the right is the component that is designed to dissipate the energy that is stored in the spring in a suspension model. When the spring compresses or stretches, it stores potential energy, which can cause the spring to oscillate back and forth. The damper is designed to dissipate this energy by converting it into heat, which helps to reduce the amplitude of the oscillations and provides a more controlled response to the excitations from the road **[18]**.

4.5.3 Requirements for the Suspension System

Before finalizing the choice of shock absorbers, the team established a set of requirements that the suspension system must fulfill. These requirements were as follows:

- The suspension system shall be able to withstand a weight of 300 lbs.
- The system shall be underdamped, with a damping ratio ranging between 0.3 and 0.7 **[18]**.

The design of the off-road wheelchair's suspension system necessitated a load-bearing capacity of 300 lbs. or more, for several critical reasons:

Firstly, adequate stiffness is required to maintain stability and safety, preventing potential structural failure.

Secondly, a robust suspension system is crucial for absorbing and distributing the impact forces encountered on rough terrains, minimizing user discomfort.

Finally, a system designed for higher weight capacities typically exhibits enhanced durability and longevity, reducing the frequency of necessary repairs or replacements **[20]**. Therefore, a suspension system capable of supporting 300 lbs. or more is paramount for ensuring off-road wheelchair safety, comfort, and durability.

A damping ratio below 0.3 would indicate a lightly underdamped system. In such a system, the suspension would not be able to effectively dissipate the energy generated by the impacts from uneven terrain. This could result in excessive bouncing and oscillations, leading to an uncomfortable and unstable ride. Additionally, the underdamped system may have a longer settling time, meaning it would take more time for the suspension to return to its equilibrium position after encountering a bump or obstacle. This extended settling time can negatively impact the overall ride quality and stability of the wheelchair **[18]**.

On the other hand, a damping ratio above 0.7 would indicate a heavily underdamped system. In such a system, the suspension dissipates excessive energy, which can result in a stiff and harsh ride. The damping forces would be too strong, limiting the suspension's ability to absorb impacts and vibrations effectively. This can lead to discomfort for the user and a reduced ability to traverse rough terrains smoothly **[18]**.

By specifying a damping ratio between 0.3 and 0.7, the team aimed to strike a balance between comfort and control. This range allows the suspension system to effectively absorb and dissipate energy from impacts while minimizing excessive bouncing or harshness. It ensures that the wheelchair maintains stability and provides a smoother ride over rough and uneven terrains, thereby enhancing the overall user experience **[18]**.

4.5.4 Weight Distribution on the Wheelchair and Selection of the Suspensions

Using the center of gravity which was situated close to below the chest of the user and over mid-thigh region as a cutoff. The team found that based off the weight distribution of the user on the wheelchair that 35% of the weight of the user was distributed towards the front part of the frame, the front suspensions, and the front casters and 65% of the weight was distributed towards the rear part of the frame, the rear suspensions, and the large tires. This can all be depicted in Figure 45. Finding the weight distribution was crucial when it came to determining what spring stiffness to use in the front and in the back of the wheelchair.

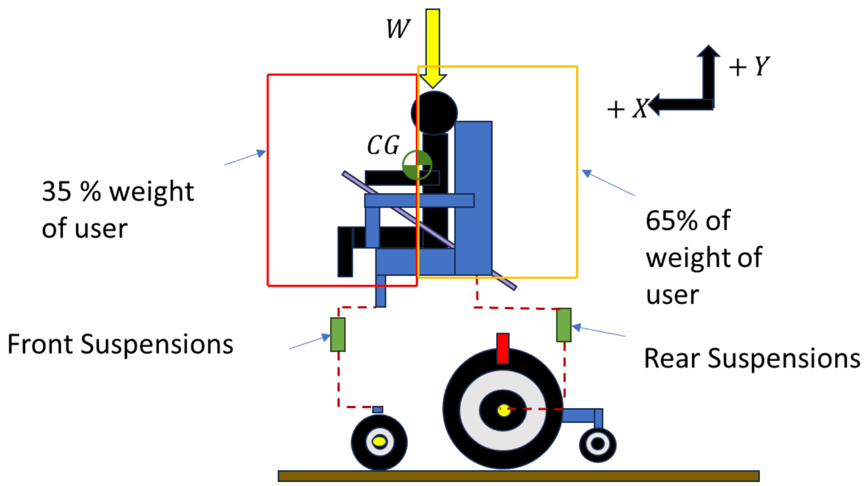

Figure 45. Distribution of Weight on Wheelchair

To quantify these percentages for a 300 lb. user, the team calculated that 105 lb. will rest on the front suspensions and the front casters and 195 lb. will be distributed on the rear suspensions and the large wheels.

4.5.5 Placement of the Shock Absorbers

The front shocks shown in Figure 46 and circled in red were placed inwards directly beneath the seat as opposed to outwards because the team wanted the shocks to be closer to each other and to the center of gravity. By having the shock absorbers closer to each other and to the center of gravity, the suspension system absorbs and distributes more effectively the impact forces encountered during off-road use. This configuration helps maintain better traction and reduces the risk of tipping or losing control. This configuration also improves weight distribution. It allows for more efficient weight transfer during acceleration, braking, and cornering, enhancing overall handling and maneuverability **[20]**.

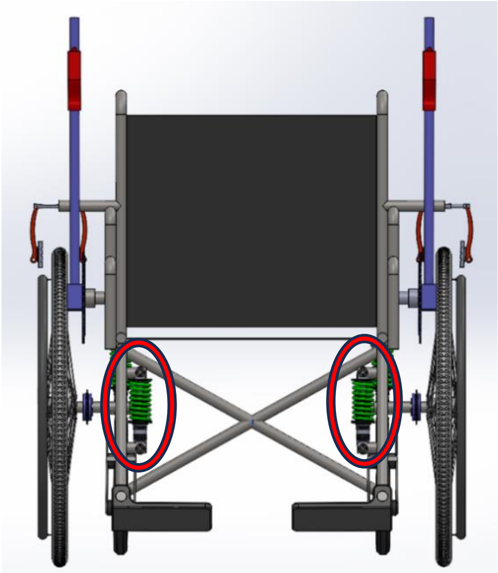

Figure 46. Front Suspensions placement

The rear shocks shown in Figure 47 and circled in red were extended backwards behind the seat as opposed to directly beneath it. The team noticed that placing the suspensions directly beneath the seat would create interference between the shocks and the components of the propulsion system. To prevent that from happening, mounting brackets were used to isolate them backwards where they can only interact with the frame and the large wheels without causing interference with other subsystems.

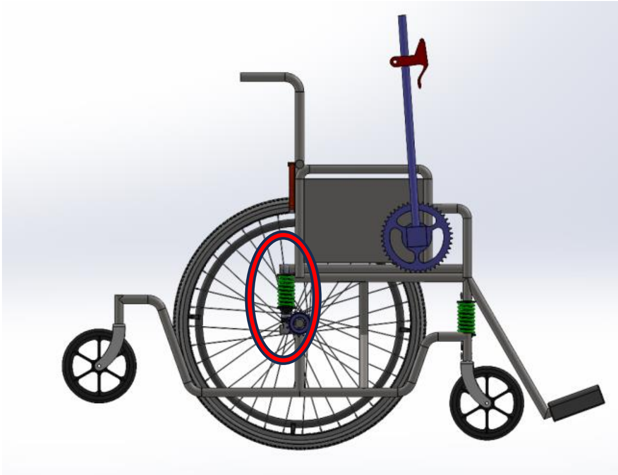

Figure 47. Rear Suspensions placement

5.0 Experimentation

5.1 Subsystem 3 – Brake System

Before getting straight into the how the brakes were tested, it is important to make introduce why it was done. The brakes are essentially the only way the user can stop the wheelchair, without them the user could end up in a fatal accident. Therefore, the reason for testing the brakes was to ensure that they would work as expected. The Code of Federal Regulations for Mountain Bike Brakes requires that the brakes stop the whole system no more than 15 ft given an initial velocity no less than 22 $\frac{ft}{s}$ **[23]**. The Code of Federal Regulations for Mountain Bike Brakes also requires the calipers to be properly attached to the wheelchair **[24]**. It should also be noted that the reason a brake system was added was due to most standard wheelchairs having just a parking brake that can be found in Figure 48. With a parking brake, it would require the user to be in a static position to activate it. Therefore, since this wheelchair is going to be subjected to steep and rough terrains it was crucial to make sure that the brakes would do their job.

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Figure 48. Silver Sport 2 Wheelchair used for testing

Therefore, the way that the brake system was tested by using an application accessible from a smartphone named Phyphox. Through this application, the deceleration of the wheelchair was found. The caliper brake system that was used was from the company Boao. It was important to get the correct area size of the brake pad as this ensured the force that would be applied from it would stop the wheelchair. That area came out to 1.08 in^2 and was provided in the caliper brake's specifications. After ensuring the appropriate brake pad area size, the next step was to attach the caliper brake to the wheelchair. This was done by using by cutting two woods pieces, with one having dimensions of a length of 4 in and width of 2 in. This first piece was what the caliper bolt was attached to. Another piece was cut using wood once again with dimensions of a length of 5 in and width of 2 in. This piece was then attached to the first piece using a 0.25 in, 2 in long screw. Note that two of these same attachment pieces were made since there are two caliper brakes. Each is attached to the large wheels of the wheelchair because the large wheels are the driving wheels and where the brakes will be needed to stop the whole system. Figure 49 then shows the wood attachments and caliper and their positioning on the wheelchair. Now Figure 49 does show that a clamp was used to secure the caliper from moving. This was to ensure no movement of the caliper because if there was any movement, then the brakes would not stop the wheelchair as expected. Now the brake included brake handles to activate the brake system, those were positioned on the armrests and can be seen in Figure 49. Having the brakes positioned, the next step was to collect data.

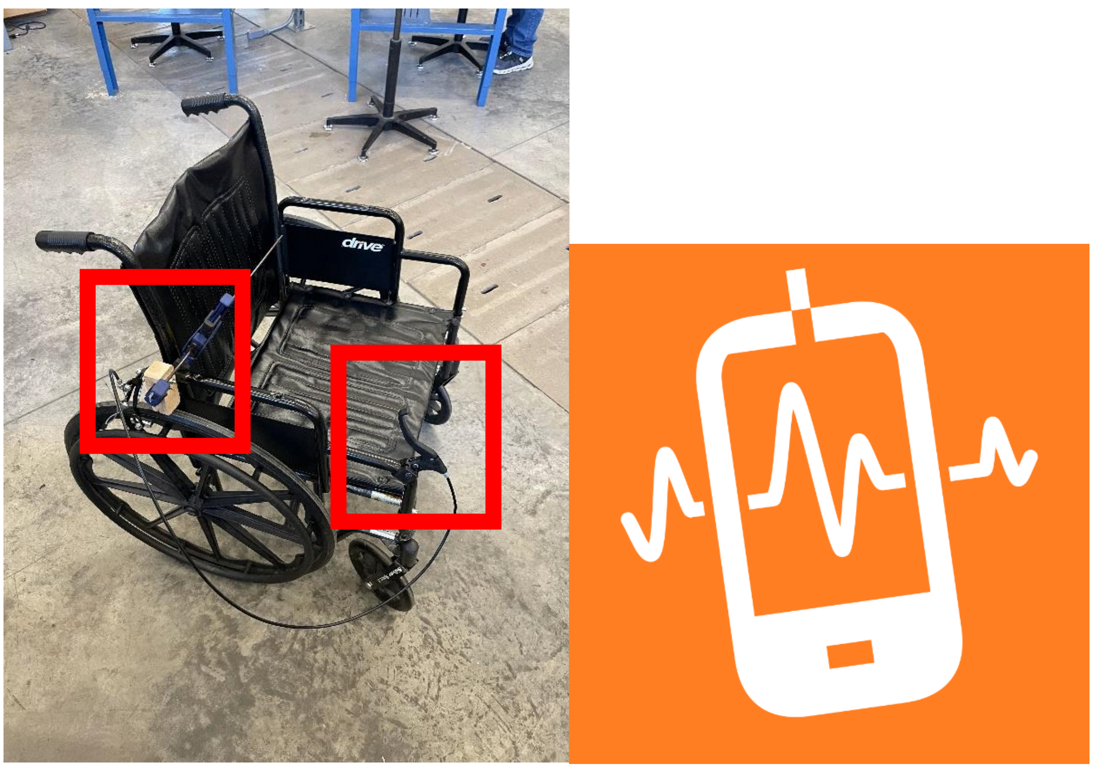

Figure 492. The image to the left is the Attachment Piece for Caliper and Brake Handle positioned on the wheelchair and the image to the right is the Phyphox logo.

The data that was collected was the deceleration of the wheelchair, the time it takes the wheelchair to stop, and the distance it took the wheelchair to stop. The testing was done outside the Applied Engineering Center at the University of Southern Indiana. Figure 50. Shows the layout of how the testing was done. How it worked was, once the user passed the starting point as shown in Figure 50, the stopwatch started timing. Having passed the starting point and the stopwatch on, the user would then use the brake handles to activate the caliper brakes. Once the brakes were applied and the wheelchair came to a halt, the stopwatch stopped as well. Then the stopping distance was collected by measuring the front end of the caster wheel using a 25 ft measuring tape that was stretched out to approximately 12 ft as shown in Figure 50. The measurement was taken from the starting point to the point the wheelchair stopped. Through this procedure Phyphox was also used by resting on the lap of the user and collecting the deceleration in the horizontal direction. Once stationary Phyphox was then stopped in sync with the stopwatch, hence, collecting the deceleration. Now Phyphox collects the raw data, that is why it was important to collect the time as to match it with the raw data and get the correct deceleration value.

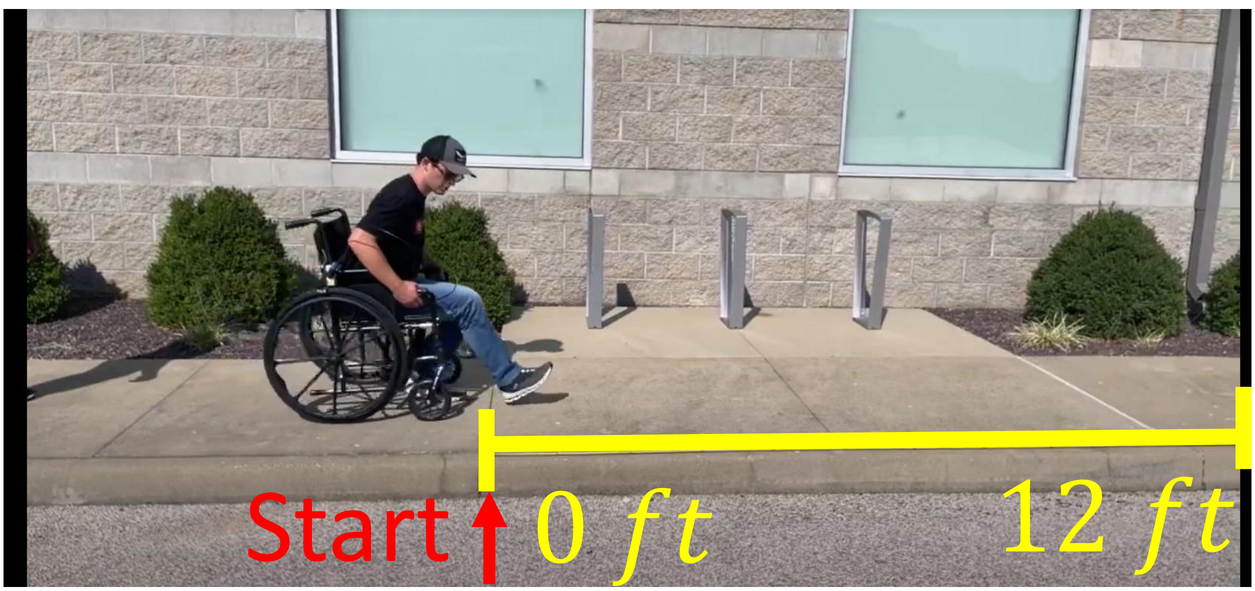

Figure 50. Testing done for Caliper Brakes attached to the wheelchair

The data that was collected from testing can be seen in Table 2. As mentioned earlier the data that needed to be collected was the stopping distance, the stopping time, and the deceleration of the wheelchair. It was needed in order to find the initial velocity of the trials to ensure that it meets the Code of Federal Regulations of Mountain Bike Brakes **[23]**. To find the initial velocity the following kinematic equation was used, $\Delta x = V_i t + \frac{1}{2}at^2$. The stopping distance also could not exceed a distance of 15 ft as per the Code of Federal Regulations of Mountain Bike Brakes **[23]**. The results, as shown in Table 2, demonstrate that for the two trials conducted, the brakes did meet the standard set by the Code of Federal Regulations. In these two trials the caliper was properly attached and did not move, therefore meeting the standard set by the Code of Federal Regulations.

Table 2: Collected Data from Testing

Trial	Time (s)	Distance (ft)	Deceleration $(\frac{ft}{s^2})$	Initial Velocity $\left(\frac{ft}{s}\right)$
1	1.7	3.17	31.6	28.6
2	1.7	3.17	31.9	28.2

However, this wheelchair was designed to be subjected to steep and tough terrains. Therefore, testing was needed to verify that this brake system would do its job. This testing was done on the new bike trail at the University of Southern Indiana since it had some steep hills as shown in Figure 51. However, in the first trial on an incline, the wood attachment ended up shearing as shown in Figure 51. This was expected to happen since the wood attachment piece is known to not be a strong material for these types of scenarios. Therefore, no results were obtained for inclination. Now an attachment piece was designed for the brakes but due to a lack of welding experience, it was not attached to the wheelchair frame. Therefore, no more testing was conducted for the braking system.

Figure 51. The image to the left is the sheared, wood, attachment piece after the first trial on an inclination and the image to the right is the inclination that was used for testing

Therefore, comparing the values of what was collected from just testing with no inclination to the theoretical values. Table 3 shows that the area of the brake pads was off by 0.01 in^2. Which is good as the brake pad area is needed to be an ideal size in order to have force that would stop the wheelchair when it is moving. Table 3 also shows the stopping distances and stopping times of both the theoretical and experimental. When comparing the stopping distances, the theoretical and experimental values differed by 0.36 ft. This can be due to the coefficient of friction that was used as well as the area brake pad size. In the theoretical, the highest value for the coefficient of friction was used to account for the worst contact friction that would act on the wheels of the wheelchair. This is one of the few reasons that the stopping distances were different. The same could be said for the stopping time, where the theoretical value came out to 0.470 s with the average time from the experimental data came out to 1.4 s. This would be due to the initial velocity used in the theoretical, which was 15 $\frac{ft}{s}$. This was to account for the max initial velocity that the wheelchair would go from the propulsion system.

Table 3. Theoretical vs Experimental Data

Theoretical	Experimental
1.07 in^2	1.08 in^2
3.53 ft	3.17 ft
0.470 s	1.4 s

In conclusion, although the values did not match up completely, they were still relatively close and the reasons for it were stated towards the end of the discussion. One being that the coefficient of friction was accounted for at a high value to account for the worst. The other being the initial velocity being at a staggering 15 $\frac{ft}{s}$ as that is what the propulsion system should create to move the wheelchair forward. Another conclusion from testing the brake system was that the biggest problem was not the braking system stopping the whole wheelchair, but getting an appropriate attachment piece that allows for the caliper to have it stay in place without moving when it is in motion. This leads to the next discussion which will be discussed later in the report about looking into using hydraulic disk brakes rather than sticking with caliper brakes.

5.2 Subsystem 4 – Suspension System

Testing was performed in order to calculate the damping ratio for the suspension system. Therefore, a wooden platform with holes for both ends of the shocks was constructed as shown in Figure 52. Considering the springs used, the equivalent stiffness of the system turned out to be 600 lbs./in and that only includes the rear suspensions. The springs highlighted in the red boxes were placed at 28 inches apart which is equivalent to the distance where they would be placed on the wheelchair. Knowing that the wheelchair is designed for a 300 lbs. user, the system built was to withstand a weight of 195 lbs., which in this case represents 65% of the total weight of the said user being applied on the rear shocks. These shocks were selected to be placed in the back of the wheelchair. A weight of 230 lbs. was applied on the wooden platform as shown in Figure 53. The team exceeded 195 lbs. due to the fact that the suspension system will be subject to displacement inputs whenever the wheelchair meets an obstacle. The accelerometer from Phyphox was used to record the overall acceleration of the system upon impact. The data recorded yielded to the graph shown in Figure 54 on which it can be seen the impact which is brought to dissipation in approximately 0.8 second.

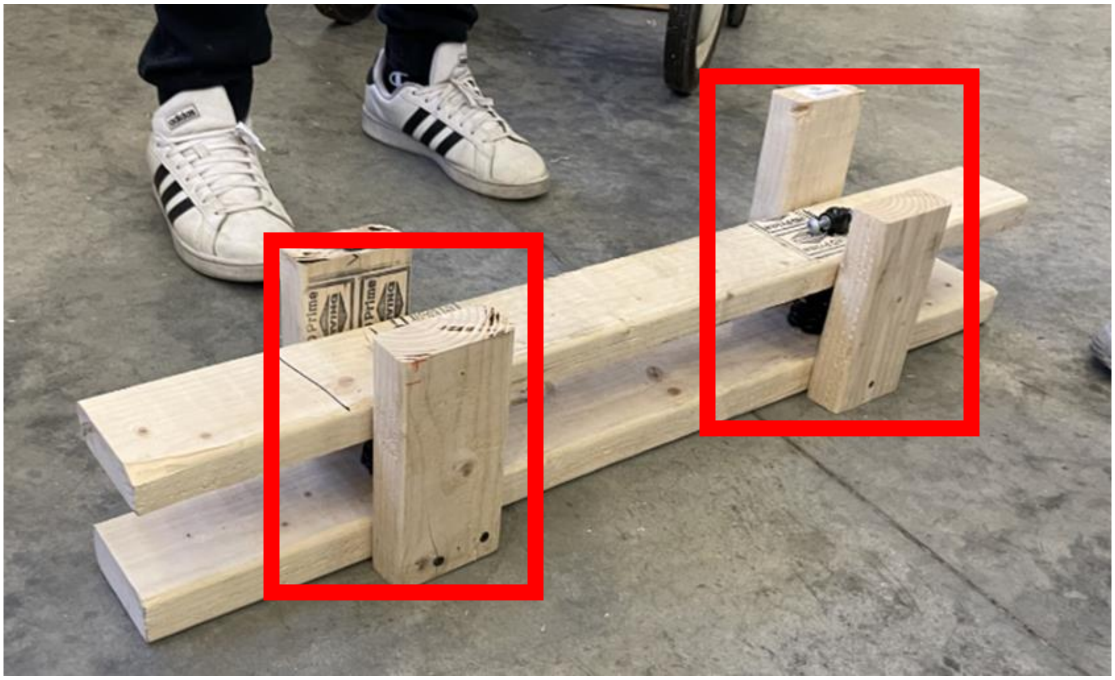

Figure 52. Platform Built for Testing

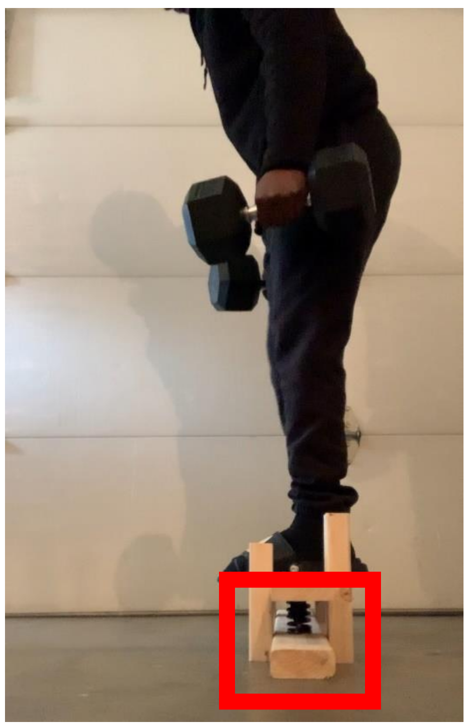

Figure 53. Testing Done for Suspension System

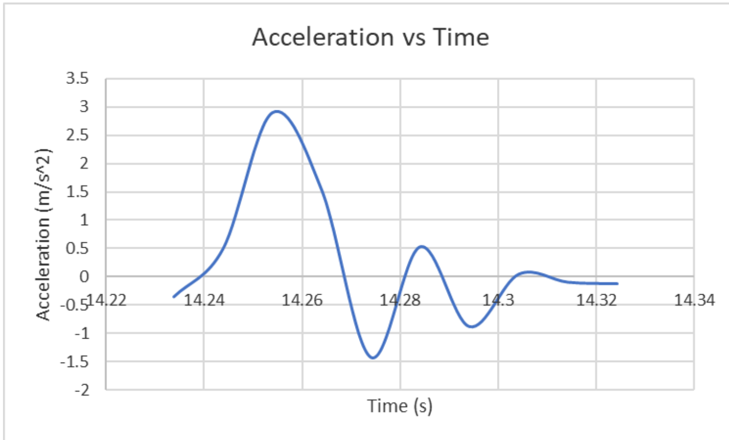

Figure 54. The image to the left shows the acceleration of the system upon an impact plotted against the time that it takes the acceleration to dampen. The image to the right is the Phyphox Logo.

Following testing, the logarithmic decrement variable that quantifies the rate at which the amplitude of vibrations decreases over time was calculated as follows in equation (18). It consists of taking the logarithm of the ratio of the largest peak to the lowest peak and multiplying that logarithm by the inverse of the number of periods these two peaks.

$$\delta = \frac{1}{n}\ln\left(\frac{x(t)}{x(t+nt)}\right) = \frac{1}{2}\,ln\left(\frac{2.8989}{0.0413}\right) = 2.126 \qquad (18)$$

With n being the number of periods to dissipation, being the acceleration value, and $x(t+nt)$ being the value of the last peak, and δ being the logarithmic decrement variable **[21]**. Ensued was the calculation of the damping ratio for the suspension system calculated in equation (19) was to be in the range of 0.3 to 0.7.

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} = \frac{2.126}{\sqrt{4\pi^2 + 2.126^2}} = 0.321 \qquad (19)$$

The damping ratio turned out to be 0.321. That indicates that the suspension will work effectively to bring the vibration to rest over a relatively short period of time. From the data, that time was measured to be 0.8 second.

Figure 55. Rear View of the Prototype. In the Red Boxes are the Rear Suspensions

6.0 Disposal Plan

For the disposal of the prototype design of the Off-Road Manual Wheelchair, most of the steel and aluminum components will be taken to Green Metals Inc. in Princeton, Indiana. For all other components, they will be dispersed in the Gibson County Landfill in Fort Branch, Indiana. None of the materials will require any special disposal methods.

7.0 Budget

Table 4. Offroad Manual Wheelchair Budget/Cost

Sub-System	Cost
Frame	$354.15
Propulsion System	$137.22
Brake System	$19.95
Suspension	$294.86
Total Cost	**$806.18**

8.0 Economic and Environmental Analysis

The design of the Off-Road Manual Wheelchair has proven to make an economic impact by creating a affordable solution for the an off-road wheelchair. The total cost of the of the wheelchair comes to $806.18. This is a reasonable cost for individuals in need for an off-road wheelchair for recreational use. Also, the design utilized bicycle components that are common in most areas in the world. This allows individuals to get possible replacement parts at competitive pricing and in a timely manner. The sub-systems also have mechanical components that are similar in design to bicycles. This would allow the user to have it maintained and worked on in bike shops.

The Off-Road Manual Wheelchair has little environmental impact. The main environmental concern of the Off-Road Manual Wheelchair is the impact it has on the off-road terrains. The wheelchair is designed to traverse over terrains such as grass, light sand, concrete, and dirt, and it could potentially alter the terrains in which it is traversing. Also, the rubber tires used for the wheelchair will emit rubber particles in the air as it is used over time. These impacts are very minimal and will cause no harm to the environment.

A lever-propelled wheelchair would require human energy to operate, which is a renewable and sustainable source of power. This eliminates the need for electricity or fuel consumption, making it highly energy efficient. It will also require fewer resources for construction and maintenance compared to a motorized alternative. This would help minimize the extraction of raw materials and reduce overall resource consumption.

9.0 Future Work

9.1 Frame

Future work for the frame of the wheelchair could consist of cambered drive wheels. The team did not design cambered wheels because of the worry of interference of the cambered wheels with the other sub-systems. As with having the wheels angled the caliper braking system would also have to be angled to match the wheel angles to make consistent contact with the tires. Also, because the driving wheels would be angled inward there would be less space to install the propulsion system. The potential advantage of cambered wheels is that they would increase the stability of the Off-Road Manual Wheelchair from side to side. The current design has anti-tipping wheels for the forward and backward direction, but it does not impact the side to side stability.

9.2 Propulsion System

For future work on the propulsion system, the main concern was the effects of the shock absorbers on the chain and sprocket. Specifically, the shock absorbers minimal deflection could create inconsistent chain length and create too much slag on the chain connection. This would likely lead to quicker failure of the chain. To ensure that the chain length is stable on the propulsion system, a chain tensioner was considered to maintain a specified chain length and prevent any slag. Chain tensioners were considered for this issue for the Off-Road Manual Wheelchair, but unfortunately not enough time or knowledge was explored for the possible implementation of this useful mechanism. Also, having the ability to have a gear shifter on the wheelchair was considered. This would allow the user to change gear ratios based on the terrain and slope grades they were traversing. The design of a gear shifter on the Off-Road Manual Wheelchair would make it stand out even more so when compared to other off-road wheelchairs and being challenging.

9.3 Brake System

For future work on the brake system, looking into replacing the caliper rubber brakes with hydraulic disc brakes. That is because there were two methods about incorporating a braking system, one being the caliper brakes that were used in this project and the other being a hydraulic disc brake. In a hydraulic brake system, rather than using a steel wire that pulls the caliper to create friction, hence stopping the system **[1]**. The hydraulic brake has a disc brake on which a caliper with smaller dimensions acts the same as used in this project **[1]**. The difference is the Bowden cable for a hydraulic disc brake would contain lubrication known as hydraulic oil that maintains the longevity of the disc brake **[1]**. This lubrication in return also prevents the caliper and disc brake from creating a fire if the brakes are activated abruptly **[1]**. This brake system for future work should be investigated, not only because of what was explained but because the use of a hydraulic brake and a chain and sprocket system has coexisted for some time **[1]**. This project feared that the brake and propulsion system would interfere with each other therefore discarded the possibility of using a hydraulic disc brake. Therefore, it should be further researched to justify that it does stop the system and if it does, determine if keeping the lever arm propulsion system would be affected by adding a hydraulic disc brake.

9.4 Suspension System

For future work on the suspension system, the team could evaluate the possibility of tilting the shocks at a certain angle. Tilting the shock absorbers would change the suspension geometry on the wheelchair. This could affect the wheel travel, ride height, and the overall suspension performance. The angle of the shock absorbers will determine how they compress and extend in response to bumps and impacts. That could also alter the damping forces, potentially affecting the wheelchair's stability, comfort, and response to different terrains. The team would need to carry out testing to find out whether that alteration is positive or detrimental to the wheelchair. Off-road wheelchairs often encounter lateral forces during aggressive maneuvers or uneven terrain. It would also be essential to test whether tilting the shock absorbers helps alleviate these side loads or not **[20].**

10.0 Lessons Learned

There were many lessons learned from completing the Off-Road Manual Wheelchair project. Most of these lessons learned involved building the actual Off-Road Manual Wheelchair prototype. First, the team learned that ordering materials as soon as the critical design was completed was ideal. The team ordered some of the parts later than initially expected and this came at a great cost. The most crucial component, the drive wheel rims, did not get shipped in until early November. This caused a delay in building the prototype and ultimately caused the team not to complete it fully in early December of 2023.

Secondly, the team also had difficulty when it came to welding components on the prototype frame. This was due to the inadequate knowledge and experience the team members had with welding. Luckily, Justin Amos, the engineering shop supervisor out at the Applied Engineering Center, was able to help us get trained on welding and also help weld our rear suspension brackets on the prototype frame. Although we had proper training with welding, our welding technique was not adequate enough to weld all of the different sub-systems onto the prototype frame.

Lastly, learning how to work as a team was a lesson learned during the senior design project. The team had to get accustomed to how each team member operates and thinks, and how to divide the project equally in four. The team decided to split the Off-Road Manual Wheelchair in four different sub-systems per the requirements that needed to be met. This allowed each team member to work equally and individually on the project, but it also required the team to have to work together to ensure each sub-system would work with one another.

11.0 Conclusion

The team designed an Off-Road Manual Wheelchair with the addition of an upper and lower frame, lever and gear propulsion system, caliper braking system, and a spring and damper suspension system. Concepts for each sub-system of the Off-Road Manual Wheelchair were created through extensive literature review and engineering calculations based off applied engineering knowledge. Each sub-system design was created and combined through SolidWorks, a three-dimensional parametric design software, to form the final design of the Off-Road Manual Wheelchair.

For the frame, an anti-tipping analysis and finite element analysis was conducted to ensure the subsystem met all corresponding requirement of supporting a weight of 300 pounds and supporting all mechanical sub-systems. The addition of a chain and sprocket with a lever-arm met the requirement of adding a lever propulsion mechanism for the propulsion system. Gear ratio calculations based off literature review ensured that the chain and sprocket design was more ideal for steeper inclination than other off-road wheelchairs and mountain bike designs. Although the propulsion system was designed for steep inclination, further testing needs to be conducted on the prototype to ensure it will go up a 25% slope. Next, adding a caliper braking system completed the requirement of adding a braking system. The caliper braking system design proved that it would stop the wheelchair, but without an adequate attachment piece it was not able to test on steep inclination. The suspension system designed met the requirement of supporting 300 lbs. and the addition of a suspension on the Off-Road Manual Wheelchair. Also, all the sub-systems created a combine Off-Road Manual Wheelchair weight of 51 lbs. This fell under the 60 lb. weight requirement. Below shows the requirements that have been checked off.

The Offroad Manual Wheelchair shall…

- Support a weight of 300 lb.
  - Per the Americans with Disabilities Act (ADA) **[6]**
- Include a lever-arm propulsion mechanism.
- Move up a 25% slope.
  - ADA requires a 15% slope **[6]**
- Include a manual braking system.
- Include a suspension system.
- Weigh less than 60 lb.

Furthermore, the prototype is still being built to ensure that the propulsion system combined with the other sub-systems could move up a 25% slope. So far, the protype includes the base upper and lower frame, front caster wheels, 26-inch drive wheels, driven free wheel sprockets and the rear suspensions. Figure 58 and Figure 59 below show the prototype build.

Figure 56. Isometric View of the Incomplete Protype

Figure 57. Rear View of the Incomplete Prototype

Further implementation and testing still needs to be done to ensure that the Off-Road Manual Wheelchair design would be viable for consumer use and to complete all the requirements listed. Overall, this design has given the team insightful knowledge on machine design, teamwork, project management, time management, and engineering techniques and calculations. The team will use this experience and the knowledge gained for upcoming projects and careers to come.

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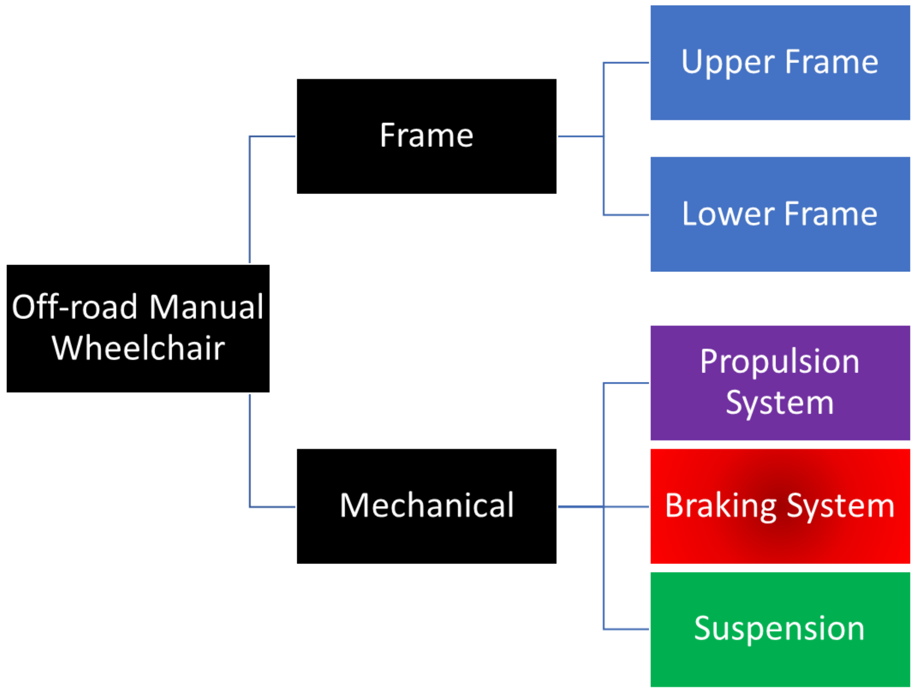
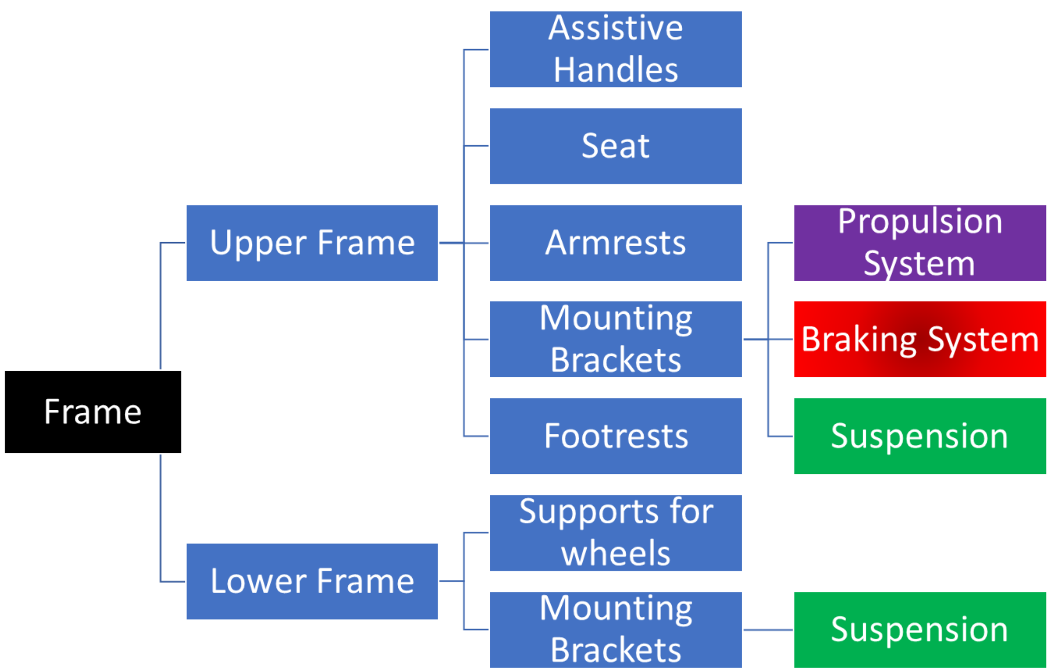
Appendices

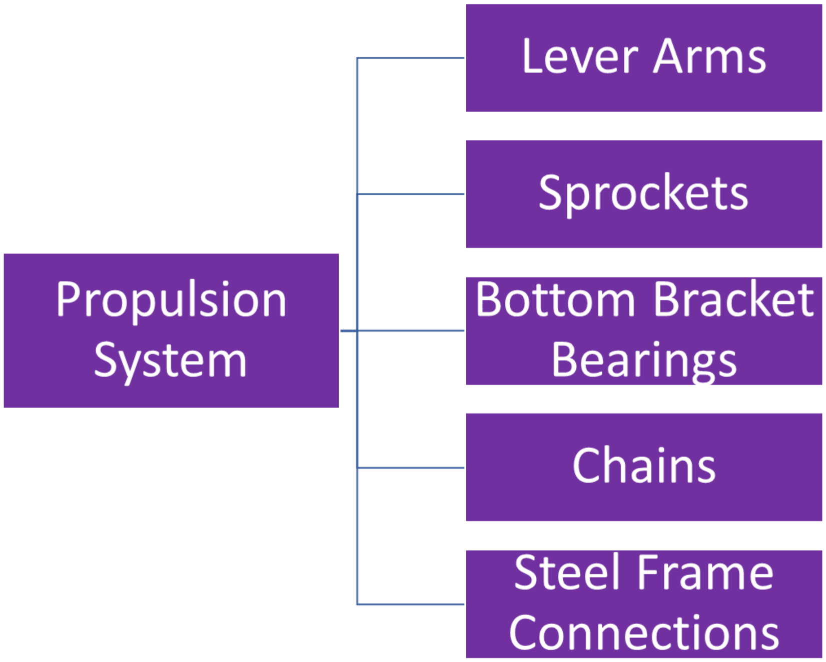
APPENDIX A: Sub-System Hierarchy Breakdown



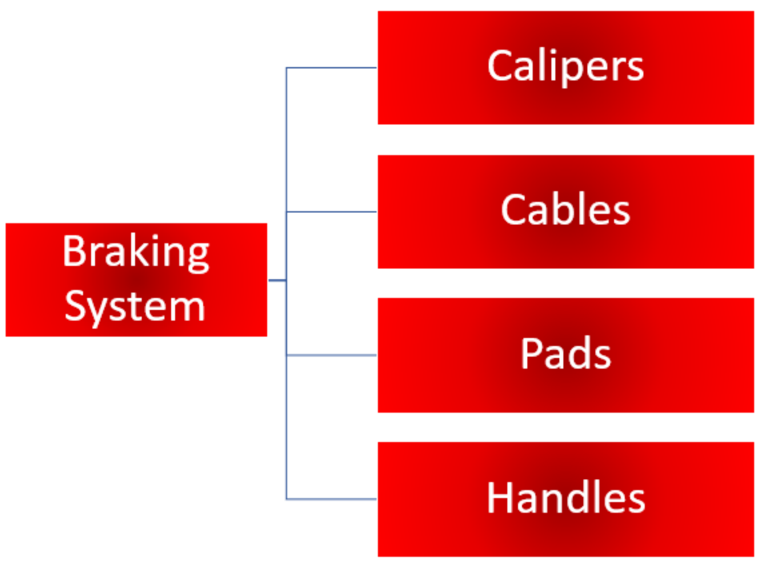
APPENDIX B: Frame Sub-System Hierarchy



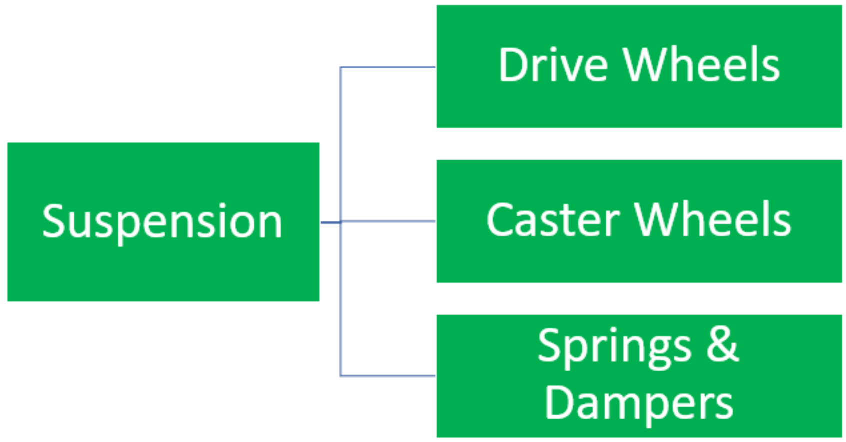
APPENDIX C: Propulsion System Sub-System Hierarchy



APPENDIX D: Braking System Sub-System Hierarchy



APPENDIX E: Suspension Sub-System Hierarchy



Appendix F: Dynamic Analysis Conducted on the Wheelchair to find an ideal Brake System

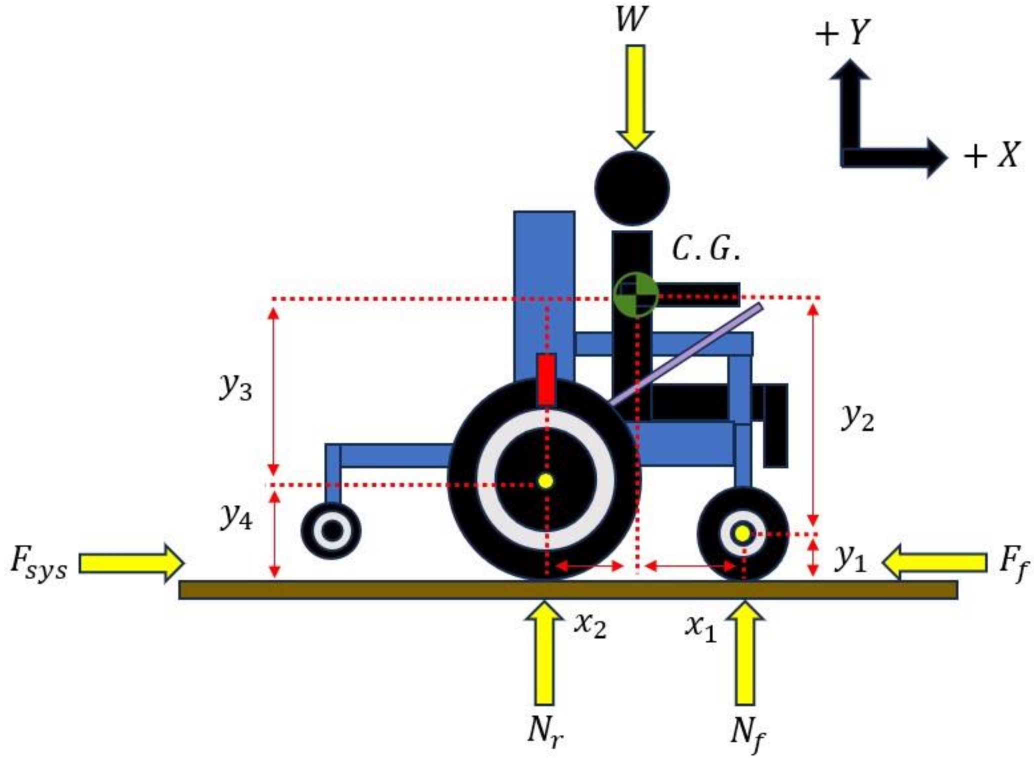


Figure 42. Free-Body Diagram of Wheelchair for Analysis of Tires

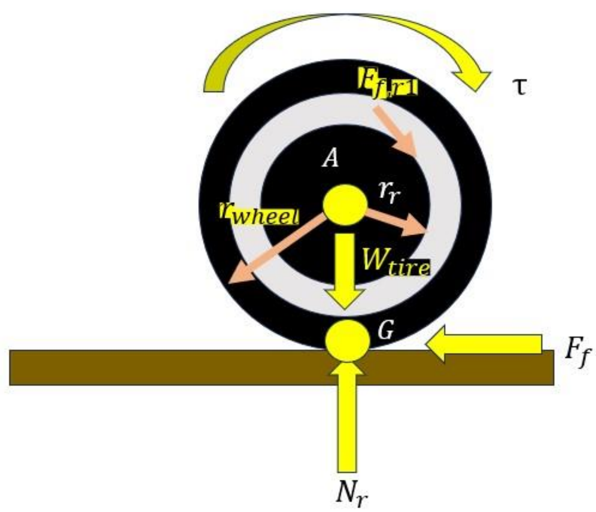


Figure 43. Free-Body Diagram of Rear, Drive Wheel

The following equations were derived using Figure 42 and Figure 43 to find the reaction forces that act on the tires. In return it would help to find the force of the aluminum cables that are used to close the calipers together. These equations use the summation in the horizontal and vertical directions to find the normal forces on the rear and front wheel of the wheelchair. A moment at point G was needed to find the normal forces.

$$\sum F_x = 0$$

$$f_1 + f_2 = (ma)_{sys} \tag{10}$$

$$where\ F_f = f_1 + f_2$$

$$\sum F_y = 0$$

$$N_r + N_f - W_{total} = 0$$

$$N_r + N_f = W_{total} \tag{11}$$

$$\sum M_G = 0$$

$$-(x_2)W_{total} + (x_1 + x_2)N_2 = -(y_4 + y_3)(ma)_{sys} \tag{12}$$

$$f = \mu N$$

$$(ma)_{sys} = \mu_T(N_r + N_f) \tag{13}$$

Equation for friction:

$$F_f = \mu N = \mu_T(N_r + N_f)$$

$$(ma)_{sys} = \mu_T(N_r + N_f) \tag{14}$$

Plug Equation (13) into (14):

$$-x_2W_{total} + (x_2 + x_1)N_f + (y_4 + y_3)\mu_T(N_r + N_f) = 0$$

$$-x_2W_{total} + (x_1 + x_2)N_f + (y_4 + y_3)(\mu_T)(N_r) + (y_4 + y_3)(\mu_T)(N_f) = 0$$

$$-x_2W_{total} + (x_1 + x_2)(\mu_T)\big(N_r\big) + ((x_1 + x_2) + (y_4 + y_3)(\mu_T))(N_f\big) = 0 \tag{13'}$$

Solve for N_2 in equation (12):

$$N_f = W_{total} - N_r \tag{12'}$$

Use equation (12') to plug into (13'):

$$-x_2W_{total} + (y_4 + y_3)(\mu_T)(N_r) + ((x_1 + x_2) + (y_4 + y_3)(\mu_T))(W_{total} - N_r) = 0$$

Now solve for N_1:

$$(y_4 + y_3)(\mu_T)(N_r) + ((x_1 + x_2) + (y_4 + y_3)(\mu_T))(W_{total} - N_r) = x_2W_{total}$$

$$(y_4 + y_3)(\mu_T)(N_r) + (x_1 + x_2)W_{total} + (y_4 + y_3)(\mu_T)(W_{total}) - N_r(y_4 + y_3)(\mu_T) - N_r(x_1 + x_2) = x_2W_{total}$$

$$N_r((y_4 + y_3)(\mu_T) - (y_4 + y_3)(\mu_T) - (x_1 + x_2) = x_2W_{total} - W_{total}(x_1 + x_2) - W_{total}(y_4 + y_3)(\ \mu_T)$$

$$N_r = \frac{W_{total}}{-(x_1 + x_2)}(x_2 - (x_1 + x_2) - (y_4 + y_3)(\mu_T))$$

$$N_r = W_{total}(\frac{x_1 - (x_1 + x_2) - (y_4 + y_3)(\mu_T)}{-(x_1 + x_2)})$$

$$N_r = W_{total}\left(\frac{x_1 + (y_4 + y_3)(\mu_T)}{(x_1 + x_2)}\right) \tag{13''}$$

$$N_r = (300\ lbs)\left(\frac{(16\ in) + (28\ in)(0.7)}{(21\ in)}\right) = 508.57\ lbs$$

Plug equation (13'') into equation (12'):

$$N_f = W_{total} - W_{total}(\frac{d_1 + (h)(\mu_T)}{L})$$

$$N_f = W_{total}(1 - \left(\frac{d_1 + (h)(\mu_T)}{L}\right))$$

$$N_f = W_{total}\left(\frac{d_1 - (h)(\mu_T)}{L}\right) \tag{12''}$$

$$N_f = (300\ lbs)\left(\frac{5\ in - (28\ in)(0.7)}{21\ in}\right) = -208.57\ lbs$$

We can also calculate the friction forces acting on the rear wheel and the front wheel using the values found:

$$f_1 = \mu N_r = (0.7)(508.57\ lbs) = 356\ lbs$$

$$f_2 = \mu N_f = (0.7)(91.89\ lbs) = -146\ lbs$$

$$F_{friction} = f_1 + f_2 = 356 - 146 = 210\ lbs$$

With these values we can calculate the deceleration of the system rather than theorizing a value of $5\frac{ft}{s^2}$:

$$m_{sys} = \frac{300\ lbs}{\left(32.2\frac{ft}{s^2}\right)} = 9.3168\frac{lbs * s^2}{ft}$$

$$a_{sys} = \frac{f_1 + f_2}{m_{sys}} = \frac{356\ lbs - 146\ lbs}{9.3168\ (\frac{lbs * s^2}{ft})} = 22.54\ \frac{ft}{s^2}$$

The values found for the terms $f_1, f_2,\ N_1,\ and\ N_2$ were obtained to be $f_1 = 356\ lbs, f_2 = -146\ lbs,\ N_r = 508.57\ lbs,\ \ N_f = -208.57\ lbs$. These values will then help to find the force of the cable that is needed to design the appropriate sizes for the brake pads.

$$-r_R f_{r1} + r_{wheel} f_1 = 0 \qquad (14)$$

$$-r_R(\mu_R)(n)(F_{cable}) + r_{wheel}(\mu_T)(N_r) = 0$$

$$\mu_T = \frac{r_R \mu_R n F_{piston}}{r_{wheel} N_r}$$

$$F_{cable} = \frac{r_{wheel} N_r \mu_T}{r_R \mu_R n} \qquad (14)$$

Equation (8) is used to find the force of the cable which resulted to be $F_{cable} = 298.58\ lbs$. Once the value of the force of the cable was found, the next step was to use the value to find the area of the brake pad that would match this cable force. The equation to find the area size of the brake pad was derived as follows:

$$F_{caliper} = P_{cable} * A_{brakePad} \tag{15}$$

Now the value for the force of the caliper was $F_{caliper} = 298.58\ lbs$ and for the pressure of the cable was $P_{cable} = 280\ psi$, as that is the maximum pressure that a Bowden cable is able to withstand. A Bowden cable is just a steel wire that connects the caliper and the handle. Having the values and rearranging equation (9), the area size of the brake pad was found:

$$\boldsymbol{A_{brakePad}} = \frac{F_{caliper}}{P_{cable}} = \frac{298.58\ lbs}{280\ psi} = \mathbf{1.07\ in^2} \tag{15}$$

The next step was to find the time it would take for the wheelchair to fully stop. Finding that time was done with the following equations, it should be mentioned that these values are given in the list of symbols table:

$$KE = \frac{1}{2} m_{sys} v_{sys}^2 = \frac{1}{2}\left(9.3168 \frac{lbs * s^2}{ft}\right)\left(15 \frac{ft}{s}\right)^2 \tag{16}$$

$$\boldsymbol{KE = 1048.14\ lbs * ft = 12577.68\ lbs * in}$$

$$\omega = \frac{v}{r_{wheel}} = \frac{15\left(\frac{ft}{s}\right)}{13\ in} = \frac{15\left(\frac{ft}{s}\right)}{\frac{13\ in}{12\ in} * 1\ ft} \tag{17}$$

$$\boldsymbol{\omega = 13.8 \frac{rad}{s}}$$

$$F_{clamp} = F_{caliper} * 2 = (298.58\ \ lbs)(2) \tag{18}$$

$$\boldsymbol{F_{clamp} = 597.16\ lbs}$$

$$F_{friction} = F_{clamp} * \mu_r = (597.16\ lbs)(0.5) \tag{19}$$

$$\boldsymbol{F_{friction} = 298.58\ lbs}$$

$$\tau_r = F_{friction} * R_{effecient} = (298.58\ lbs)(13\ in) \tag{20}$$

$$\boldsymbol{\tau_r = 3881.54\ lbs * in}$$

$$\theta = \frac{KE}{\tau_r} = \frac{12577.68\ lbs * in}{3881.54\ lbs * in} \tag{21}$$

$$\boldsymbol{\theta = 3.24\ rads}$$

$$t = \frac{\theta * 2}{\omega} = \frac{(3.24\ rads)(2)}{\left(13.8 \frac{rad}{s}\right)} \tag{22}$$

$$\boldsymbol{t = 0.470\ s}$$

Having the time it would take for the wheelchair to come to a stop, the stopping distance can also be found as follows:

$$x_{stop} = \frac{1}{2} * v * t = \frac{1}{2} * 15 \frac{ft}{s} * 0.470s \tag{23}$$

$$\boldsymbol{x_{stop} = 3.53\ ft}$$

APPENDIX G: Single Degree of Freedom Approach

In order to determine the system's dynamic response, a single degree of freedom approach was taken. In that approach, the system namely the user and the upper frame is simplified to a concentrated mass connected to a spring and a damper. The spring represents the equivalent stiffness of the system, while the damper represents equivalent damping characteristics. The mass, spring, and damper are interconnected, and their behavior can be described using Newton's second law of motion. That concentrated mass assumed to be moving along a single direction or axis in particular the y-axis due to the compression of the spring, would react in response to displacement caused by the obstacle from the road on the shocks and subsequently on the overall system. This approach provides insights into the system's natural frequency, damping ratio, and response to external forces or disturbances. It also allows to theoretically find the time it takes for the vibrations to dissipate depending on the displacement input.

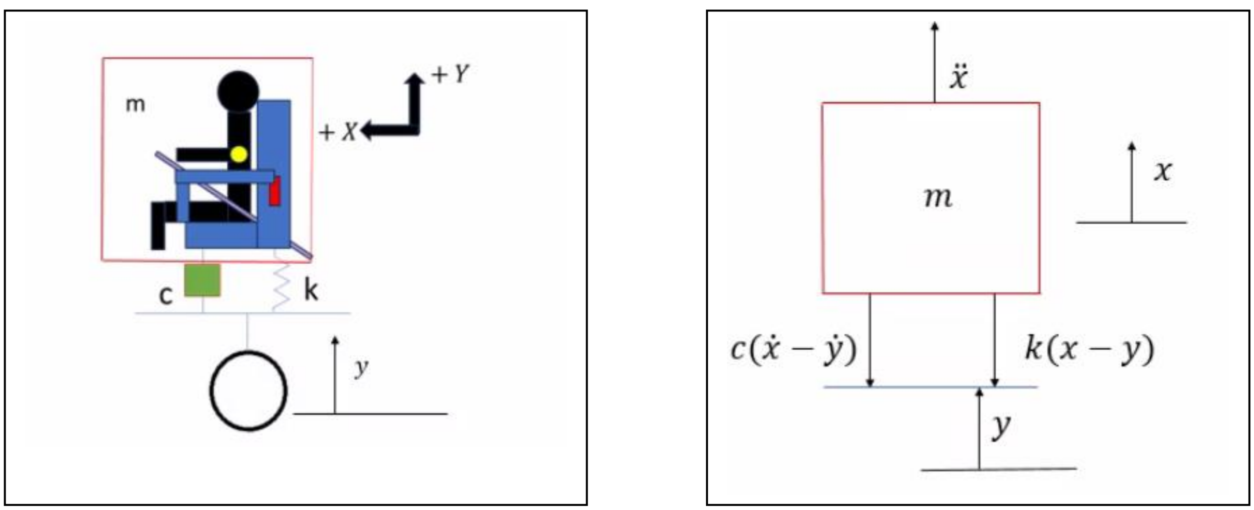


Figure 58. The Image to the Left is a Representation of the Single Degree of Freedom Model. The Second Image to the Right is the Free-Body Diagram of the Model. Y is the excitation from the Road Causing and acceleration of the Concentrated Mass (user and upper frame). On the Other End, the Resistance from the Damper and the Spring are Counteracting the Excitation from the Road.

Using Newton's second law:

$$\sum F = m\vec{a}$$

$$-F_d - F_s = m\ddot{x} \tag{24}$$

$$-k(x-y) - c(\dot{x}-\dot{y}) = m\ddot{x}$$

$$m\ddot{x} + c\dot{x} + kx = \ ky + c\dot{y}$$

By rearranging the differential equation (20), we can derive the standard form:

$$\ddot{x} + \frac{c}{m}\dot{x} + \frac{k}{m}x = \frac{k}{m}y + \frac{c}{m}\dot{y}$$ (Here we divide both sides by the mass m)

$$\ddot{x} + 2\zeta\omega_n\dot{x} + \omega_n^2 x = u$$

We are able to find:

The natural frequency:

$$\omega_n = \sqrt{\frac{k}{m}} \tag{25}$$

$$\omega_n = \sqrt{\frac{7200\ lbs/ft}{\frac{230\ lbs}{32.2\ ft/s^2}}}$$

$$\omega_n = 31.75\frac{rad}{s} = 5.053\ Hertz$$

The period of oscillation:

$$T = \frac{1}{\omega_n} \tag{26}$$

$$T = \ \frac{1}{5.053 Hertz}$$

$$T = 0.1979\ s$$

The damping constant:

$$c = \ 2m\zeta\omega_n \tag{27}$$

$$c = 2 \times \frac{230lbs}{\frac{32.2lbs}{1slug}} \times 0.321 \times 31.75\ \frac{rad}{s}$$

$$c = 145.6\ slugs.\frac{rad}{s}$$

MATLAB Code for Step Response

```
t = (0:0.01:3);
Sys1 = tf([1],[230/32.2 23.17 600*12])
[y1,T1] = impulse(Sys1,t)
Sys2 = tf([1],[230/32.2 23.17 600*12])
[y1,T1] = step(Sys2,t)
step(Sys2,t)
```

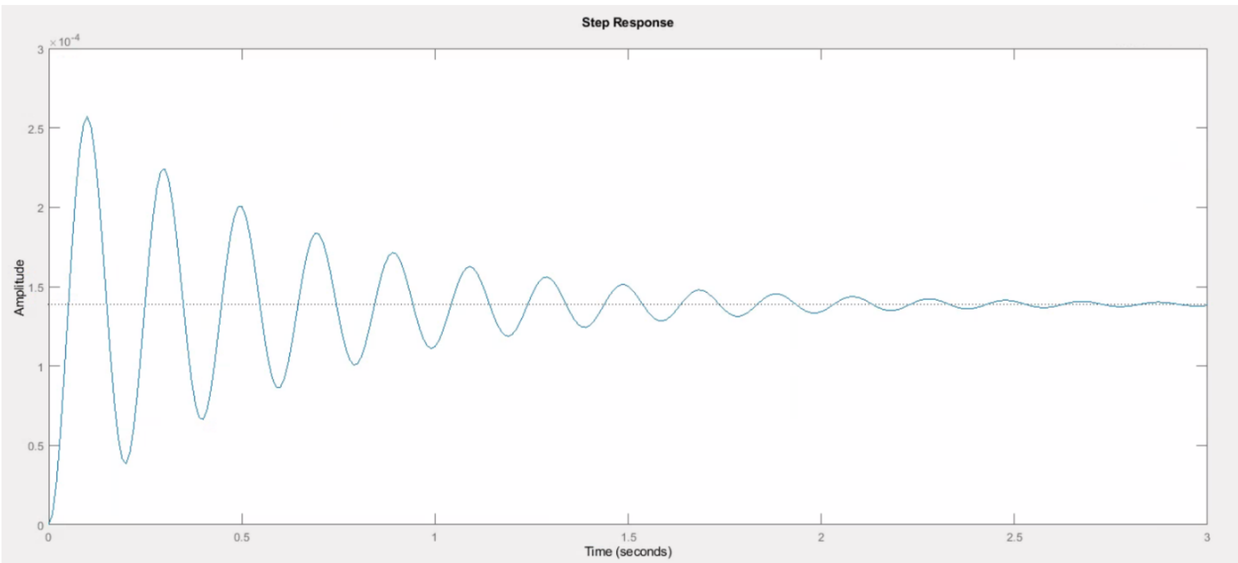


Figure 58. Step Response Plot

Time to dissipation:

$$T_{total} = T \times n \tag{28}$$

It took around 0.8 seconds for the oscillations to dissipate while testing the suspension.Using the 0.8 second obtained experimentally. This can be seen in our graph on figure 54. Here we use Matlab to verify that time Period.

$$T_{total} = 0.1979\ s \times 4$$

$$T_{total} = 0.7916\ s$$

T_{total} is the time to dissipation obtained from the MatLab Code.

APPENDIX H: Anthropometric Data Used

Table 8. Body Weight Percentage Chart ***[7]***

Segment	Males	Females	Average
Head	8.26	8.2	8.23
Whole Trunk	55.1	53.2	54.15
Thorax	20.1	17.02	18.56
Abdomen	13.06	12.24	12.65
Pelvis	13.66	15.96	14.81
Total Arm	5.7	4.97	5.335
Upper Arm	3.25	2.9	3.075
Forearm	1.87	1.57	1.72
Hand	0.65	0.5	0.575
Forearm & Hand	2.52	2.07	2.295
Total Leg	16.68	18.43	17.555
Thigh	10.5	11.75	11.125
Leg	4.75	5.35	5.05
Foot	1.43	1.33	1.38
Leg & Foot	6.18	6.68	6.43

Appendix I: Failure Modes and Analysis (FMEA)

Item	Failure Modes	Cause of Failure	Possible Effects	Prob.	Level	Possible action to reduce failure rate or effects
Tires	• Rupture • Disengage	• Faulty sizing • Over pressurization • Damage from transportation	Blowout/ destruction of tire	Medium	Critical	Inspection and checking of pressure. Inspection of sizing of tire and rim.
Gears	• Slipping • Seizing • Rupture	• Incorrect gear sizing • Incorrect gear ratio • Faulty material	Mechanism failure	Low	Non-critical	Review in design and construction of mechanism. Review material selection.
Frame	• Buckling • Fracturing	• Over loading • Defective material • Damage from transportation or handling • Stress concentrations	• Harm to operator • Wheelchair immobilized	Low	Critical	Intense review of design, construction, material selection, and quality after transportation.
Seat	• Fracturing • Buckling	• Stress concentrations • Defective material • Overloading	Harm to the operator	Low	Critical	Intense review of design, construction, material selection, and quality after transportation.
Lever	• Stiffness • Fracturing	• Incorrect gear ratios • Defective material • Overloading	• Mechanism failure • Harm to the operator	Low	Non-critical	Review in design and construction of mechanism. Review material selection.

Item	Failure Modes	Cause of Failure	Possible Effects	Prob.	Level	Possible action to reduce failure rate or effects
Solid Works	• Bad Design • Corrupted Files	• Incorrect use of software • Computer/software issues	Incorrect analysis on the sketches	Medium	Critical	Inspection and updates to the design in Solid Works. Keep up to date back up files saved as much as possible.
Schedule Conflict	Completed items due dates are not met	Miscommunication between the team	Design not completed	Low	Critical	Add margins to project schedule. Keep communication and participation up within the team.
Calculations and/or Simulations	Faulty Design	Incorrect Calculations or data used for calculations and simulations	Design fails or is not completed	Medium	Critical	Intense review of calculations and simulations. Check with hand calculations.
Prototype (if applicable)	Components don't fit together	Incorrect part tolerances	Prototype not completed	Low	Critical	Intense review of design, construction, material selection, and quality of parts.
3D printed parts (if applicable)	Printed part fails	• Incorrect filament type • Incorrect sizing	• Part failure • Incomplete construction	Low	Non-critical	Review material selection and review print code.