Design and Evaluation of a Propulsion Aid Device for Folding Wheelchairs

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Abstract

Upper-body injuries caused by overuse from manual wheelchair propulsion is a common challenge that many wheelchair users face. While there are propulsion aid devices on the market, these devices are often expensive, increase the footprint of the wheelchair, or do not provide the necessary requirements for physical movement and accessibility. Our team sought to create a propulsion aid that would address these issues by improving ease of use, enhancing maneuverability, and engaging in sustainable prototyping processes. The final result is a functioning prototype of a tiller-controlled device and attachment system for folding wheelchairs that not only fulfills these requirements but meets all necessary ADA and engineering standards for this category of medical device.

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1.0 Introduction

Wheelchair users make up 15% of Americans, and of those users, 11% manually propel their wheelchairs [1]. The repetitive motion of propelling a wheelchair, as well as the unnatural position that this motion puts the user in, can easily lead to shoulder and wrist injuries for many. For these users, a propulsion aid device is often the best option to avoid these injuries, however, the high cost of these devices and design limitations can detract from the benefits.

Without aid from insurance, propulsion aid prices range from $1,100 to above $8,000, which can create a financial barrier to access of these devices [2], [3]. Additionally, this limitation is not entirely mitigated by insurance. In order to be eligible for a propulsion aid covered by Medicare, a patient must have been using a manually propelled wheelchair for at least one year and display a need for the device. If coverage is provided, it is restricted to push-rim activated propulsion aids devices which may not meet all of the users accessibility needs [4].

The covered push-rim activated devices typically include a rear powered wheel, as do joy-stick controlled propulsion aids. These rear-wheel devices typically exhibit inferior obstacle traversal due to the wheel placement and inherent lack of traction. On the other hand, front-wheel devices, which are typically tiller controlled, provide better traction and obstacle traversal, but the powered wheel is typically mounted in front of the footplates leading to an increased turn radius and the inability to approach tables, cabinets, and other surfaces. The only popular tiller controlled device on the market which has the option to place the power wheel behind the foot plates is the UNAwheel; however, this UNAwheel configuration requires a high level of trunk control for the user to attach the device, which limits the number of people who are able to benefit from such a device. Additionally with the global issues that this world is facing it is critical that sustainable principles were at the forefront of the design process. Leading the team to use primarily recycled and repurposed materials throughout the design and prototyping process.

The team set out to design and prototype a device that would address these issues by improving the ease of use, enhancing maneuverability, and utilizing sustainable prototyping. Through collaboration with a local wheelchair innovation expert, Charles Croteau, the project began with pre-existing proof of concept of a tiller controlled propulsion device which consisted of an electric scooter and a Quickie 2 folding wheelchair. After conducting interviews with two manual wheelchair users and continued conversations with Mr. Croteau, the team created the foundational goals of the project to address the client needs and reevaluated each classification of propulsion aid device based on these requirements. The conversations verified that a tiller-control device would best fit these needs, and the following client statement was derived to guide the project. The goal of this project was to design and build a user and budget friendly, tiller controlled wheelchair propulsion device placed in line with the caster wheels for the aid of folding wheelchair users while using sustainable prototyping and production methods. In general, this design should:

- Decrease the amount of effort the user must exert to propel themselves in their wheelchair.
- Allow for better maneuverability and ease of use for a lower cost than what is currently on the market for wheelchair propulsion aid devices.
- Include the use of sustainable prototyping methods and materials evaluated based on research of the environmental significance of manufacturing and prototyping product waste.

The design requirements and constraints were then created to ensure that these goals would be reached. The requirements addressed the weight requirements of the device, improving the ease of use and increasing the maneuverability compared to similar devices on the market, and the material selection as part of improving sustainability, performance, and cost. The constraints were set to ensure that the design requirements were met, and that the device would meet the Americans with Disabilities Act compliance.

Through brainstorming, the use of Pugh matrices, and design iterations, the team was able to select the optimal design for the device. It would consist of a crossbar installed on the frame of the wheelchair and utilize a gate latch style design for attaching the power-column of the electric scooter to the wheelchair. Over the course of several months, this design was verified using rapid prototyping processes and finite element analysis, then manufactured through the use of CNC milling, water jet cutting, 3D printing, and welding. The resulting prototype was then tested to check compliance against the design requirements. The final product is a functioning prototype of a tiller controlled device and attachment system for folding wheelchairs that not only fulfilled the primary requirements but met all necessary ADA and engineering standards for this category of medical device.

2.0 Background

2.1 The Mechanics of a Manual Wheelchair

The ADA defines a wheelchair as "a manually-operated or power-driven device designed primarily for use by an individual with a mobility disability for the main purpose of indoor or of both indoor and outdoor locomotion" [4]. It is estimated that over 2.7 million people in the United States use wheelchairs as their primary means of mobility [5]. Wheelchairs allow for an increase in mobility and thus can greatly contribute to the user's independence.

Propulsion is one of the most important needs when operating a wheelchair and, for most manual wheelchair users, using the upper extremities is the main method for operating and maneuvering a wheelchair [6]. This form of propulsion occurs in two phases: the push phase and the recovery phase. The push phase happens when the hand uses the push-rim, denoted in Fig. 1, and pushes the wheel down allowing the wheelchair to roll forward. The recovery phase is the period where the user's hands disengage from the rims and go back to the starting position, ultimately repeating this cycle [6]. Over time, these actions can become strenuous and tiring for the user which can lead to overuse of the upper extremities and thus injuries to their shoulders and wrists.

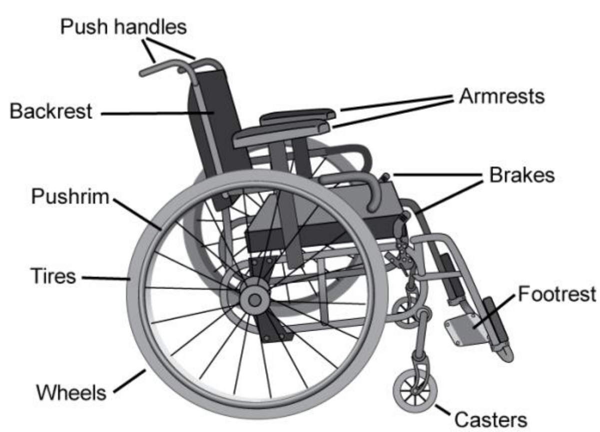

Fig. 1. Depiction of a typical manual wheelchair [7].

Upper body strain is merely one aspect of wheelchair mechanics that may lead to injury. Around 70% of wheelchair-related injuries are due to tipping and falling out of one's chair, with a majority due to extreme conditions including inclines above ADA standards, 7.125 degrees, and curbs or inclement weather [8]. A chair will tip when the forces and the moments acting on the chair become unbalanced. More specifically, in a situation where the wheels on the chair are unlocked, this occurs when the center of gravity of the user and the chair combined becomes positioned behind the rear axle, which is illustrated in Fig. 2 [9]. Fracture lacerations and contusions tend to be the most common injuries among wheelchair users often on the user's head, neck, trunk, wrists, or hands [8]. This tipping effect poses a great risk to the user, especially if the user often frequents uneven terrain, steep inclines, curbs, or when transitioning into the chair [10]. As a result of the danger of wheelchair tipping, it is important to consider the force distribution in the wheelchair when designing and analyzing any sort of attachment that may influence these forces.

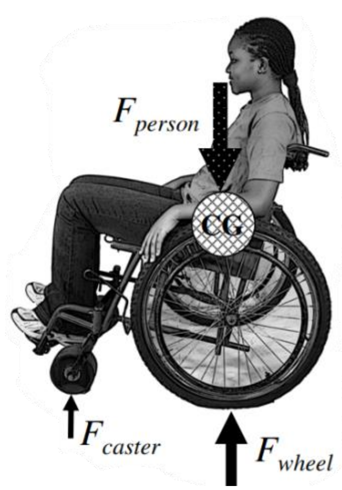

Fig. 2. Center of gravity of a person in a wheelchair [9].

2.2 Market Review

2.2.1 Review of Usability of Common Propulsion Aids

Power assist devices provide manual wheelchair users with a method for eased propulsion of their chair, ultimately allowing for a decrease in shoulder and wrist injuries, quicker means of travel, and general mobility improvement. These power assist devices are broken up into three primary categories based on Healthcare Common Procedure Coding System definitions: push-rim activated, joystick control, and till control [11]. Under each of these categories, there are several devices on the market that address the needs of wheelchair users in different ways, providing each design with its own strengths and weaknesses. Reviewing pre-existing wheelchair power assist devices was integral in creating a foundation for the design and understanding of the customer needs.

2.2.1.1 Push-Rim Activated Power Assist Devices

Push-rim activated power assist devices work by using special wheels, or an attachment to the pre-existing wheels of the chair, that can determine the force that a user places on the wheels to exert the needed propulsion or braking assist. For this type of device, steering a wheelchair is a familiar motion for the user as it is done through using their hands to manipulate the push-rims. One of the most common push-rim activated systems is SmartDrive shown in Fig. 3. The main component of the SmartDrive system is a motorized wheel that attaches to the back of a manual wheelchair. This wheel is controlled by a speed-control dial placed towards the front of the chair within the user's reach. Once attached, the user is able to set their desired speed and operate their chair as normal, but with more ease due to the propulsion provided by the motorized wheel. Additionally, this device is relatively lightweight, weighing approximately 12.5 pounds, and is compact in size making it fairly easy to travel with, store, or lift [12].

Fig. 3. Rear view of a chair with the SmartDrive attached [13].

There are some drawbacks to this system as well that should be considered when selecting a device or designing a new one. When looking at this design and ones like it, rear-wheel power systems can have difficulty traversing surfaces or obstacles compared to front or mid-wheel power systems [14]. With this system being fixed to the back of the wheelchair and underneath the seat, reaching the attachment while operating the chair can be difficult for some users, making it challenging to monitor the system and adjust it when the user is faced with obstacles in their path. Additionally, the placement in the rear of the chair can make it difficult for the user to attach or detach on their own, depending on their physical abilities. Finally, if the user finds it difficult to steer their chair using the push-rims, this type of power-assist may not fully address their needs.

2.2.1.2 Joystick Controlled Power Assist Devices

Joystick controlled power assist devices attach to manual wheelchairs and allow for manual wheelchairs to function like a fully powered chair. There are several different attachment methods for joystick control integration with manual wheelchairs, but in general, they add additional powered wheels to the chair and a control system on the armrest of the chair that houses inputs for speed and direction.

The Alber e-fix, depicted in Fig. 4, replaces the standard wheels on a manual chair with an e-fix drive wheel that connects to the battery and control unit. The end result is a fully powered chair that may be used manually if the user chooses to uncouple the wheels from the control unit. The joystick control also provides ease of use for wheelchair users with a wide range of physical abilities and a simple to operate control panel. Each step of the attachment can be done without tools, and the individual components are compact for storage.

Fig. 4. Side view of a wheelchair with the Alber e-fix system installed [2].

Despite the ease of installation and use, and the compact dimensions of the components, there are aspects of the device that may negatively impact a user's experience. The overall weight of the system is at least 42 pounds for the standard model, and up to 72 pounds for the Alber Eco model. Adding weight to the chair has the potential to make traveling with the chair more difficult [2].

A similar power assist, the Spinergy ZX-1 Power Add-On, shown in Fig. 5, uses a motorized rear-drive system that is connected to a joystick control system. The user attaches their manual wheelchair to it by backing their chair over the attachment system which then locks onto the chair automatically, which is an easy attachment method as it requires manual wheelchair motions that the user is familiar with. The joystick, similar to the Alber e-fix, provides a method of steering that users with varying physical abilities would find easy to operate. While this system is easy to operate, its large size, 27" x 26" x 21", and weight, 75 or 84 pounds depending on the battery option, may make it difficult for many to travel with [15]. Additionally, similar to the push-rim power aids, rear-wheel power can be more difficult to use when traversing over obstacles [14].

Fig. 5. Side view of a wheelchair with the Spinergy ZX1 installed [15].

2.2.1.3 Tiller Controlled Power Assist Devices

Tiller controlled power assist devices attach primarily to the front end of manual wheelchairs and are powered using a form of a lever to control the orientation of a motorized wheel. Many of these devices resemble electric scooters in terms of both form and function and are common in the power-device market.

The EZRide power assist, shown in Fig. 6, is representative of a typical tiller control power assist found on the market. The power column of the device connects to an additional crossbar which attaches directly to the manual wheelchair. Once attached, the motorized wheel sits in front of the footrests and caster wheels of the chair. The design of the EZRide makes the end product easy to steer for the target users, and the front-wheel drive makes the attachment ideal for using the wheelchair to traverse obstacles [3]. The placement of the wheel, however, leaves the user needing to reach far out in front of themselves in order to control the steering. The placement also increases the footprint of the chair, and thus the turn radius, meaning it would be more difficult to use in tight spaces or to reach surfaces in front of the user such as tables or counters with the device attached.

Fig. 6. Image of the EZRide power assist in use [3].

A similar device is the UNAwheel Mini which is depicted in Fig. 7. The device works similarly to the EZRide, but is a smaller, more compact design increasing ease of traveling with the device and usability. This design has an attachment option which places the drive wheel behind the user's feet, which is much closer to the front casters than the EZRide [16]. This difference means that the UNAwheel Mini can be used in tighter spaces than the EZRide or similar devices and can also allow the user to approach counters and tables with minimal issues; however, the device would need to be removed for a user to fully sit under a desk.

Fig. 7. The UNAwheel Mini placed behind the footrests of a wheelchair [16].

The primary drawback in the UNAwheel design is the mechanics for attaching the device in this placement option. In order to allow for proper traction between the front drive wheel and the ground, the front caster wheels must be lifted slightly for more weight to fall on the drive wheel. To attach the device, the user must lean far forward, placing the device at a low angle to the ground, connect the power column to an added crossbar, then lean back and pull the power column towards themself. This angle of the device and the leaning the user must do for attachment can be seen in Fig. 8 [17]. Given that some manual wheelchair users have limited trunk control, this motion for attaching the mechanism could limit potential wheelchair users from benefiting from this device.

Fig. 8. Person demonstrating the attachment for the UNAwheel [17].

2.2.2 Product Price Points and Economic Implications

Insurance coverage and the price points of wheelchair propulsion aids play a large factor in whether the devices are accessible by the intended market. Under Medicare, the only classification of power assist devices that may be covered are push-rim activated. Additionally, in order to receive coverage for this device, the beneficiary must use a self-propelling wheelchair for at least one year and have the device deemed necessary by a licensed medical professional [18]. The limitations on this coverage mean there is a potential financial barrier to users seeking a propulsion aid device, should push-rim devices not meet their mobility needs or if they have been using a manual wheelchair for less than one year. TABLE I details the costs of the previously discussed propulsion aids on the market.

TABLE I

SUMMARY OF ASSOCIATED COSTS TO REVIEWED PROPULSION AIDS

Ref.	Product	Classification	Covered by Medicare	Upfront Cost
[12]	SmartDrive	Push-rim activated	Yes	$6,600
[2]	e-fix	Joystick controlled	No	$8,275
[15]	Spinergy ZX-1	Joystick controlled	No	$7,995
[3]	EZRide	Tiller controlled	No	$1,099 - 2,899
[16]	UNAwheel	Tiller controlled	No	$2,900

From the table, it can be seen that a major benefit of the SmartDrive system is that it may be covered by the user’s insurance providing an accessible means of obtaining the device. Without taking insurance coverage into account, tiller controlled systems are significantly cheaper than other categories of propulsion aids, meaning they may be the best option for those who do not mean qualifications for coverage or require a form of propulsion assist that does not require manipulation of the push-rims.

2.3 Environmental Consideration

In modern society, material waste is a significant downfall in manufacturing, as scrap material often ends in a landfill as opposed to being recycled. Often, the production and refinement of these materials are energy intensive, contributing to the large carbon footprint of manufacturing. Additionally, these are finite materials in which today's society is heavily reliant on using; however, nonferrous metals such as steel and aluminum are infinitely recyclable materials, meaning they can be recycled indefinitely without losing strength or integrity. Unfortunately, statistics show that only 30% of global steel is produced using recycled content which leaves the remaining product to be wasted. This remaining material occupies landfill space, pollutes the air, water, and soil, and can negatively affect human health [19].

2.3.1 Primary Process for Metal Recycling

There are three means of recycling nonferrous metals, all of which work to extract liquid and solid mixtures so that they may be purified for reuse: electrowinning, precipitation, and metal sensors. Once the materials have been properly separated, reformed, and refined the materials can get modeled into stock and shaped into its next practical use [19].

2.3.1.1 Electrowinning

Electrowinning is the process that uses electricity to extract the dissolved metals. To accomplish this extraction, solid waste from landfills or other waste mixtures is combined and placed into a liquid solution. The waste then dissolves into the liquid producing a leach solution. Electric currents then pass through electrodes that are submerged into the leach solution, which causes a thin chemically reduced layer of nonferrous materials to separate from the rest of the waste and rise to the top of the liquid. This material may then be easily extracted and removed [20].

2.3.1.2 Chemical Precipitation

Chemical precipitation is one of the most affordable applications of metal recovery. For this application, the waste starts in an aqueous state and then the pH of the solution is adjusted so that the dissolved metals ions can be converted into a solid phase. Hydroxide and sulfide precipitation are the most common methods, but there are many compounds which may be appropriate for use with particular metals. This practice is applicable primarily to heavy metals such as iron, lead, and copper. Although steel alloy is a ferrous metal, its primary component is iron making this method applicable to its recycling process [21].

2.3.1.3 Metal Sensors

The last major method of nonferrous metal recycling is known as metal sensors. Metal sensors are a relatively new method of sorting and extracting metals that uses sink-float gravimetric treatments or manual methods. This treatment is done by determining each material's atomic density and paring that density to the proper material in the tank. This process then allows the material to be properly separated from the mix of metals it is combined with in the tank and reformed into a refinable state of like materials [19].

2.1.1 Material Choice Analysis

When looking into creating a sustainable device for wheelchair users, material had to be factored into the chosen design. In order to ensure the final materials used in the design met both the mechanical and sustainable requirements, a material analysis was conducted for all manufactured components. Research was conducted on different materials and their properties looking at recyclability, the energy required to create the stock, machinability, cost, and the ability to meet the structural requirements set for the component. The primary materials considered for these manufactured components were aluminum, low carbon steel, and low alloy steel.

2.1.1.1 Aluminum

Aluminum is one of the most plentiful nonferrous metals and is commonly used in engineering practices. The material is low cost, lightweight, durable, corrosion-resistant, and conductive. In terms of producing usable aluminum from the raw material, the smelting process used is energy intensive. This process converts bauxite to anhydrous alumina using the Heroult process. This process for the primary production of aluminum consumes 47 megajoules per kilogram of energy whereas secondary production only consumes 2.40 megajoules per kilogram of energy. Creating a stock state of recycled aluminum only emits 5% of the greenhouse gas that is used in the original refinement of the material. With recent technological developments, one ton of recycled aluminum can save up to 14000 kilowatt-hours of energy, 7.6 cubic meters of a landfill, and an average exhaust emission of 350 kilograms of $C0_2$. The process of aluminum recycling with one of the three aforementioned methods, is described in the flow diagram depicted in Fig. 9 [19].

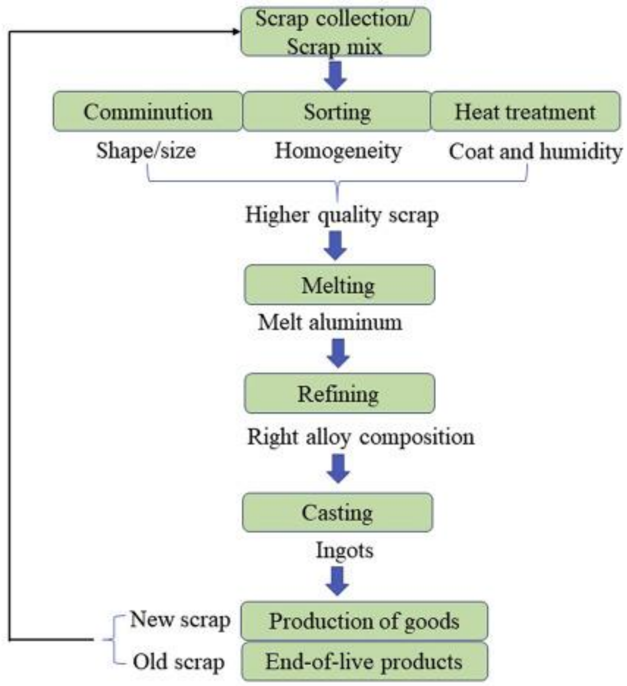

Fig. 9. Flow diagram of aluminum recycling processes [19].

2.1.1.2 Low Carbon Steel

Low carbon steel, or mild steel, is the most common form of steel as it is economically affordable, contains 0.05-0.25% carbon making it malleable and ductile, has a low tensile strength, and is easy to form and machine with the proper tools [22]. Steel production is responsible for over 1.9 gigatons of CO_2 emission annually. Steel is generally made from extracting iron ores from mines or from remelting steel scraps creating second life pieces. When recycling steel two primary methods may be used: iron; the main component of steel could be reused and extracted for a second life in the precipitation processes explained in 2.3.1.2 Chemical Precipitation and mixed with the remaining elements in the steel. Alternatively, given steel's highly magnetic properties, steel can be easily extracted from mix metal waste streams and be combined and remelted into larger stock. Using secondarily sourced steel scraps uses 5-7 gigajoules of energy and emits 0.1 tons of carbon dioxide when creating 1 ton of crude steel. When using primary sources iron ores 18-22 gigajoules of energy are used, emitting 1.0-2.0 tons of carbon dioxide when creating the same 1 tons of crude steel. Unfortunately, it is estimated that 85-90% of steel scraps have already been extracted and are being produced into new steel. With the current consumption patterns, it is estimated that by 2050 second life steel production will only account for 44% of global steel production [23]. As seen in Fig. 10 below, this increased secondary production but does not slow the demand of primary production, ultimately showing that although carbon steel production is making great strides to being more sustainable, as of now a lot of work still needs to be done so that the material production can be more energy efficient.

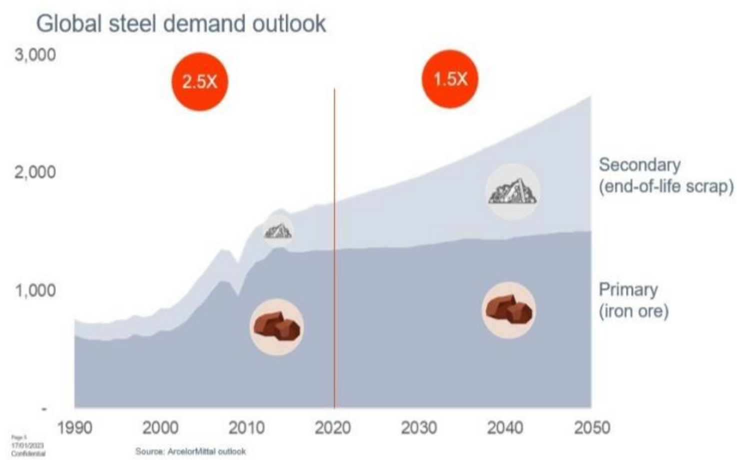

Fig. 10. Global steel demand outlook to 2050 [23].

2.1.1.3 Low-Alloyed Steel

Low alloy steels are ferrous metals that are similar to carbon steels, but benefit from adding elements like nickel, chromium, molybdenum, manganese, or silicon increasing the hardenability and material toughness after heat treatment. Comparatively to carbon steel, the added alloys can reduce impacts from environmental degradation, strengthening the metal. The analysis for low alloyed steel is similar to that of low carbon steel, where steel is 100% recyclable by the conversion of scraps into any grade of steel based on the metallurgical processes involved. Often, low alloy steel is chosen to be produced through primary steel production as it is cost-effective and easier than secondary production, as the amount of alloyed material may be unknown in secondary production. The primary limiting factors with recycling steel are the lack of recycled stock and the added risk of imprecise quantities of alloying elements negatively impacting the grade and mechanical properties of the steel [24].

2.1.1.4 Final Material Selection

Based on the presented data, it was determined that for the optimal environmental considerations and manufacturing successes, aluminum should be used for any custom components for the device. Aluminum does not lose quality or durability in second life production and additionally there is no added risk of increasing the risk of imperfections. As aluminum is a natural element whereas steel is a compound, mistakes in the second life production do not change the metals composition affecting the materials appeal. The recycling methods for the material remain relatively simple and the variety of recycling processes that may be used allow for a greater variety of needs to be met increasing the ability for the material to be recycled. As previously mentioned, using recycled material is consistently more energy and carbon efficient in production, showing that virgin production increases the environmental risk associated with resource production compared to the recycling process. While using recycled materials is the ideal choice from a sustainability standpoint, it should be noted that in some instances there is a wider range in properties of the stock material due to the increased risk of unwanted alloying elements; however, recycled metals are tested and held to a high standard and are sufficient for a wide range of engineering applications. As with any material, it is important that safety factors accommodate for this wider range of possible properties, to ensure the safety of the user remains a priority.

3.0 Project Strategy

To begin the project, it was crucial to lay out explicit needs and goals so that the design of the device would be guided, and its success could be evaluated.

3.1 Initial Client Statement

The goal of this project was to design and build a user and budget friendly, wheelchair propulsion device for the aid of folding wheelchair users while utilizing sustainable prototyping and production methods. In general, this design should:

- Decrease the amount of effort the user must exert to propel themselves in their wheelchair.
- Allow for better maneuverability and ease of use for a lower cost than what is currently on the market for wheelchair propulsion aid devices.
- Include the use of sustainable prototyping methods and materials evaluated based on research of the environmental significance of manufacturing and prototyping product waste.

This device should be designed with a wide variety of ability levels in mind to broaden the potential market for it as well as help a larger number of people. This range includes users with varying levels of trunk control, hand mobility, and upper extremity strength.

3.2 Revised Client Statement

It was evident that the original client statement was too broad to derive accurate and helpful design requirements from; therefore, it was important for the device placement and classification to be decided. As covered in 2.2 Market Review, there are three distinct categories for propulsion aids: push-rim activated, joystick controlled, and tiller controlled. As stated in 1.0 Introduction, Mr. Croteau had created a rough proof of concept of a tiller control system which placed the wheel of the propulsion aid behind the user’s feet to reduce the area needed to turn, but it was important to explore all potential designs for a propulsion aid to find which would best meet the needs in the original goal statement. In order to narrow down the client statement and create clear goals for the project, interviews with manual wheelchair users were conducted to gain more insight on the requirements of a propulsion aid device.

3.2.1 Interviews

After receiving IRB approval, two wheelchair users were interviewed in addition to the continued conversations with Mr. Croteau. The interviews were focused on understanding these users' experiences with manual wheelchairs as well as power assist devices, which can be seen by the questions asked in Appendix A. One of the key takeaways from these conversations was that rear-wheel devices that are on the market are difficult to use in outdoor terrain and wear-down quite frequently; however, from both background research and conversations with Mr. Croteau, it was noted that front wheel devices are better at traversing varied terrain due to their ability to pull the chair over the obstacles from the increased traction they provide. More weight is put on the powered wheel of the front-wheel devices than the powered wheel of the rear-wheel devices which allows for more traction. This increased traction is due to the fact that when using the rear-wheel devices, all four wheels of the wheelchair itself remain on the ground as well as the device’s wheel, so the weight is distributed to five wheels; however, in front-wheel devices, the caster wheels of the wheelchair are lifted off of the ground during attachment, so the weight is distributed between three wheels.

Mr. Croteau also shared his negative feedback on the front wheel devices that are already on the market. These issues primarily stem from the placement of the wheel, as many place the device in front of the caster wheels and footplates which increases the overall footprint of the wheelchair. This not only makes moving in tight spaces more difficult, but often leads to the handlebars of the tiller controlled devices sitting far from the user, leading to potential arm and back strain due to the user having to reach far forward. Further details on the findings from the interviews may be found in Appendix B.

3.2.2 Analysis of Device Placement and Control

To decide on the best device placement and control, a pros and cons analysis was conducted to compare the different options. TABLE II shows the comparison between tiller controlled devices in line with the caster wheels, tiller controlled devices in front of the caster wheels, joystick controlled devices under the chair, and push-rim activated devices under the chair. Details from the original client statement, initial research, and user interviews were used to inform the analysis. Ultimately, it was found that a tiller controlled device placed in line with caster wheels would be the best option to meet the initial goals.

TABLE II

EVALUATION OF PROPULSION AID TYPES AND PLACEMENT

Device Placement	Pros	Cons
Tiller Controlled, In Line with Caster Wheels	● User can approach counters and tables ● Reduced footprint compared to tiller controlled devices in front of the caster wheels ● Reduced turn radius ● Increased traction for traversing obstacles ● Easy to monitor device attachment ● Cheaper than joystick and push-rim activated options	● Possibility for reduced stability ● User cannot sit under desks and tables with the device attached
Tiller Controlled, In Front of Caster Wheels	● Increased stability compared to tiller controlled devices in line with the caster wheels ● Increased traction for traversing obstacles ● Cheaper than joystick and push-rim activated options	● Users cannot approach counters and tables ● Users cannot sit under desks and tables with the device attached
Joystick Controlled, Under Chair	● Intuitive controls ● Accommodates for a wide range of user physical ability ● User can approach counters and tables ● In some instances user may sit under desks and tables with the device attached	● Expensive ● Complicated electronics
Push-Rim Activated, Under Chair	● Steering done with manual wheels which is familiar to users ● User can approach counters and tables ● User may sit under desks and tables with the device attached	● Traversing obstacles and rough terrain can be difficult ● System is behind user limiting the user’s visibility of the device

3.2.3 Revised Client Statement

From this analysis, the client statement was modified to provide a narrowed goal for the project as follows:

The goal of this project was to design and build a user and budget friendly, front wheeled tiller controlled wheelchair propulsion device placed in line with the caster wheels for the aid of folding wheelchair users while using sustainable prototyping and production methods. In general, this design should:

- Decrease the amount of effort the user must exert to propel themselves in their wheelchair.
- Allow for better maneuverability and ease of use for a lower cost than what is currently on the market for wheelchair propulsion aid devices.
- Include the use of sustainable prototyping methods and materials evaluated based on research of the environmental significance of manufacturing and prototyping product waste.

This device should be designed with a wide variety of ability levels in mind to broaden the potential market for it as well as help a larger number of people. This range includes users with varying levels of trunk control, hand mobility, and upper extremity strength.

3.2 Technical Design Requirements

The overall design requirements were detailed in the client statement, and based upon these, explicit design goals and constraints were developed to ensure these overall requirements were reached.

3.2.1 Goals

Upon conducting research, interviewing manual wheelchair users, and talking with subject matter expert Mr. Croteau, the following goals were developed.

3.2.1.1 Weight Requirement

The wheelchair that was provided for the project helped to set the weight limit of the device. The Quickie 2 Wheelchair, which has a weight limit of 250 pounds [25]. This weight was used to carry out the design verification calculations as well as simulations to find the factor of safety of the designed device.

3.2.1.2 Ease of Use

As this device is meant for use by people with a large range of abilities, it had to be designed to be generally easy to use with intuitive operations. Our goal was for this product to be usable for people with limited trunk control, hand mobility, and overall upper extremity strength which ultimately restricts the design of the components that users would directly interact with.

3.2.1.3 Maneuverability

When researching other tiller controlled devices, low maneuverability was prevalent due to the position of the device as previously discussed. The device had to be placed in line with the caster wheels to allow the user to approach tables, counters, or other objects and to decrease the turn radius compared to other tiller controlled devices.

3.2.1.4 Material Selection

Upon researching different sustainable methods to create the device it was determined that recycled or retired materials and standard pieces would be primarily used in prototyping. Aluminum was selected as the material for the final prototype because it is 100% recyclable, monetarily inexpensive, strong, and easy to obtain and machine.

3.2.2 Constraints

From conversations during interviews and market research the following design constraints were set.

- The main purpose of this device is to allow for more accessibility for the user. In order to optimize accessibility, the chair as well as the device must be able to be transported alongside each other by use of an average car. The constraint to address this need is that both the chair and device must be able to fit in a sedan trunk at the same time.
- To provide means for accessible transportation, the device must be able to attach and detach with only what is provided by the device for the chair to fold. Therefore, any pieces that inhibit the chair from folding must be able to be removed or altered without the use of tools.
- To provide means for accessible transportation, the device must not be so heavy as to inhibit users from manipulating the device when it is not attached to the wheelchair. The wheelchair itself weighs 28.6 pounds and users are assumed to be able to move this by themselves; therefore, the propulsion aid device could not weigh more than this weight [25].
- With this being a wheelchair device and designed for people with disabilities, it had to meet the Americans with Disabilities Act (ADA) compliance for operating conditions. These standards include the minimum turn radius and the minimum incline angle the device must be able to operate.
- The attachment and detachment mechanism had to meet ADA compliance for required hand strength for operation.
- As the goal of this project was to design a device that is more accessible than the devices

already on the market, this design had to have a better attachment angle than similar devices. The device that is most similar to what this device would be in terms of position is the UNAwheel, which, as can seen in Figure 8, causes the user to lean forward to attach the device, which some users may find difficult. The angle of the device is estimated to be about 30 degrees with the ground; thus, this design must have a greater angle of attachment from the ground.

- The device had to meet the Engineers' Toolbox standard for the factor of safety for the material type and conditions it would be experiencing.

3.2.3 Standards

The following standards expand upon the previously detailed design constraints for the propulsion aid device.

3.2.3.1 Turn Radius

According to the 2010 ADA compliance standards, Section 304, the turning space for a circular area must be 60 inches [26]; therefore, the user must be able to turn 360 degrees in a 60 inch circle while using the device.

3.2.3.2 Ramp Angle

According to the ADA standards, Section 405, an accessibility ramp must have a slope ratio of no more than 1:8 [26]. This means that its incline can be no more than 7.125°. Also, the maximum rise is 30 inches meaning that the maximum distance to travel up a ramp can be no more than 241.87 inches or roughly 20 feet. As a result, the device must be capable of driving the chair up and down a ramp of this incline.

3.2.3.3 Force to Open

According to the ADA standards, Section 309, any operable parts must be able to be opened using no more than 5 pounds [26]. Therefore, the maximum force that may be required for operation of the attachment mechanism must follow this standard.

3.2.3.4 Factor of Safety

Engineering Toolbox defines standards for factors of safety dependent on the materials used and the loading conditions of a device. This device fell under the category of "For use with less tried and for brittle materials where loading and environmental conditions are not severe," and therefore, its factor of safety had to be in the range of 2.5 to 3 [27].

3.4 Management Approach

Prior to each working term, a Gantt chart was created to outline a schedule for completing each aspect of the project. This schedule served as a tool for goal setting, measuring progress, and ensuring the design could be executed by the end of the working period, all of which may be found in Appendix C. It is important to note that our Gantt charts were updated throughout the year, when necessary, in accordance with any unexpected delays outside of the team's control, most notably, the temporary closure of WPI's Washburn Shops.

4.0 Design Process

4.1 Proof of Concept

4.1.1 Modifications to the Existing Proof of Concept

Before moving forward with the design process for the device and attachment mechanism, the team furthered Mr. Croteau's proof of concept of a front wheel propulsion aid that is placed in line with the caster wheels, to ensure moving forward with this design would meet all outlined constraints. The proof of concept that was provided to the team consisted of an electric scooter steering column attached to a piece of wood which was fastened to a metal bar that was fastened to the frame of the chair with the battery positioned to be placed on the user's lap. This proof of concept allowed the team to envision possible designs that allow the wheel to remain close to the user and the wheel, but it unfortunately was not stable and therefore was not usable causing a need to redesign the proof of concept. In the first step of this initial redesign, the standing proof of concept had to be disassembled so that it could be replaced to prove that a similar design could be feasible to build. Given the column was designed for an electric scooter it was inaccessible to use sitting in a chair. To fix this design issue, the team shortened the power-column to be suitable for operating while seated. Shortening the column was done by having team members sit in the chair to determine comfortable height for hand placement, using pipe cutters and a circular saw to cut the column, and using scrap pipe and bolts to create a splint for the two halves of the shortened column. The battery that was used in the original proof of concept was broken, so it was replaced by a battery from a different repurposed electric scooter. To attach the column to the chair, a piece of wood cut into the shape of the frame of the chair was used and attached with three U-bolts: two bolts were placed to attach the wood to the chair and the third was used to hold the column in place as shown in Fig. 11. Further details of the creation of the power-column and the team's use of repurposed materials throughout prototyping are detailed in 4.2 Environmental Prototyping.

Fig. 11. Fixed proof of concept of the propulsion-aid.

4.1.2 Proving Design Validity Through Testing

These modifications resulted in a fixed propulsion aid that could be driven for testing to ensure that this design would meet the clients' needs. With this proof of concept, the first test conducted was ensuring that the turn radius would remain in the five-foot radius outlined in the desired constraints. This was done by successfully turning the chair within a circle drawn in chalk. The wheelchair and population aid system were also tested by driving around WPI's campus and Mr. Croteau's workshop to ensure the system would successfully perform on ramps and hills. It was found that, with the proper speed setting, the propulsion system could go up short ramps of 14 degrees and would be able to succeed on any ADA compliant ramp. It was also tested to traverse over bumpy roads and downhills where it performed with minimal issues.

Traversing up and down hills and across rough terrain also provided physical reassurance that with this design, the system tipping backwards over the rear axle would not occur.

4.2 Environmental Prototyping

In any design process, it is important to consider the environmental costs associated with designing a new product. To limit the amount of waste that was created in all aspects of this project, it was decided to use repurposed materials for all prototyping when possible, and to adapt components of two older, broken electric scooters to create the base of the final product. In order to ensure adapting existing products would be a more sustainable solution, three case studies regarding adapting products and recycling materials were compared. These case studies related to different aspects of the project including use of recycled materials, recycling lithium-ion batteries, and restoring retired parts, in order to create a better understanding of current sustainability efforts in large scale manufacturing.

4.2.1 Analysis of Case Studies

In a study conducted by Vandkunsten Architects in Copenhagen, Denmark in 2019, it was concluded that much of industrial waste can be repurposed and used safely in other projects. This information was retrieved by performing Life Cycle Analysis on wood, steel, brick, concrete glass, soft flooring, and vinyl prototypes where all materials performed well, with the exception of vinyl which was deemed too toxic to become marketable. Repurposed steel and wood, the two elements most used in the team's prototyping process, were concluded to lower the negative environmental impacts compared to using conventional products by a significant margin. Fig. 12 below shows the research conducted by the scientist on a ten-point scale that assessed the performance on the criteria listed on the X-axis. The dotted line at five on the accessed performance axis indicates the ranking of conventional alternatives. Above the dotted line indicates improvement from the conventional alternatives which includes but does not limit to virgin materials [28]. This study helped prove the benefits of using recycled wood and steel and allowed them to be applied into the prototyping procedures in the team's design ensuring that science back environmental implementation would be used in the creation of the device.

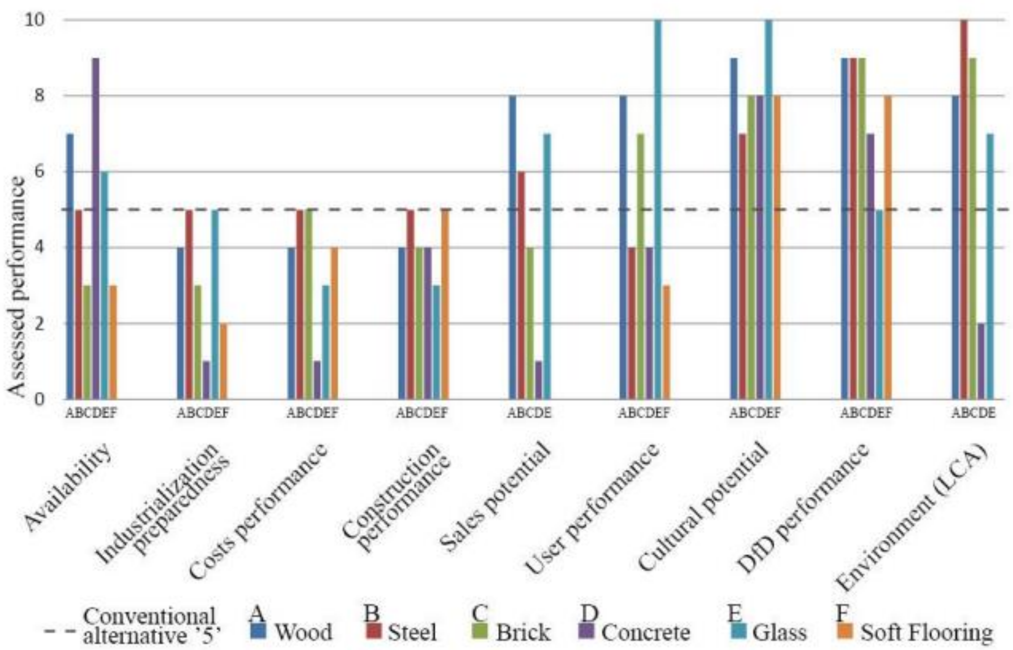

Fig. 12. Performance indicators for the materials used in the case study [28].

The team also consulted a published research paper discussing Fernando Enzo Kenta Satos' research with reusing retired car parts with the goal of conserving the energy consumed by the automotive industry to make informed decisions when reusing material. It was found that in Japan, the third highest vehicle market in the world, there was estimated to be around 4,000,000 tons of waste created from retired car parts. Santos worked to see if it was possible to reduce this number by conducting a small sample test disassembling a car and separating and analyzing the components and materials used. It was determined that 30% of the weight from the discarded vehicle was able to be recycled. The study discussed the viability of reusing parts of the discarded vehicle as opposed to the parts going to a landfill or scrap yard and the environmental significance of these decisions. It was found that saving and reusing the engine and the transmission contributed to the largest carbon dioxide savings per vehicle [29]. Although this study focuses on a larger scale item the basics can still be applied in the team's prototyping. For the purposes of applying these findings to the propulsion-aid device, the equivalent parts being the motor and the battery can be implemented instead. Similarly to Santos' conclusion, the team determined that repurposing the available electric components such as the motor and the battery can contribute to reducing the carbon footprint of the final product.

The final study examined was conducted by Songyan Jiang, where it was found that in two common lithium-ion battery recycling methods, hydrometallurgical and direct recycling, can reduce life cycle greenhouse gas emissions up to 54%. It was also found that the direct recycling of nickel manganese cobalt oxide and nickel cobalt oxide has a higher and more significant reduction in greenhouse gas emissions as it creates less secondary pollution. The latter battery discussed was proven to be the more sustainable battery due to the greater usability for the recycled materials. The most significant conclusion from this study, which has been proven in similar research, remains that battery recycling, done at the end of the batteries' useful life, has concluded to lack a significant impact on the reduction of greenhouse gas emissions as the majority of the energy intensive process is performed in the creation of the product. The study does conclude that reusing batteries that are still usable in another application or reusing recovered materials from end-of-life batteries does contribute to reducing these emissions and demands as it results in the manufacturing of fewer new products. In summary trying to restore end of life batteries has negligible environmental effects but applying usable working batteries into other applications has been proven to save a lot of waste and reduce unnecessary greenhouse gas emission. These findings do not mean that there is not enough benefit to warrant battery recycling, but rather highlight that reusing a material or part in its original state, or one that is similar, gives the product a longer lifespan before recycling [30]. With this conclusion, the team decided that attempting to fix the battery of the original scooter was not an environmentally justifiable option, and instead adapted a second battery to meet the needs of the original scooter. Expanding the lifespan of the battery that became unusable when its paired motor failed created a greater impact then the alternative as it does not add to the production, but instead adapted existing products to address different needs and therefore, reduced the product's carbon footprint.

4.2.2 Repurposed Materials in the Power-Column Design

With the information that was gained from these case studies, it was determined that in order to make a product that is carbon stable, the team would use primarily second life material in any application not requiring custom parts. This decision was based on the research conducted verifying that reducing the use of virgin materials would limit the greenhouse gas emissions produced in the creation of the final product. Using second life products can come with challenges in the building process, as the workpieces used typically were not created with the second life product in mind. With access to two electric scooters both with different functioning components, several modifications were needed to be made to the salvageable components and create a functioning power-column. The motor controller that came with the original scooter that the team had access to had many faulty wires and connections that needed to be fixed and resoldered so that the scooter would work properly. Given the scooter was being reused, it did not come with its charging cord, so the team worked to create one with the proper voltages to ensure battery safety requirements were met. Given the first life of the device was meant to be ridden standing, the team had to resize the height of the scooter column to comfortably fit a person in a wheelchair. Additionally, the footboard of the scooter that the user was meant to stand on had to be removed and the bearing box had to be adjusted so that a removable attachment for the wheelchair could be added. As previously mentioned, the team was fortunate and an additional broken electric scooter with a functional battery was procured saving the environmental and fiscal costs of purchasing a new lithium-ion battery. Additionally, with the shop experience that Mr. Croteau had, he was able to give the team access to a large stockpile of an assortment of different wood, metal, plastics, fixtures, and wheels that, with minor adjustments, were able to use to create prototypes and final aspects of the project. This access allowed the team to primarily recycle materials for much of the prototyping and non-custom aspects of the product. When it came to finalizing the design, it was chosen to make all machined components out of aluminum as it is 100% recyclable and WPI's campus works closely with a group that recycles the machine shops' metal scraps.

4.3 Propulsion Aid Design

Once the selection of a tiller controlled front drive system was confirmed, the design work could be broken down into subsystems for further design consideration. As part of the initial design selection, it was deduced that a semi-permanent crossbar would need to be attached to the frame of a wheelchair to increase the ease of connecting and disconnecting the attachment. With this component in mind, these subsystems are the steering column, the crossbar, and the attachment mechanism.

4.4 Subsystem Design Options and Alternatives

4.4.1 Steering Column

Looking at the market, the basics of the design of the steering column is universal, with handlebars that control the wheel direction, steering, and braking and a motorized wheel at the bottom that provides the forward motion. Due to this universality, alternative designs to these specific subsystems did not need to be considered. Design work on the steering column consisted of finding appropriate height for user comfort, preparation for the steering column half of the attachment mechanism, which is discussed further in the attachment mechanism section, and creating a mounting system for the motor controller and battery. The electric scooter that Mr. Croteau had used for his proof of concept served as the base for the column and components were rebuilt as necessary, as discussed in the previous sections.

4.4.2 The Crossbar

Early in the design process, it was decided that given the limited time frame and the size of the team, fabrication and detailed design of the crossbar may be beyond the scope of what would be reasonable to accomplish. In order to place the necessary focus on the main component of the design, the attachment mechanism, a fixed crossbar was incorporated into the final product; however, design alternatives were created and evaluated to show what the best crossbar solution would be with the necessary time and resources.

Four design alternatives were discussed and evaluated for the design of the crossbar, all with the goal of creating a stable bar to attach the propulsion aid to without interfering with the collapsibility of a folding chair. Each idea also followed the premise that attachment of the crossbar or crossbar connection points using tools may be allowed for initial setup but should be able to manipulate the bar in any way necessary using their hands from installation on.

The first design idea was a telescoping crossbar that would be fixed at both ends. This design would require a bar to be fixed to the lateral bars under a chair and would have a hinging mechanism in the center of the bar that would allow the bar to go from a rigid state to collapsing in on itself which would allow the chair to fold normally. The second design uses the same fixed ends to the bar, but rather than telescoping in to allow the chair to fold, would use a hinge placed in the middle to have the bar fold backwards when the chair is collapsed. The third design idea would be a solid crossbar with releasable end attachments on both ends of the crossbar, such as a pin or latch. This design would allow the bar to be rigid during use of the propulsion device, and removed completely, without the use of tools, in situations where the chair needs to be folded. The last design considered is a hybrid of the first and third design presented. The crossbar would have detachable ends, allowing the bar to be removed to fold the chair, but have two telescoping segments which would allow for the bar to be adjusted to account for different chair sizes. The sketches for each considered design can be seen in Fig. 13. These designs were further evaluated through the use of a Pugh Matrix, which may be found in Section 4.5.1 Crossbar Selection.

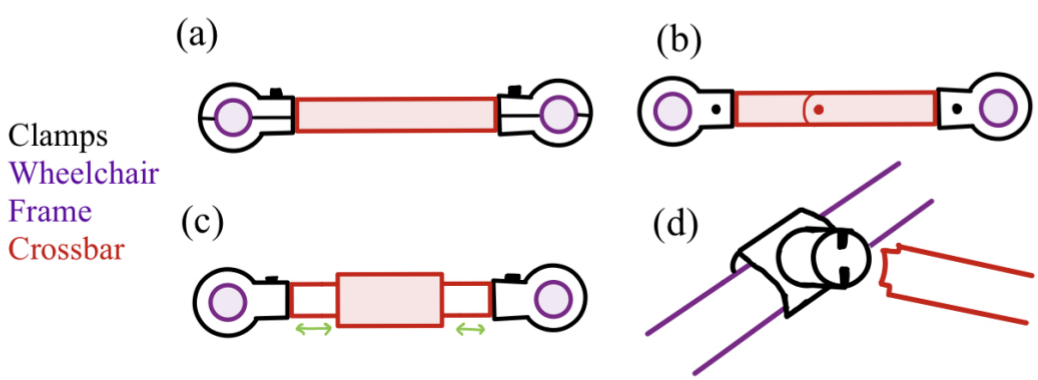

Fig. 13. Considered designs for the propulsion aid crossbar.
(a) Solid crossbar. (b) Hinging crossbar. (c) Telescoping crossbar. (d) Attachment section of telescoping crossbar.

4.4.3 The Attachment Mechanism

When talking with potential users, it was realized that a small mechanism that requires little hand strength, is easy for the user to operate, and allows the power-column to be securely fixed when operating, would be the main focus when working on this design. For the mechanism to be successful it was determined that it must lift the caster wheels in the attachment motion to result in enough traction on the power-column wheel. It was also determined that due to the timeframe of the project, consideration of manufacturability and ease of prototyping would also be critical to the success of the project. There were multiple quick release mechanisms that were ruled out at the beginning of ideation before the gate latch style mechanism was decided upon. This decision was a result of this latch style best suiter user needs due to its intuitiveness.

Three different gate latch-based designs were ideated and evaluated: one with a single latch, one with double latches, and one that had a hook and latch. It was evident that there needed to be two main components involved in each of these designs: one attached to the wheelchair itself through the crossbar and one attached to the power-column. The component on the power-column, intuitively, needed to be on the bearing box to allow for steering, without the need for the attachment mechanism itself to move. As building a new bearing box with the necessary geometry was beyond the scope of what was feasible for this project, it was decided that a collar would be placed around the existing bearing box to provide the needed attachment features. In addition to each design requiring similar attachment components, they also assumed a similar attachment movement. The power-column would be wheeled toward the user, angled away from the wheelchair, and part of the collar would engage with the attachment. Then, the user would pull the power-column handlebars towards them to lift the caster wheels of the wheelchair off the ground, at which point another part of the attachment would lock the rotation of the power-column.

The single latch, as seen in the hand sketch below (Figure 14a), has a spring-loaded top and a base with holes for the pegs of the collar to slide into and when that happens the latch would lock holding the collar in place. A mechanical stop would dictate the rotation of the power-column to lift the caster wheels. This stop would result in the user having to hold the power-column up against the stop during operation. A hook and latch design was also evaluated (Figure 14b). The collar for this design would have both a set of pegs and a hook on as can be seen in the image below. The hook would be able to attach to the crossbar allowing for the rotation of the power-column to lift the caster wheels, then having the latch lock the power-column into a vertical position. Lastly, there was the double latch design (Figure 14c). This design would consist of two latches stacked on top of each other. The collar would have two pegs on each side that fit into the latch mechanism. The lower latch would be engaged first, then the upper one would engage once the power-column is rotated into place. The power-column would then be locked in a vertical position.

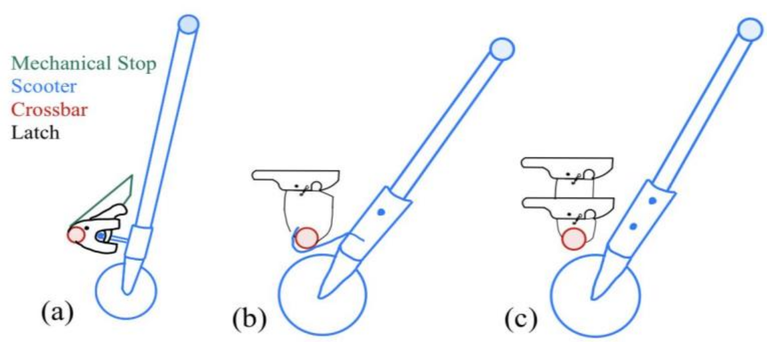

Fig. 14. Initial sketches of considered attachment mechanism designs.
(a) Single latch design. (b) Hook and latch design. (c) Double latch design.

4.5 Design Selection

To select from the designs presented, Pugh Matrices were completed for each subsystem. Each design option was ranked based on categories derived from the project goals and criteria that were relevant to each respective subsystem in addition to feasibility of the design. Once each design criteria were selected, they were weighted using scale from one to the total number of criteria, with one being the least important. Then, each design was ranked against each other under each criterion, with one serving as the design that is least likely to appropriately fulfill that need. To create a fair evaluation, each team member rated each matrix separately, and the results of the team were averaged for the final results.

4.5.1 Crossbar Selection

Five criteria were selected for judging potential crossbar designs: ease of prototyping, ease of use for end users, ease of wheelchair transport, adaptability for different wheelchairs, and security of the bar while the device is in motion. Security while in motion was deemed the most important criteria as it is crucial when considering the usability and safety of the final product. Ease of use for the end user was ranked next, as it directly corresponds to one of the pivotal goals of making this product usable by those with limited physical ability. Adaptability for different wheelchairs was thought to be the next most important as having the device fit with different wheelchairs frames, as opposed to having to make a custom device for every different wheelchair, would broaden the market for the device. Ease of prototyping was then ranked as it had to be feasible to create the device within the designated time frame, but the needs of the customer were more important than the needs of the team. Lastly, ease of wheelchair transport was considered as, based on interviews and research, this was the customer need that was least important in the functionality of a propulsion aid device. The completed Pugh matrix based on these decisions can be seen in TABLE III below.

TABLE III

PUGH MATRIX FOR CROSSBAR DESIGN

Idea	Ease of Prototyping	Ease of Use for End User	Ease of Wheelchair Transport	Adaptability	Security While Wheelchair is in Motion	Weighted Total
Weight	2	4	1	3	5	
Fixed Telescoping	3.33	3.00	3.67	4.00	3.67	43.00
Middle Hinge Crossbar	2.67	3.00	3.00	3.00	3.00	37.33
Detachable Solid	4.00	3.33	2.67	2.67	4.00	41.00
Detachable Telescoping	3.67	3.33	3.67	4.00	3.33	44.67

With the results of the Pugh matrix, it was determined that a telescoping crossbar with detachable ends would best meet the client needs and project goals. A second matrix was created to further expand on this design choice through the type of telescoping mechanism that should be used. This Pugh matrix illustrated that the bike clamp method was the best selection based on its high security in motion, ease for the end user, ease of prototype. The simple design of the bike clamps would be intuitive for the user. There would be two bike clamps one-third of the way from the ends that would be connected with a bar so that both clamps can be operated at the same time. The crossbar will be telescoping having tapered ends so that it can easily attach to itself adding security to the design. The details of the other telescoping designs considered and the results of the matrix may be found in Appendix D.

Unfortunately, over the course of this project, time constraints prohibited the ability for the telescoping bar to be included in the final design. With a three-person team and a limited amount of time, the team elected to prioritize an innovative solution on the attachment mechanism, as this was the component of the design that would address the majority of the client's needs. For the final prototype, a semi-permanent, fixed crossbar was used due to its simplicity and ease of implementation.

4.5.2 Attachment Mechanism Selection

The applicable categories for the attachment mechanism Pugh matrix were ease of prototyping, ease of use for the end user, and security while in motion. Security while the wheelchair is in motion was once again deemed as having the highest level of importance. Next, the ease of use for the end user was prioritized, and, finally, ease of prototyping was considered.

The single latch idea scored the lowest on the Pugh matrix as the user having to hold it in the vertical position would make the device difficult to operate and less secure than desired. The double latch design placed second due to concerns that it may be more difficult for the user to line up the scooter to the attachment mechanism on the wheelchair and were concerned about its manufacturability in the scope of this project. Lastly, the hook and latch placed first on the Pugh matrix as it was believed that it would be the easiest for the user to attach the power-column and would be secure in motion resulting in the best user experience. The details of these results are highlighted by TABLE IV.

TABLE IV

PUGH MATRIX OF THE ATTACHMENT MECHANISM DESIGNS

Idea	Ease of Prototyping	Ease of Use for End User	Security While Wheelchair is in Motion	Weighted Total
Weight	1	2	3	
Single Latch	3.00	1.00	2.00	11.00
Double Latch	1.33	2.00	3.00	14.33
Hook and Latch	2.00	3.00	3.00	17.00

4.5.3 Comparison of Viable Mechanism Options

Two of the three attachment designs were then further evaluated for their viability. The hook and latch was found to be the best design option, but there was concern for its ability to meet the design constraint of its attachment angle, which was the main reason for evaluating two designs. Although the hook and latch design was ranked first, there were reservations on this design's attachment angle, so both this design and the double latch design were further evaluated. Prototypes for each design option were created to find which would best fulfill the design requirements.

4.5.3.1 Hook and Latch Design

In order to truly understand the attachment movement, a proof of concept was made for the hook and latch design as this was the simpler design from a prototyping standpoint. The prototype was created with recycled wood, PVC pipes, gate latches, and a small wheel. One PVC pipe was used as the crossbar, and another was modified to serve as the hook. The wheel was attached to the wood plank to represent the power-column. The pegs of the gate latches and the hook were then screwed to the wood plank to simulate the collar. The gate latches were then screwed onto another wooden plank that was affixed to the wheelchair above the crossbar to simulate them being attached to the crossbar. The final proof of concept can be seen in Fig. 15. Testing of this prototype showed that the assumed attachment motion was viable and allowed the next steps of the design to begin.

Fig. 15. Proof of concept of hook and gate latch design.

This successful proof of concept not only validated the attachment motion, but also showed that the attachment angle for this design was promising and allowed the design process to continue. CAD models were created to polish the geometry of the design, and further test the general success of the proposed latch mechanism. This design was then 3D printed on an Ultimaker PLA 3D printer. A test piece with pegs replacing the power column was printed so that the mechanism could be more handheld for checking the geometry. This iteration can be seen in Fig. 16 below.

Fig. 16. First 3D print of the gate latch and hook design.

With the success of the last two prototypes, the final model was drawn with minor edits to the latch from the initial prototype for better tolerancing and designing the collar. This was then 3D printed (Fig. 17) and tested for the attachment angle by putting the collar around a PVC pipe with the same outer diameter as the bearing box.

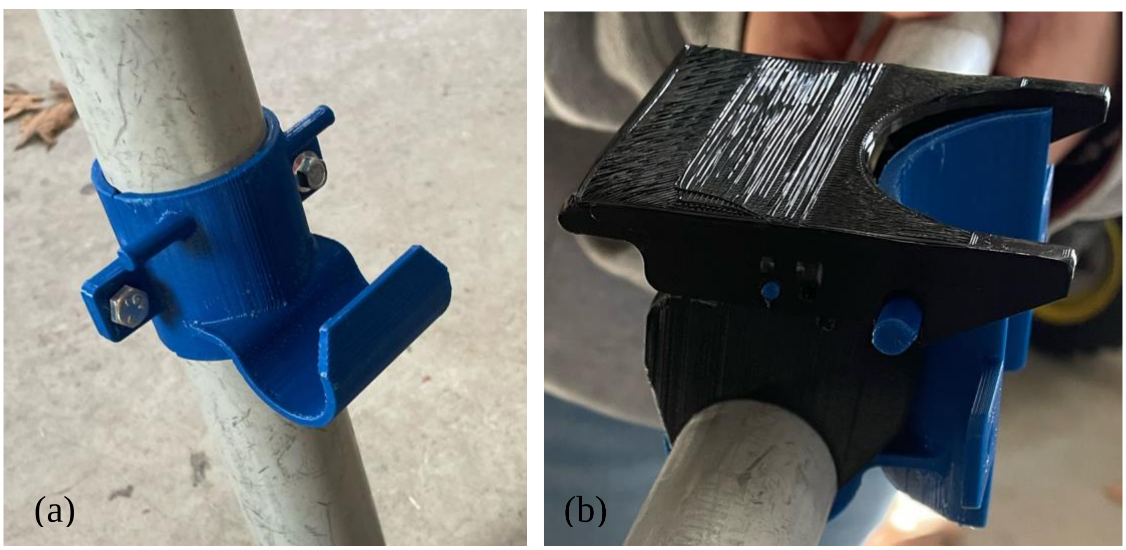

Fig. 17. 3D printed hook and gate latch attachment mechanism.
(a) collar on PVC piping acting as scooter. (b) latch mechanism with attachment half of the collar attached

Upon testing the attachment motion with the 3D printed prototype, it was determined that the angle of attachment would be approximately 20 degrees from the ground as can be seen Fig. 18, which is significantly less than the design constraint for attachment angle. Upon further analysis, it was determined that this change in attachment angle between this prototype and the proof of concept was caused by the hook on the 3D print being extended further vertically than the PVC pipe hook did. The hook would have to pass entirely underneath the crossbar to fully latch around it. Through creating a longer hook to ensure stability, this lowered the point at which the device had to be positioned to accomplish this attachment, which was not realized in the proof-of-concept stage of the design. The hook needed to be extended to ensure security when the scooter is attached, because if it was not, the scooter could come partially unattached if the wheel slipped forward. This was missed on the proof of concept because the wooden plank holding the gate latches acted as a mechanical stop that would not allow the hook to slip off. As the hook's length provided security, the hook could not be shortened as safety was important in this design.

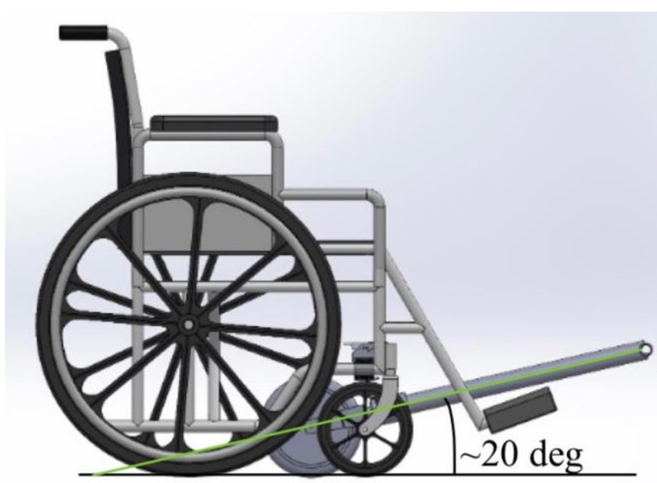

Fig. 18. CAD model showing the attachment angle with hook and gate latch design.

4.5.3.2 Double Latch Design

The second design evaluated further was the double latch mechanism. The general principle is similar to the hook and latch, in that a lower part of the mechanism would engage while the caster wheels remain in contact with the ground, then the power-column would be tilted toward the user to lift the caster wheels until the upper part of the mechanism engages locking the position. For this design, it would be two pegs locking into two latches as shown below in Fig. 19.

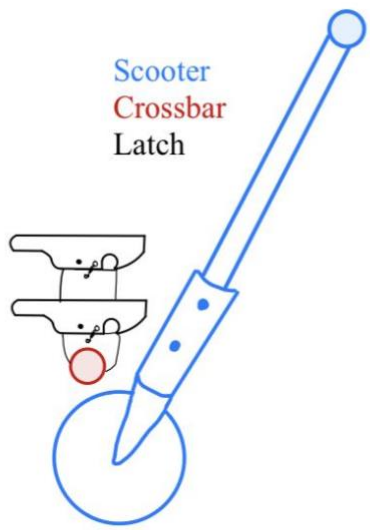

Fig. 19. Double gate latch design sketch.

Due to the complexity of the design, a proof of concept could not be efficiently made with readily available materials. As the general motion was proven by the hook and gate latch initial proof of concept, geometric analysis of the location of the pegs and latches for attachment were done to calculate the attachment angle. This analysis also provided further details on the attachment geometry that would be used for the creation of a CAD model. Using the power-column dimensions and the wheelchair dimensions, the location of the lower peg, the first peg to attach, was calculated. These dimensions included where the peg would fall on the power-column's bearing box and how high from the ground it would sit when put into the latch. The bearing box on the power-column started at nine inches up the column from the bottom of the wheel. The bearing box was 2.75 inches tall, to allow for enough space between the two pegs and clearance from the top and bottom of the bearing box, the bottom peg would be half an inch higher than the start of the bearing box, putting it at 9.5 inches from the bottom of the wheel when the scooter is held vertically. The bars of the wheelchair's frame that the crossbar attaches to had their centers at 8.5 inches, thus the lower latch position was set to line up with the center of the frame and thus the crossbar. These dimensions gave the following relationship, seen in Fig. 20. The letter J denotes the position of the peg when locked into the latch when the scooter is at the lowest angle necessary. This geometry resulted in a predicted attachment angle of 55.7 degrees with the ground, denoted by α. The predicted angle exceeds the constraint of being greater than 30 degrees with the ground, prompting further evaluation of the double latch mechanism.

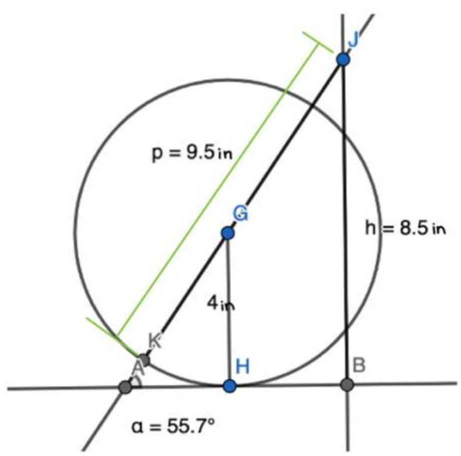

Fig. 20. Geometric analysis of the double latch design.

The CAD model created allowed for detailed design decisions to be made for the latch mechanism as well as the collar for the bearing box as shown below in Fig. 21. The holes on each of the latch tops as well as the latch bottom are for springs to be installed to hold the latches closed. The tail on Latch Top 2 would be used to release Latch Top 1, the first latch the collar interacts with during attachment once it is pressed down to the appropriate height. The tail allows for one motion to unlock both latches making it easier for the user to operate. The final step in evaluating the double latch design was 3D printing the model to test its operation. These tests proved successful; therefore, the double latch met both operation and angle of attachment criteria.

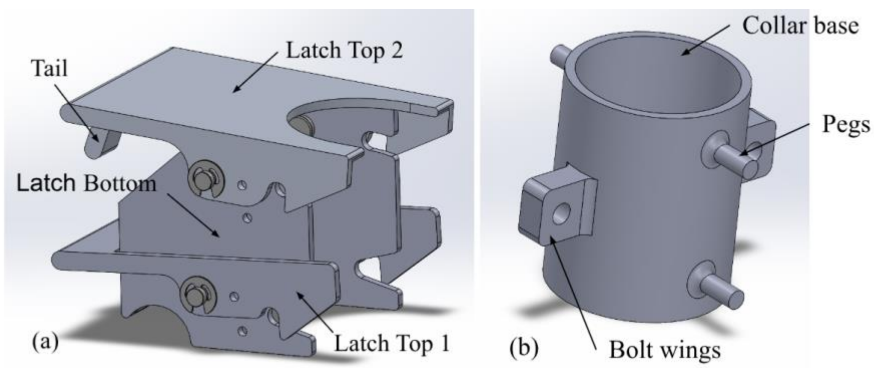

Fig. 21. Double latch design CAD model.
(a) Latch mechanism. (b) Collar.

4.5.3.3 Final Design Selection

Ultimately, the hook and latch design was successful in providing an attachment method that would lift the caster wheels and keep the power-column secure during use. However, due to the necessary hook geometry needed for a secure attachment, the angle of attachment would not meet the project specification and, therefore, the double latch design was the better of the two design options. The success of the 3D printed double latch designs mitigated concerns of the bearing box being difficult to align with the latches, and the geometry analysis proved that the attachment angle would be well within the desired range.

5.0 Detailed Design

To prove the validity of the final attachment design in comparison to the design requirements and that the design would be safe for the end user, a series of calculations and simulations were conducted. This process began with an analysis of the weight distribution of the power-column, user, and wheelchair system which allowed for a detailed understanding of the forces that would be acting on the power-column. From this analysis, the last component of finalizing the details of the design could be completed which was conducting finite element analysis of the attachment mechanism using the Ansys software. This iterative process included further analysis of the forces acting on each individual component of the attachment mechanism and a series of simulations which were used to inform design decisions, and ultimately ensure the final prototype would meet the minimum safety standard. Lastly, the springs used to hold the latches closed were discussed in terms of reaching the criteria for the force to operate as laid out by ADA compliance.

5.1 Weight Distribution of the System

The center of gravity of the wheelchair was calculated by averaging the measured center of gravity from research data that was retrieved of a typical wheelchair with someone sitting in it, with that of the measured COG of the power-column attachment using the equation found in [31]. First the typical COG of someone sitting in a wheelchair was calculated, accounting for the slight angle between the front and back wheels due to the addition of the power-column attachment. The front wheel was measured to be raised by 1" off the ground and trigonometry was used to find the new COG with respect to the back axle. The COG of the system was found to be at $(4.557'', 21.336'')$, with the origin being between the center of the axel. See Appendix E for the full calculations.

5.2 Analysis of the Forces on the Attachment Mechanism

In order to ensure the success of the attachment mechanism and the safety of the device user, further analysis was conducted regarding the forces that act on the attachment mechanism in situations of standard use. This process included dynamic calculations to find the forces that act on each part of the mechanism followed by using these results to conduct Ansys simulations of the attachment design.

5.2.1 Calculation of the Forces

Prior to beginning the analysis, it was first decided which scenarios of use were important to consider to ensure user safety. These situations considered the entire system: the wheelchair, user, and propulsion aid. To find the forces acting on the overall attachment, the forces applied on each of the four pegs of the collar needed to be determined, as the reactive forces on the latch mechanism would be equal and opposite the pegs.

First, the system in a static environment was analyzed. These forces were simply found through referencing the previously discussed weight distribution calculations that were conducted and the maximum weight of a user being that of the set weight limit of the device, 250 pounds. Once the forces acting on the front wheel were known, the normal force was then used to find the forces distributed through the pegs.

The other scenarios for analysis were the system in motion moving forwards and the system in motion moving backwards. Though there is no reverse option on the propulsion aid, a user caught in a tight space might wish to rotate their handlebars 180 degrees to achieve a backwards motion making it important to consider for user safety. Given that the system will experience the highest forces when accelerating from stationary, maximum weight capacity of the wheelchair, the weight distribution calculations previously discussed, and an overestimation of acceleration taken from similar scooter models of 3.385 feet/seconds^2 were used to deduce the maximum forces on each of the collar pegs. The final results can be seen in TABLE V below, and detailed calculations for these results may be found in Appendix F [32].

TABLE V
SUMMARY OF FORCES EXPERIENCED BY THE ATTACHMENT MECHANISM

Situation of System	Force on Top Pegs Combined (lbs-f)	Force on Top Individual Pegs (lbs-f)	Force on Bottom Pegs Combined (lbs-f)	Force on Bottom Individual Pegs (lbs-f)
Stationary	30.9	15.45	30.9	15.45
Moving Forwards	177.9	88.95	207.8	103.9
Moving Backwards	177.9	88.95	207.8	103.9

5.2.2 Ansys Simulations of the Attachment Mechanism

Using the results from the previous section and the CAD models of the design, Ansys simulations were created for each of the desired scenarios. The model was created using Static Structural analysis, as dynamic effects due to the acceleration of the scooter were taken into account in calculating the forces. The latch mechanism assembly and collar assembly were modeled separately for each of the three scenarios to simplify the simulations. The Poisson's ratio and modulus of elasticity for each material used were entered into Ansys to provide the necessary information for the simulation. A breakdown of these values and the parts that they were assigned to may be seen below (Table XI).

TABLE VI

SUMMARY DATA NECESSARY TO RUN ANSYS SIMULATIONS

Reference	Material	Poisson's Ratio	Modulus of Elasticity (psi)	Parts Applied To
[33]	Aluminum T6061	0.33	10,000,000	Latch Bottom Latch Top 1 Latch Top 2 Collar Base
[34]	1045 Steel	0.29	23,600,000	Clevis Pins in Latch Assembly
[35]	4140 Steel	0.29	29,700,000	Collar Pegs

For the simulation of the attachment mechanism, the face where the mechanism is welded to the cross bar was denoted as a fixed support and for the collar the inside wall of the collar was marked as a fixed support. In each simulation the Von Mises stresses and deformation were analyzed in order to ensure no parts were failing or experiencing enough elastic deformation to impact attachment alignment.

To determine appropriate mesh settings for the simulation, the simulation of the attachment assembly with all features hidden except for Latch Top 1 was run with decreasing mesh size in order to find where the maximum stress converged. Given that Latch Top 1 had the highest chance of failure, this part was used to test convergence as it would provide the most insight into the behavior of the assembly. During this test for convergence, it was noted that the location of the maximum stress of the part changed as the mesh decreased, from the front of the latches where the pegs attached to the holes for the Clevis pins which was unexpected. Upon conducting further simulations to test why this effect was occurring, it was deduced that this occurred because the assembly constraints from Solidworks made it so that the Clevis pins and latch were behaving as fixed, as opposed to having rotational freedom that the pins should allow. This ultimately drastically increased the stresses around the pin hole at smaller meshes, of element size 0.0085 inches and below. Any attempts to correct this relationship, unfortunately resulted in not having enough constraints for Ansys to process the model. To correct this issue, moving forward the stresses of the respective latch top taking the highest load was analyzed in its own simulation, where the pin holes were marked as cylindrical supports.

Convergence was tested again, using the forward moving simulation of Latch Top 1 on its own. Not only did this get rid of the effect of the maximum stress moving, but it also allowed for decreased computation times and accurate probing of the maximum stress. As seen in Fig. 22 below, the mesh converged at approximately 20,000,000 elements, which corresponded to a mesh element size of 0.015 inches. This mesh size of 0.015 inches was used in all subsequent simulations.

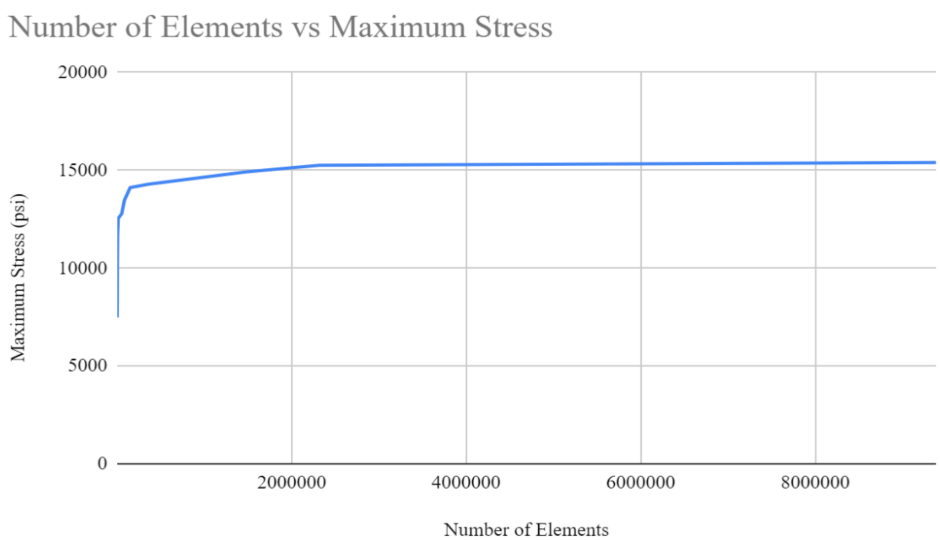

Fig. 22. Graph of the mesh convergence in the Ansys simulations.

Once the simulations were complete, the data was gathered on the maximum stress on each part in each simulation, and the factor of safety of each part was calculated using its yield strength. Throughout the process of running these simulations, there were a few instances where the attachment mechanism was below the desired factor of safety, one of which being the design for Latch Top 1 in the convergence test. To correct these instances, changes were implemented in the design so that it could better handle the forces from the pegs. While many of the changes that were made simply involved increasing the thickness of the part and adjusting the assembly as needed, the guiding path for the collar pegs was also adjusted, so that, once latched, all vertical loads were placed on the latch bottom, as opposed to being placed on either latch top. The change in this guiding path can be seen in Fig. 23, which shows the design before and after this adjustment and how it changed the location of the vertical loading.

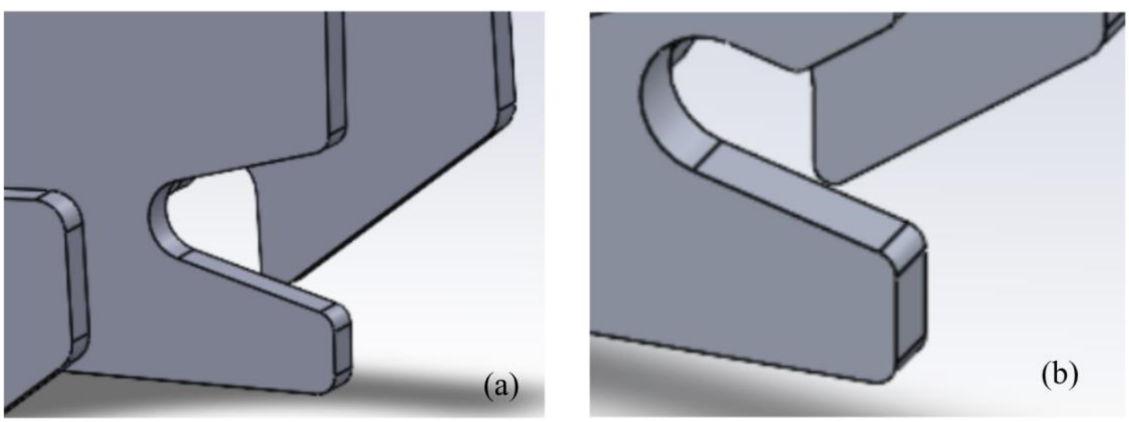

Fig. 23. Guiding paths for the pegs of Latch Top 1.
(a) Original guiding path. (b) Final guiding path for better force distribution.

After implementing these changes, successful results were achieved proving the design would successfully perform within the needed factor of safety range. A summary of these results is highlighted in TABLE VII below. It is important to note, that in the case of the latch bottom, the area surrounding the weld would experience a decreased yield strength due to the exposure of high heat, while the weld itself would be stronger than the original aluminum. Due to this, only the maximum stresses on the area surrounding the weld was considered, with a yield strength estimated to be 50% of the yield strength of the aluminum [36].

TABLE VII
SUMMARY OF ANSYS SIMULATION RESULTS

Ref.	Part	Material	Maximum Stress (psi)	Scenario Stress Occurs	Yield Strength (psi)	Factor of Safety
[33]	Latch Top 1	Aluminum T6061	14,111	System Moving Forward	40,000	2.835
[33]	Latch Top 2	Aluminum T6061	13,075	System Moving Backward	40,000	3.059
[33], [36]	Latch Bottom (Surrounding Weld)	Aluminum T6061	5,646.3	System Moving Forward	20,000	3.542
[34]	Clevis Pins	1045 Steel	22,619	System Moving Forward	65,300	2.887
[33]	Collar Base	Aluminum T6061	12,847	System Moving Forward	40,000	3.114
[35]	Collar Pegs	4140 Steel	16,741	System Moving Forward	219,700	13.123

As noted from the results, the highest stresses occur primarily in a scenario where the system is accelerating forwards. The results from the simulation of the attachment assembly, Latch Top 1 on its own, and the collar can be seen below in Fig. 24. Overall, a factor of safety of

2.835 was reached using worst-case scenario simulations. This factor of safety alone places the device in the upper half of the target range of 2.5-3, although the conservative estimations used means our actual factor of safety is likely higher. These results prove the design is safe for use. Additional images from all the simulations may be found in Appendix G.

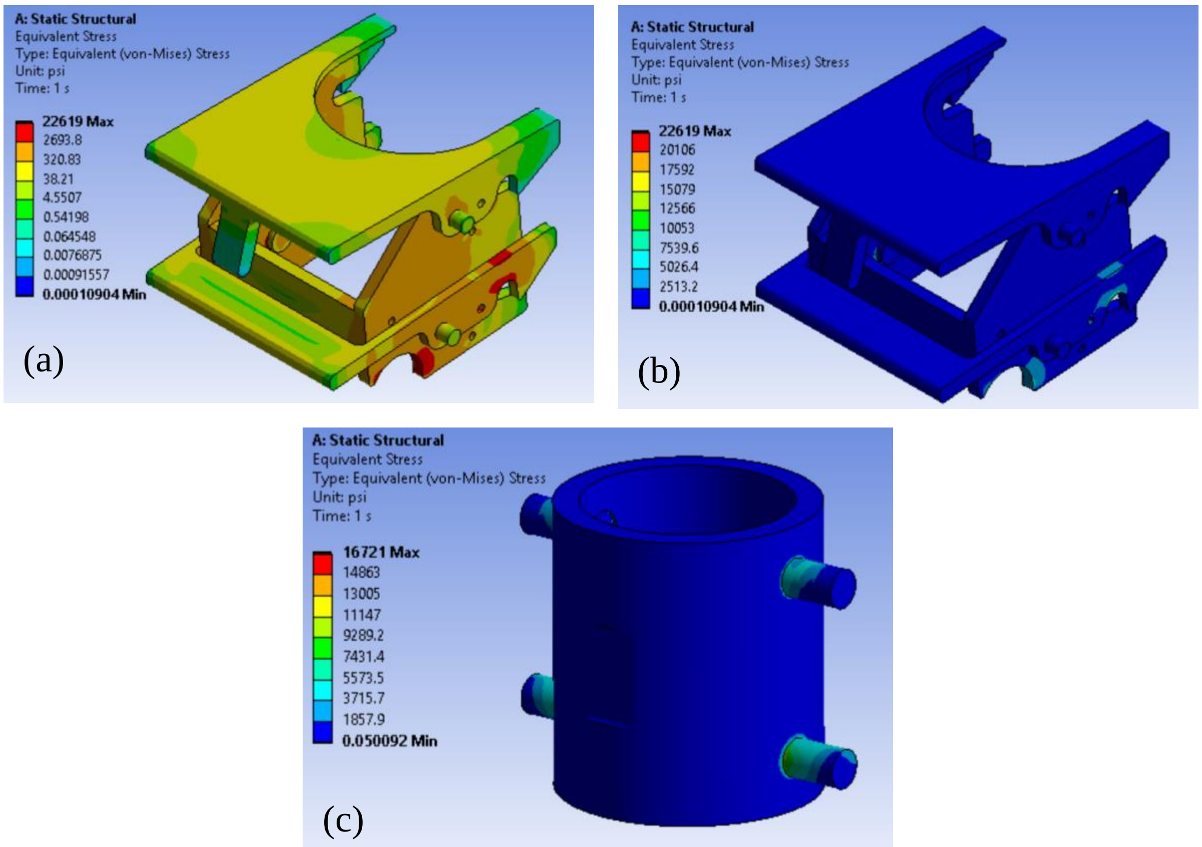

Fig. 24. Results from Ansys simulations in the moving forward loading scenario. (a) Logarithmic results of the latch mechanism. (b) True scale results of the latch mechanism. (c) True scale results of the collar.

5.2.3 Tearout Calculations for the Latch Tops

As the latch tops are held to the latch bottom by pins which are located relatively close to the edge of the latch tops, it was important to calculate the necessary distance from the center of the hole to the edge. This analysis was done by using the following equation: $\sigma = \frac{FOS*P}{2*\delta*T}$ [37], where FOS is the factory of safety (3), σ is the maximum shear stress for aluminum (27,000 psi) [33], P is the force applied (300 pounds, the total of the horizontal and vertical load), T is the thickness (0.190 inches), and δ is the distance to the edge. The necessary distance was found to be 0.088 inches, and this was then applied to the design.

5.3 Spring Selection Justification

As laid out in 3.2.3.3 Force to Open, the force necessary to operate the latch could not exceed five pounds. Based on the geometry of the latch, the latch tops do not experience any vertical force, so the springs only have to counteract the weight of the latch tops. Both latch tops did not weigh more than one pound, so it was clear that whatever spring was able to hold down the latches without applying extra force, would allow for the operating force to not exceed five pounds.

6.0 Manufacturing

Once the ANSYS simulations verified that the factor of safety for each component was within the safety range defined in the constraints, manufacturing on the design began using a variety of manufacturing techniques and processes.

6.1 Manufacturing Plan and Final CAD Model

With the aid of an assigned lab assistant, Jakub Jandus, from WPI's Washburn Shops a plan was derived for the manufacturing of each individual component as laid out in Table VIII.

TABLE VIII

MANUFACTURING PLAN FOR ALL PARTS

Part	**Stock Material**	**Process**
Crossbar Clamps	Internal diameter of 1 in	1. Attach to wheelchair and crossbar 2. Drill vertical holes on each side of crossbar 3. Place bolts in the holes to mitigate crossbar rotation
Crossbar	Aluminum pipe 1in diameter 2 ft length	1. Use miter saw to cut stock material to appropriate length
Latch Bottom	Sheet metal 0.190 in thickness 12 in width and length	1. Waterjet cut the faces from the sheet metal 2. Weld the three faces from the cut pieces
Latch Top 1/Latch Top 2	Aluminum block 4in x 1.5 in x 3 ft	1. Use a CNC band saw to cut to length 2. Use a CNC mill
Latch Top 2 Tail	PLA filament	1. 3D print the tail 2. Place heat set inserts in the print 3. Bolt the tail to Latch Top 2
Mechanical Stop Pins/Spring Pins	Aluminum dowel pins ⅛ in diameter ¾ in long	1. Use an arbor press to press fit pins where needed 2. Use a hacksaw to cut indentations in pins to hold springs secure (for spring pins only)
Collar Base Halves	Aluminum pipe 2 in internal diameter ¼ in thickness 3 in length	1. CNC mill the peg holes on each piece of stock 2. Use a miter saw to cut the pipes in half 3. Grind the edges flat
Collar Pegs	Steel dowel pins ⅜ in diameter 1 in long	1. Use an arbor press to press fit the pegs
Collar Bolt Wings	Sheet metal 0.190 in thickness 12 in width and length	1. Waterjet cut the wings from sheet metal 2. Weld the wings onto the collar
Clevis Pins	¼ in diameter ½ in usable length	1. Placed to secure the latch tops to the latch bottom

For the pieces being milled and waterjet cut, minor adjustments to the CAD model were needed to accommodate for each process's requirements and limitations. The final CAD model can be seen in Fig. 25. For the waterjet cut pieces, the latch bottom was modeled to be three different pieces: the two sides and the back wall. The side pieces for the latch bottom were modeled to have three, ⅛ inch holes for aluminum pins to be press fit into. The two pins closer to the peg locations would be used to connect the springs that would hold the latch tops down, and the one near the back of the latch bottom would be used as a mechanical stop to limit the rotation of Latch Top 1. Latch Top 2 did not require a mechanical stop, due to its inherent interaction with the top face of the latch bottom. The bolt wings on the collar halves were also modeled as separate pieces that would be welded onto the milled collar base.

For the CNC milled pieces, chamfers and fillets were added to the edges and corners of the latch tops as can be seen in Fig. 25. Additionally, it was decided the tail of Latch Top 2, which pushes down on Latch Top 1 to ensure the latches can be released in one motion, would be created through 3D printing and then bolted to Latch Top 2 using heat set inserts. This alteration was made to increase the manufacturability of the latch, and this did not impact the function of the tail since it carries loads of less than 5 pounds. The collar base was modeled as seen in Fig. 25, with the two holes serving as the locations for press fitting the steel dowel pins and the flat indents as level surfaces for welding the bolt wings. This collar model was to be machined twice on two separate stock pieces, which would then be cut in half. This method was chosen to ensure the collar pegs would truly be perpendicular to the highest point of the collar's outer surface for each half, allowing them to sit in line once the collar was attached to the power column.

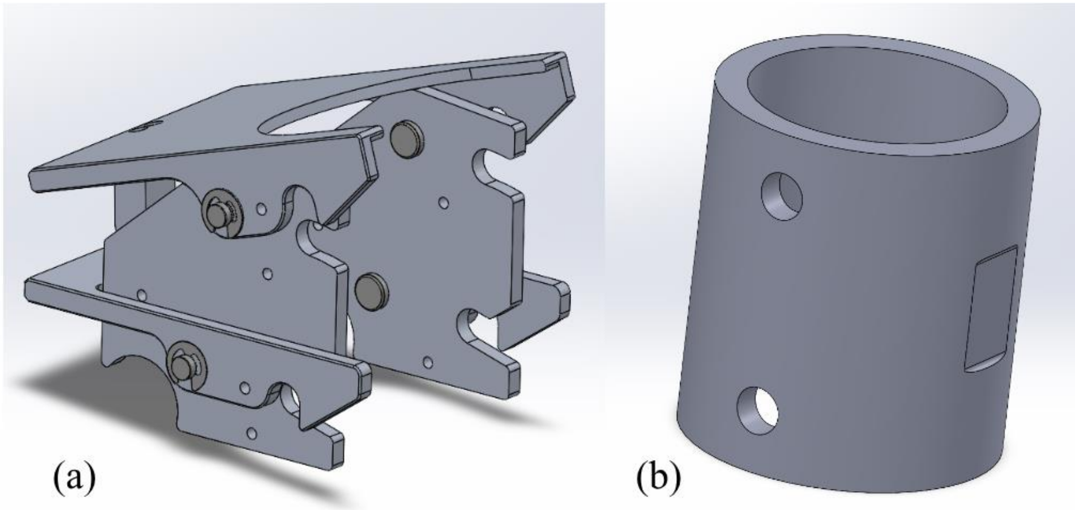

Fig. 25. Final manufacturing CAD models.
(a) model of the manufacturing latch mechanism. (b) model of the collar base for machining.

6.2 Crossbar

To prepare the wheelchair for the attachment device, the fixed crossbar had to be installed and altered to fit the chair width. Framing fittings were installed on the frame of the wheelchair, and the distance between the fittings was measured to ensure appropriate crossbar width. Then the two foot long, one inch diameter, aluminum pipe was cut to size using a miter saw, and the cut edges were ground using a belt sander to reduce the safety hazard created by sharp edges before being placed between the fittings.

6.3 Waterjet Cutting

With the use of the waterjet cutter in the PracticePoint lab at WPI, and the aid of Taylor Frederick, the walls of the latch bottom and the collar wings were created. In order to operate the waterjet cutting machine, a DXF file was created with the two-dimensional profiles of each piece, as can be seen in Fig. 26. Extra parts were created for the latch bottom to compensate for the possibility of error in the welding, as this part was crucial to the collar pegs correctly aligning for proper attachment engagement. Samples of the resulting pieces are depicted in Fig. 26.

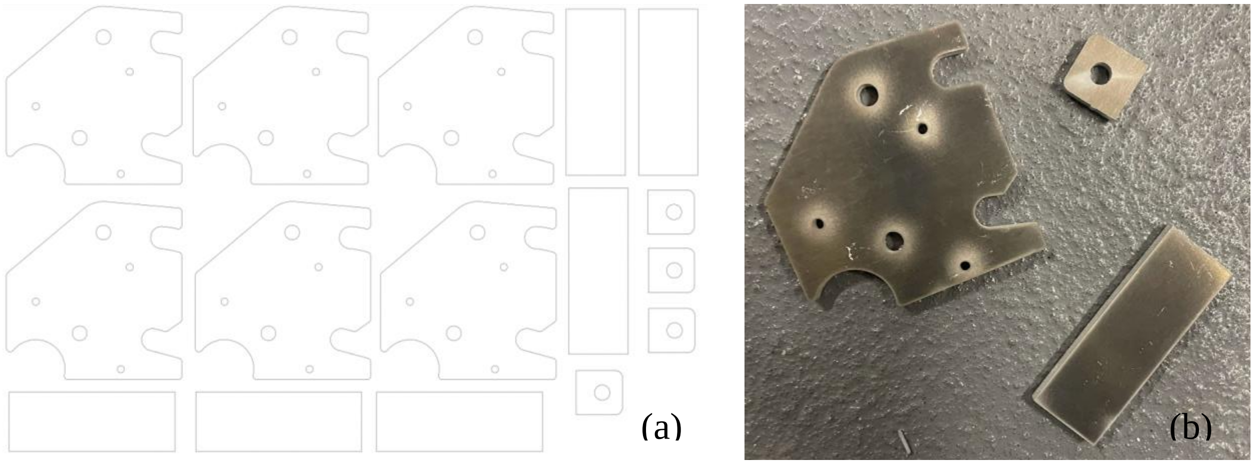

Fig. 26. Waterjet cutting photos.
(a) DXF file for waterjet cutting. (b) waterjet cut pieces.

6.4 CNC Machining

With the use of the Haas CNC mills in the Washburn shops on campus, and the aid of Jakub Jandus, the collar halves, Latch Top 1, and Latch Top 2 were created.

6.4.1 Fusion 360

The first step in the CNC process was to use CAM software to create the proper tool paths and setups for machining. The CAD models created on Solidworks were transferred into Fusion360, where the operations to be carried out on the mills would be defined. A combination of facing, drilling, milling, reaming, and chamfering was necessary for the completion of each part.

6.4.2 Press Fit Test Piece

To ensure that the press fits were done with the correct tolerancing, a test piece was created that contained holes made with various processes and tools to see which provided that best result. From the tooling available at Washburn Shops, three methods of preparing the hole for the collar pegs and two methods of preparing the holes for the aluminum pins were evaluated. After press fitting, to test the relative strength of each fit the plate was secured in a device and the pegs were struck with a hammer, the results of which can be seen in Fig. 27. Based on the testing, tooling was selected for each press fit type and the Fusion360 was updated to reflect this selection.

Fig. 27. Test piece for press fitting after testing.

6.4.3 Collar Machining

To make the two collar base halves, stock aluminum pipe with a 1-inch diameter, 3-inch height, and ¼-inch thickness was used. Using the Haas VM2 mill, two holes were drilled for the pegs and milled the flat edges for the bolt wings. One collar base half after milling can be seen in Fig. 28.

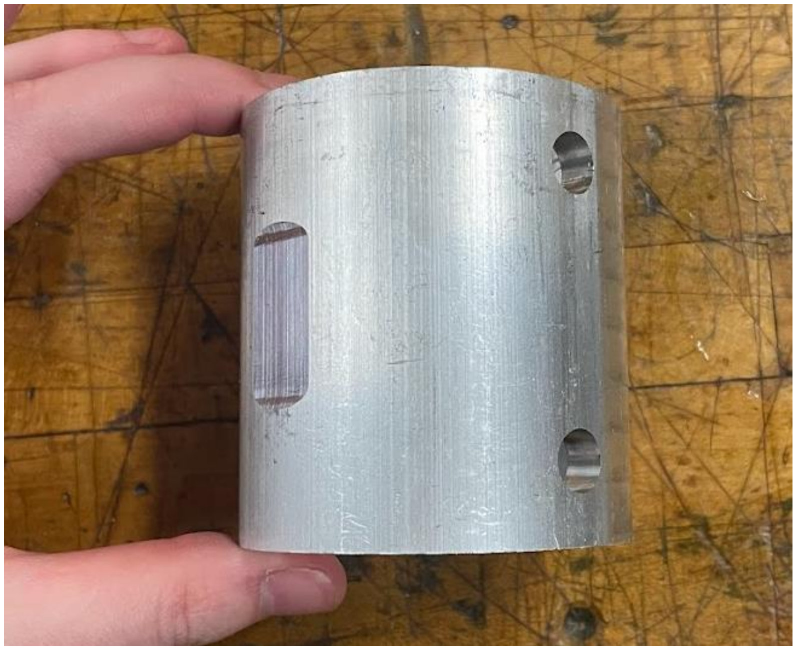

Fig. 28. A machined collar base half.

6.4.4 Latch Top Machining

Aluminum blocks of 1.5 inches tall, 4 inches wide, and 4.75 inches long were used as the stock material for the latch tops. These processes were completed with the use of the Haas Mini Mill. Four different machining set-ups were needed for each top in order to achieve the desired geometry.

6.5 Welding

The waterjet cut pieces, the collar base halves, and the crossbar were taken to a welding shop to begin the assembly process. The three pieces necessary for the latch bottom were welded together, and then onto the crossbar in the middle (Fig. 29). Additionally, the bolt wings were welded onto the collar base halves (Fig. 30).

Fig. 29. Crossbar with the latch bottom welded on.

Fig. 30. A collar base half with the bolt wings welded on.

6.6 Final Assembly

The last step to manufacturing the attachment mechanism was to assemble all the completed pieces. These steps were completed both at the Washburn shops and at Mr. Croteau's workshop.

6.6.1 Latch Assembly

To begin the latch assembly, ⅛ inch aluminum dowel pins for the springs were press fit using an arbor press in Washburn. Four were put in the latch bottom, two on each side, and two were put into each latch top. The tail for Latch Top 2 was 3D printed using PLA filament. Then, the heat set inserts were placed into the tail, and the printed piece was bolted to Latch Top 2. Next, the latch tops were placed around the latch bottom and the Clevis pins were used to secure them. The pin for the mechanical stop of Latch Top 1 was then hammered into place, as using the arbor press was not possible with this geometry, and placing the pin before assembly would have obstructed the top from being able to be put into place. A hand saw was used to create divots which would hold the springs in place and the springs were then added to the assembly. Lastly, the crossbar with the welded latch bottom was placed back on the chair with the fittings. The final latch assembly can be seen in Fig. 31.

Fig. 31. Final latch assembly.

6.6.2 Collar Assembly

Once the press fitting of the steel dowel pins in the collar was complete, an angle grinder with a cut-off wheel was used to cut each collar base half to remove the extra pipe. Then, a grinding wheel was used to remove excess material from each half to ensure there would be a gap between the two halves when they were placed around the bearing box. This gap is vital to ensure an appropriate clamping force would be applied once the collar was bolted together. The finished collar on the power column can be seen in Fig. 32.

Fig. 32. Final collar assembly installed around the bearing box.

6.6.3 Crossbar Rotation

To stop the crossbar from rotating within the fittings, a bolt was used to pin the bar within the fittings. To find the angle at which the latch needed to be oriented, the power column attached to the latch and the crossbar was rotated until the caster wheels were appropriately lifted off the ground. Then, at this rotation, the angle of the attachment for the power column was verified to ensure ease of use goals would still be met. Once it was verified that the caster wheels would be lifted correctly and the attachment angle was within the desired range, a hole was drilled through the fitting and the crossbar on each end, then a bolt was secured through each hole which acted as the rotation limiting pin.

7.0 Final Design Validation

7.1 Testing Procedure

To ensure the design met the necessary design specifications and goals laid out in Section 3.2 Technical Design, a series of tests were conducted with the final prototype. The details of these tests, how results were measured, and the range of acceptable test results are explained in TABLE IX below. As in other portions of the project, all tests, the device was used with the Quickie 2 folding wheelchair. Additionally, as the project IRB approval was only valid for interviews with wheelchair users, members of the team were used for conducting tests as opposed to external individuals. To reduce bias in the results due to team members having extensive experience operating the prototype, tests were to be conducted immediately after the completion of the prototype before this experience was gained. Additionally, each team member would attempt each individual test that required an operator once, except for the turn radius which required precise operation and had the largest room for error, in which each team member had three testing attempts.

TABLE IX

TESTING PROTOCOL

Specification	Testing Procedure	Acceptable Results
Both the chair and device must be able to fit in a sedan trunk.	The wheelchair must be collapsed, if possible, and placed into the trunk of a sedan. Then, the device is to be placed in the trunk with the wheelchair, and the trunk should be closed.	The trunk closing with both the wheelchair and device inside
Any pieces that inhibit the chair from folding must be able to be removed or altered without the use of tools.	Team members would alternate disassembling the pieces and folding the chair, using only their hands. All team members would note any instances that required excessive hand strength (defined as >5 pounds) or that they required the use of tools to continue.	All team members must be able to disassemble any attachments and fold the chair without the use of tools
The device must not weigh more than 28.6 pounds.	The device, with any components necessary for function (ie. the battery and battery casing/holding clamps), should be weighed using a scale. The weight measurement should be checked and recorded three times.	The weight must be less than or equal to 28.6 pounds during each measurement.
The attachment mechanism must follow ADA regulations for necessary hand strength to operate.	A luggage scale should be looped around the attachment mechanism. The scale should then be pulled down slowly, until the mechanism is released. The maximum load the scale displays during operation of the mechanism should be noted, and this should be repeated three times.	The maximum force to release the mechanism must be 5 pounds or less for each test of the mechanism.
A user must be able to traverse up and down ramps and hills with the maximum incline angle allowed by ADA regulations, at the maximum incline length of 20 feet.	The device will be tested by all members of the team driving the system up ramps and hills around WPI's campus that have varying slopes.	The system must successfully traverse up and down ramps and hills with a minimum incline of 7.125° and length of 20 feet. The system successfully traversing any inclines that are steeper and longer than specified will be considered as exceeding expectations.

Specification	Testing Procedure	Acceptable Results
A person using the device must be able to turn in a radius that follows ADA compliance.	A 5-foot diameter circle is to be drawn in chalk on flat pavement. The system will then be placed in the circle, with the rear axle in line with the center of the circle. Each team member will then have three attempts to complete a 360° turn in the wheelchair using the device to steer.	At least 5 of the 9 trials must show that the system remains entirely within the bounds of the circle during the turn.
The user must be able to attach the device at an angle no less than 30° from the ground.	Each team member should attempt attaching the device. While attaching, the team member should pause at the lowest point they feel the device must tilt for a successful attachment. This position will be held while another team member uses a protractor to estimate the angle of the device from the ground.	The angle between the device and the ground must be greater than 30° degrees from the ground to account for error in the measurement.
The device must function with a maximum weight of 250 pounds.	Each team member will drive the wheelchair with weights added to their lap until 250 pounds is reached to simulate a user of the maximum weight limit.	The device should properly accelerate and show no signs of its function being impaired by the additional weight.
The device must meet the Engineers' Toolbox standard for the factor of safety for the material type and conditions it experiences.	Simulations should be done on Ansys to represent worst case scenario loading on the mechanism while driving forwards and backwards as well as sitting stationary. For each respective simulation, the maximum stress each component of the mechanism faces should be recorded. The factor of safety for each component in each simulation should be calculated by dividing the material's yield strength by the maximum stress.	The lowest factor of safety calculated must fall between the range of 2.5-3, as a result below 2.5 would indicate an unsafe design and anything over 3 would indicate over engineering, or that further material could have been conserved.

7.2 Test Results

Upon completing the tests as detailed in TABLE IX, the following results were obtained and analyzed.

7.2.1 Transportation and Tool-Free Folding

Unfortunately, due to the decision to implement a fixed crossbar as opposed to the ideal design of a telescoping bar, the wheelchair is unable to fold with the device attached. Ultimately, this decision impeded any possibility for conducting the tests regarding transporting the device in a car trunk and folding the wheelchair without the use of tools, meaning that this prototype does not meet these goals. However, it is believed that with the installation of the telescoping crossbar design detailed in Section 4.5.1 Crossbar Selection and Appendix D, reaching these goals would be possible and the testing could be further explored.

7.2.2 Device Weight and Force Required for Latch Operation

In testing for both the weight of the final device and force required for latch operation, a luggage scale was used to measure the weight and force. For the weight measurement, the scale was connected to the middle of the power-column handlebars and, using the scale, the entire device was lifted from the ground. In the case of the latch operation force, the wheelchair was elevated, and the luggage scale was attached to Latch Top 2 and pulled downwards up until Latch Top 1 was fully released. All tests were performed three times to ensure accurate data was taken and the results are detailed in TABLE X below.

TABLE X

TEST RESULTS FOR WEIGHT AND LATCH OPERATION FORCE

Test	Acceptable Results	Trial 1	Trial 2	Trial 3
Device Weight	28.6 pounds or less	17.16 pounds	17.10 pounds	17.24 pounds
Latch Operation Force	5 pounds or less	1.80 pounds	1.68 pounds	2.10 pounds

As illustrated by the table, the final design successfully met the criteria for both overall weight and force required for latch operation in each conducted trial.

7.2.3 Turn Radius

After drawing a five-foot diameter circle on level ground, each team member was given three attempts at completing a 360 degree turn within the bounds of the circle. The testing layout can be seen in Fig. 33. Ultimately six of the nine trials for turning were successful, with each team member completing at least one successful turn, indicating that the turn radius constraint had been successfully met.

Fig. 33. Image of testing of the device turn radius.

7.2.4 Traversing Up and Down Inclines

After measuring the ramps and hills surrounding WPI's campus, it was found that the closest incline to the benchmark 7.125 degrees, and at least 20 feet long, was a hill on WPI's campus located on Institute Road. Using the iPhone Measure application, it was found that the incline of this hill was 8 degrees, and the path for testing spanned approximately 120 feet. Each team member was successful in traversing both up and down the hill using the propulsion-aid device. It is important to note, that for moving uphill it was necessary to adjust the speed to the highest of the three available settings and there was a clear loss in speed towards the top of the hill, though each member was able to reach the top of the hill with the deceleration experienced. This deceleration means there is a limit on the device as to how long it may maintain such an incline; however, given that the tested incline length and angle was higher than ADA standards, the device more than meets the criteria for use on inclines.

7.2.5 Device Attachment Angle

Throughout each team member's trials for attachment angle, it was concluded that the attachment angle for this device was approximately 60 degrees, which is shown in Fig. 34. This angle is almost double the minimum angle of 30 degrees, proving that the device successfully fulfills the project criteria.

Fig. 34. Photo showing attachment angle.

7.2.6 Weight Limit and Factor of Safety

As highlighted in 5.2.2 Ansys Simulations, the attachment mechanism design had a factor of safety of 2.835, placing the device on the upper half of the desired range of 2.5 – 3. This indicated that there were no concerns of the attachment experiencing material failure due to the maximum weight, but tests were conducted to ensure the power-column motor would not perform negatively due to the full capacity of the wheelchair. After the addition of the weights to one of the team members' laps while using the device to reach the weight capacity, each team member indicated that there were no signs of negative performance effects from the full weight of 250 pounds, and thus the device fulfills these criteria.

8.0 Broader Impacts

When designing and creating the product the team ensured that the engineering code of ethics was followed. With creating the device the team sought to meet two of the UN sustainability goals, Goal Three, creating good health and well-being for all, and Goal Twelve, responsible consumption and production [38]. To align with these goals, the team sought to create a low-cost device that would better human welfare and allow for equal access for accessibility. Furthermore, the team also sought to ensure the use of sustainable development was the basis of the design, manufacturing, and processes.

Medicare is the insurance that covers many people with disabilities and is how many wheelchair users get coverage for their chairs and other mobility aid devices. Custom wheelchairs are a necessity for many people who rely on mobility devices. Medicare has strict requirements dictating the users' ability to qualify for different types of mobility aids. These guidelines can cause instances in which a user would greatly benefit from a custom or an electric wheelchair, but do not meet insurance requirements to get one covered, resulting in their use of a standard manual wheelchair, limiting their ability to travel long distances, and putting them at risk for injuries caused by strain on the upper body. Additionally when a user does qualify and receive a custom wheelchair the coverage is limited, many times only covering the user when they use the device within their home [39].

Propulsion aid devices assist manual wheelchair users, but unfortunately most styles of device do not meet Medicare requirements. This lack of coverage creates an absence of financial regulation and support around these devices, often causing higher monetary costs expected to be paid out of pocket. These devices also often add unnecessary features such as cup holders, turnkey ignition, and lights which although can be useful are not completely necessary and cause for the market price to be heavily increased in addition to the already inflated prices of the medical device market. To alleviate these problems, the team sought to create a device that brought a propulsion aid back to the basics to reduce cost and while maintaining a user centered design. The 2021 United States disability report stated that the median household income with disability was $55,600 where that without disability was $82,400 [40]. As discussed, propulsion aids often have costs of up to $8,000, with an additional estimated $1,000 of maintenance, and an estimated five years of use before another device would need to be purchased. By significantly lowering the upfront cost of the device, a greater number of users would be able to buy such a device that would allow them to maintain a more active lifestyle and could decrease their risk of upper body injuries.

In the production of this device, the team also sought to use responsible consumption and production practice in both the design and manufacturing to lower the environmental costs associated with prototyping and manufacturing a new product. The project used sustainable prototyping methods such as limiting waste produced, upcycling parts and materials, and performing material analysis looking past the device's main function by ensuring that components can be recycled at the end of its life. These methods demonstrate the idea of circular economy, a practice which is becoming more commonly recognized and important in engineering.

9.0 Conclusion

Upper-body injuries caused by overuse from manual wheelchair propulsion is a common challenge that many wheelchair users face. While there are propulsion aid devices on the market, these devices are often expensive, increase the footprint of the wheelchair, or do not provide the necessary requirements for physical movement and accessibility. This project focused on creating a propulsion aid that would address these issues by improving ease of use, enhancing maneuverability, and engaging in sustainable prototyping processes. After conducting research and interviews with wheelchair users, the team conducted a year-long process entailing several design iterations, finite element analysis of components, and the fabrication of the device through CNC milling and adapting recycled materials.

Due to the small size of the team, limited time frame, and limited access to Washburn Shops, the focus of this design process was placed on the attachment mechanism between the power-column and wheelchair. This focus ultimately meant that a decision was made to use a semi-permanent fixed cross bar, as opposed to the ideal telescoping design for the bar. As a result, the final device and attachment mechanism successfully met or exceeded all the device requirements relating to the device and attachment mechanism function, the focus for this project, but was unable to attain the goals related to collapsing the folding wheelchair without the use of tools. The most notable of the areas in which the device exceeded the requirements were the attachment angle and the ramp angle. For the attachment angle, the design doubled the requirement, measuring at 60 degrees compared to the constraint of 30 degrees. For the ramp angle, the device was able to be used on an 8-degree slope for 120 feet, exceeding the ADA standard of 7.125 degrees for 20 feet for ramps. Exceeding this requirement allows for the ability of this device to be used in a variety of terrain and places that do not meet to ADA compliance.

The final result is a functioning prototype of a tiller-controlled device and attachment system for folding wheelchairs that lays the foundation for the development of a user friendly and financially attainable propulsion aid device.

10.0 Future Recommendations

Design is an iterative process where there is always a place for improving existing products, as is the case for this project. If work on this propulsion aid were to continue, there are several points of improvement for the design that were unable to be completed over the course of the year-long project. These recommendations are primarily split between two of the major subassemblies of the design: the crossbar and the power-column.

10.1 Crossbar Recommendations

As highlighted in 4.5.1 Crossbar Selection, it is believed that a telescoping crossbar will best suit the client needs. Not only would the telescoping bar allow the bar to be easily removed or collapsed to allow the wheelchair to fold for transportation in a vehicle, but it would also accommodate for a variety of chair width and frame types. An additional note for this crossbar design is that it is specific to the folding wheelchairs due to the frame style it requires, meaning it would not be suitable for use on rigid wheelchairs, another form of manually propelled wheelchair. To further expand the market and usability for this device, an adaptive component for using the telescoping bar on a rigid chair would need to be created.

As for the mechanism of telescoping adjustment, a bike clamp style design is the suggested method of release as detailed in Appendix D. This style would allow for adjusting the bar for transportation to be done without the use of tools and would accommodate for a wide range of hand dexterity and physical availability as it can be engaged or released with a flat palm or the back of the hand if needed. Ultimately, with these changes implemented it is also believed that the two project goals that the final prototype was unable to meet, fitting in a small trunk alongside a wheelchair and allowing the chair to be collapsed without the use of tools, would be fulfilled resulting in an entirely successful design.

10.2 Power-Column Recommendations

Once the final prototype was completed, there were many parts of the power-column that evidently could be improved upon. The first is to reduce the overall weight of the power-column. Though the device was below the weight limit discussed in the constraints, it may still be further reduced to decrease the effort a person must use to lift or manipulate the power-column. The bulk of the weight was from the motorized wheel and battery and given that the motor greatly exceeds expectations for mobility, it can be assumed that a smaller, lighter motor and battery may be suitable for the design. Furthermore, the current drive wheel uses a brushless DC motor for both accelerating and braking. During testing, it was found that this braking system did not provide a quick deceleration, which is often preferred in tight, crowded spaces or moving down hills. Therefore, a stronger, more direct, braking system should be incorporated. Additionally, as the final device used a combination of electronic devices from two electric scooters, a future iteration should improve on the electrical management on the device. The wiring and connections between components from the different scooters were troublesome throughout the prototyping process. While using separate broken scooters was done intentionally to maintain a sustainable prototyping process, improving the electrical components would result in a higher quality final product.

In terms of the manufacturing of the power-column, there are three key improvements. The current power-column has a splint in the middle which allows for the height to be modified from the original electric scooter. In a final version of this device the column itself should be manufactured to this height, to eliminate the need for a splint. Similarly, the bearing box should be designed to have geometry of the collar required for device attachment, eliminating the use of an external collar. Lastly, once the device is detached, it must be laid down or carefully propped up against something, which makes it difficult to switch over to manual propulsion for short periods of time. To resolve this issue kickstand or rest should be added to the power-column so it may stand up on its own while the user is not actively operating it.

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Appendix A: IRB Approval and Interview Questions

WORCESTER POLYTECHNIC INSTITUTE

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

Institutional Review Board

FWA #00030698 - HHS #00007374

Notification of IRB Approval

Date:	12-Oct-2023
PI:	Sarah Jane Wodin-Schwartz
Protocol Number:	IRB-24-0110
Protocol Title:	Front Wheel Wheelchair Power Assist
Approved Study Personnel:	Steriti, Stephanie T~Wodin-Schwartz, Sarah Jane~Jacene, Megan R~Borden, Amanda L~
Effective Date:	12-Oct-2023
Exemption Category:	2
Sponsor*:	

The WPI Institutional Review Board (IRB) has reviewed the materials submitted with regard to the above-mentioned protocol.We have determined that this research is exempt from further IRB review under 45 CFR § 46.104 (d). For a detailed description of the categories of exempt research, please refer to the IRB website.

The study is approved indefinitely unless terminated sooner (in writing) by yourself or the WPI IRB. Amendments or changes to the research that might alter this specific approval must be submitted to the WPI IRB for review and may require a full IRB application in order for the research to continue. You are also required to report any adverse events with regard to your study subjects or their data.

Changes to the research which might affect its exempt status must be submitted to the WPI IRB for review and approval before such changes are put into practice. A full IRB application may be required in order for the research to continue.

This approval is only for interviews. You will need to create a modification to your record and provide the IRB with the protocols and design of prototype /testing.

Please contact the IRB at irb@wpi.edu if you have any questions.

*if blank, the IRB has not reviewed any funding proposal for this protocol

We are students from Worcester Polytechnic Institute completing our Major Qualifying Project. We are working alongside Charles Croteau, a local wheelchair adaptation inventor, to research and design a front wheel wheelchair power assist device. We would like to talk to you about your experiences with wheelchairs and power assist devices as well as run our preliminary design idea(s) by you to see what your thoughts and feedback are. Participation in this interview is voluntary, and you may withdraw at any moment. The interview will take approximately 30 minutes and all personal and identifiable information will be kept confidential. Do you agree to partake in the interview? If so, may we record the interview and take notes for data collection purposes?

1. What type of wheelchair and/or propulsion method do you currently use?
    a. What are the pros and cons of your current chair? Is there anything that you wish was different?
2. Have you tried any power assist devices for your chair?
    a. Which ones? What did you like and dislike about it?
3. What needs do you expect to be met by a power assist device for your chair?
4. What are your thoughts on front-wheel power assist devices for manual wheelchairs?
5. There are currently front-wheel power assist devices that allow a wheelchair to be controlled like an electric scooter. We are proposing creating a front wheel power assist device that sits closer to the user than what is readily available on the market. This would allow the wheelchair to make tighter turns, approach surfaces like tables and counters, and be more compact than other front power assist devices.
    a. Would a device like this seem interesting to you?
    b. In order to bring the device closer, we are planning on placing the post for the handlebars in between the legs of the user, directly in front of the edge of the wheelchair seat. Would you find it problematic to have the post in between your legs or would this be preferred over a front power device that sticks out past the footrests?
6. How difficult is it for you to access anything underneath your seat?
    a. Do you think our design right now would be difficult to use with it being mounted under the seat?
7. Is there anything you think we should change in our design to make it easier to operate?

Appendix B: Detailed Summary of Interview Responses

After receiving IRB approval, which can be seen in Appendix A, two wheelchair users were interviewed in addition to the continued conversations with Mr. Croteau. The interviews focused on understanding the user's experiences with manual wheelchairs as well as power assist devices, which can be seen by the questions asked in Appendix A. All three of the wheelchair users shared their experiences of wrist or shoulder injuries as a result of the repetitive movement to self-propel their chairs, highlighting their needs for a propulsion aid. Two of the users shared that they use a rear-wheel device currently, but that it does not get them over many obstacles and is difficult to use in different weather conditions such as snow, rain, and ice, resulting in the need to manually propel the wheelchair while the device is operating. One user who has the SmartDrive spoke on how they found that using it on sidewalks and pavement outdoors, quickly led to deterioration in the joints of the omni-wheel segments, the rollers in the wheel that allow the chair to turn, meaning maintenance was required more frequently. When talking to Mr. Croteau, it was found that a front wheel device is better at traversing obstacles due to their ability to pull the chair over the obstacles from the increased traction they provide. More weight is put on the powered wheel of the front-wheel devices than the powered wheel of the rear-wheel devices which allows for more traction. This increased traction is due to the fact that when using the rear-wheel devices, all four wheels of the wheelchair itself remain on the ground as well as the device's wheel, so the weight is distributed to five wheels; however, in front-wheel devices, the caster wheels of the wheelchair are lifted off of the ground during attachment, so the weight is distributed between three wheels.

Mr. Croteau also shared his negative feedback on the front wheel devices that are already on the market. One of the main problems that he spoke of was how most of the propulsion aid devices on the market today, specifically tiller-controlled systems, was that their size makes it harder to move around in tight spaces like grocery store isles, small rooms, hallways, or in tight crowds. Mr. Croteau mentioned how some of the current designs and products that already exist put the user in an uncomfortable and vulnerable position that can lead to injury for the user. One of the first problems discussed was how the handlebars for many tiller control devices extend far beyond the end of the user's wheelchair, causing the user to constantly reach their arms far forward, leading to potential arm and back strain and fatigue. Another issue that was discussed was that the front wheel of the device often sits a considerable distance from the wheelchair footplates, making it difficult for a user to reach surfaces such as countertops and desks. The last major issue that Mr. Croteau discussed was the level of difficulty in attaching many of the current devices on the market to manual wheelchairs. It was found that in some cases, the closer the device is to the user, the further the user must lean forward to attach the device, increasing the difficulty of operating the propulsion aid. These experiences led the team to create a device that addressed these issues and concerns and allowed real users to influence the design so that it would be more applicable and created for the users themselves.

Appendix C: Gantt Charts by Term

Task	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Fabrication Work							
Lab and User Trainings for on Campus Workspaces	■	■					
Training on Tools at Charlie's Workshop	■	■					
Hands-on Work with Pre-Existing Proof of Concept			■	■	■		
Design Work							
Brainstorm Overall Design	■	■	■				
Brainstorm Design Attachment				■	■		
CAD of Wheelchair				■	■	■	
Design Attachment Matrix						■	■
Report Work							
Background Research	■	■	■				
Specs, Criteria, Goal Statement, and Objectives			■	■	■		
Patent Research and Meeting			■	■			
IRB Application				■	■	■	
Start calculations (Tipping/stability, turning radius)					■	■	■

A Term Gantt Chart

Task	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Attachment Work							
CAD Attachment Mechanism	■	■	■	■	■	■	
Prototype Attachment Design		■	■	■	■	■	
Test Attachment Mechanism Prototypes			■	■	■	■	
Ansys Simulations and Calculations							■
Propulsion Aid Testing							
Implement New Battery with the Scooter	■						
3D Print/Laser Cut a Casing for Battery/Motor Controller		■					
Firmly Attach Scooter using Design Dimensions			■	■			
Test Functioning Propulsion Aid					■	■	
Prepare the Scooter Column for Collar Placement							■
Report Work							
Interview Wheelchair Users	■	■					
Write Background	■	■	■				
Outline Methods/Design Section				■			
Write Methods/Design Section					■	■	■
Finalize Calculations (Tipping/Stability, Turning Radius)					■	■	■

B Term Gantt Chart

Task	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Attachment Work							
Washburn Final Trainings	■						
Finalize Design and Simulations	■	■	■	■			
Create CAM for Machining			■	■			
Create the Attachment and Collar			■	■	■	■	
Send Components Out for Welding					■		
Other Design Elements							
Finalize Steering Column Adjustments			■	■			
Create Fixed Cross Bar			■	■	■	■	
Polish Battery and Motor Holder					■	■	
Report Work							
Methods/Design Section	■	■			■	■	
Environmental Outline and Research		■	■	■	■	■	
Design Verification					■	■	■
Manufacturing						■	■
Appendix Work							
Ansys Simulation Findings						■	■

C Term Gantt Chart

Task	Week 1	Week 2	Week 3	Week 4	Week 5
Testing					
Test Turn Radius and Manueverabilty	■				
Test Ramps and Hills	■				
Test Weight and Hand Strength	■				
Report					
Introduction and Abstract	■	■			
Final Design Validation	■	■			
Future Recommendations	■	■			
ENV Design Section	■	■			
ENV Reseach, Implantation and Edits	■	■	■		
ENV Background Section		■	■		
Broader Impacts		■	■	■	
Appendix					
CAD Iterations	■	■			
Completed Calculations		■	■		
Presentation					
Complete Poster		■	■		
Write and Rehearse Presentation			■	■	■

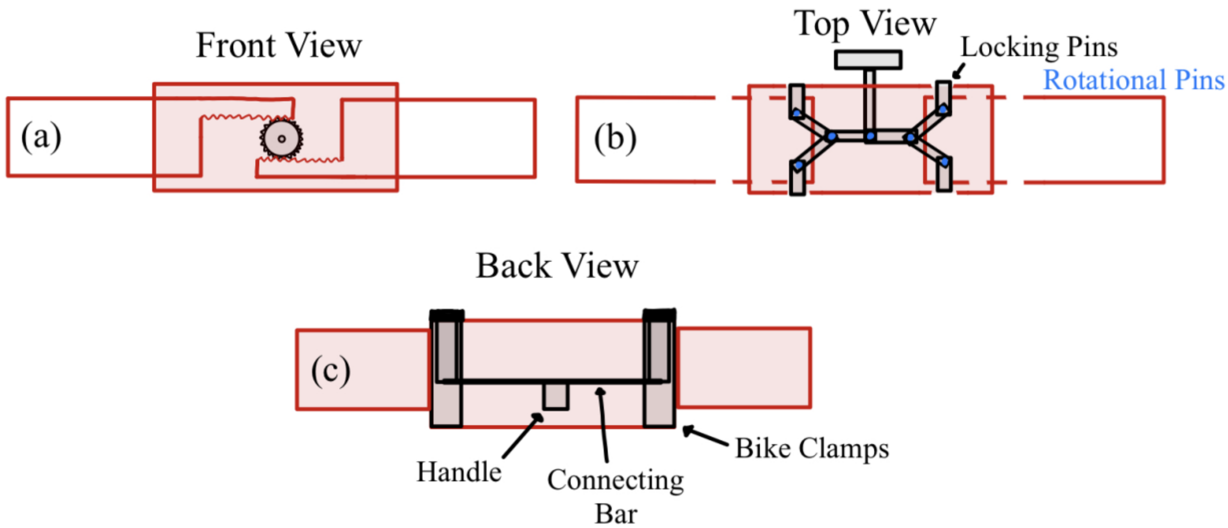
D Term Gantt Chart

Appendix D: Details of the Crossbar Telescoping Method

A Pugh matrix was carried out for the telescoping method that would be used to allow for the implementation of the telescoping crossbar (Table below). The three designs considered can be seen in the figure below. A rack and pinion design (Figure a) would allow for the telescoping segments to extend equally on each side, and some sort of pin would be put into the center of the gear to lock the position. The arm linkage design (Figure b) would use incremented holes in the telescoping sections and pins that extend using one handle in the back to lock the position. The bike clamp design (Figure c) would have a bar connecting both clamps on each end of the middle segment and a handle to open and close them together to lock the position. Increments would have to be marked on the telescoping sections so that the middle section is placed in the middle of the chair. Based on the ease of prototyping, ease of use for the end user, security while the wheelchair is in motion, and manufacturing cost based on complexity, the bike clamp design was selected as the best method.

PUGH MATRIX FOR TELESCOPING METHOD

Idea	Ease of prototyping	Ease of use for end user	Security while the wheelchair is in motion	Manufacturing cost based on complexity	Weighted Total
Weight	1	3	4	2	
Bike clamps	3.00	2.67	2.67	3.00	27.67
Rack and pinion	2.00	2.67	1.67	2.00	20.67
Arm linkage	1.00	1.33	2.33	1.33	17.00



Sketches of considered telescoping methods. (a) Rack and pinion design. (b) Arm linkage design. (c) Bike clamp design.

Appendix E: Weight Distribution Calculations

The center of gravity of the wheelchair was calculated by averaging the measured center of gravity from research data that was retrieved of a typical wheelchair with someone sitting in it, with that of the measured COG of the power-column attachment [31]. To do complete these calculations, the following points were first defined:

A: the location of the back axle of the wheelchair

B: the ground directly underneath the back axle

C: The ground directly underneath the front axle

C': the location of C after raising the front axle due to the power-column attachment

D: COG of wheelchair and person

D': COG of wheelchair and person considering the power-column attachment

First the typical COG of someone sitting in a wheelchair was calculated, accounting for the slight angle between the front and back wheels due to the addition of the power-column attachment. The front wheel was measured to be raised by 1" off the ground and trigonometry was used to find the new COG with respect to point A. Utilizing the COG measurements before accounting for the power-column attachments of (3.684",10.203"), a distance from BD equaling 12" and a distance of BC equaling 16", first the angle between CBC'(θ) is calculated by:

$$sin\theta = \frac{CC'}{BC'} = \frac{1"}{16"}, \theta = 3.58deg$$

$$tan^{-1}(\frac{AD_y}{AD_x}) = \phi = tan^{-1}(\frac{10.203}{3.684}) = 70.15deg$$

$$D'_y = \sqrt{(AC'^2 + C'D'^2)} * cos(90 - \phi - \theta) = 10.848cos(16.27) = 10.413"$$

$$D'_x = \sqrt{(AC'^2 + C'D'^2)} * sin(90 - \phi - \theta) = 10.848sin(16.27) = 3.039"$$

Once D' was calculated to be (3.039",10.413"), the total COG was found by calculating the average of this COG and the power-column COG. The power-column COG was measured to be 17" from the 12.5" from the ground, or 0.5" above point A. The terms were redefined as:

$CG_w = (3.039, 10.4133)$, as the CG of person and the chair

$CG_s = (17, 0.5)$, as the CG of the power-column

$W_w = 205\ lbs$, as the weight of the chair and person

$W_s = 25 lbs$, as the weight of the power-column.

The distance b, from CG_w to the total CG (CG_t), and the distance a from CG_s to CG_t were calculated as follows:

$$b = W_s(CG_{s_x} - CG_{w_x})/(W_s + W_w)$$

$$a = W_w(CG_{w_y} - CG_{s_y})/(W_s + W_w)$$

To get the coordinated of the total CG with respect to point A:

$$CG_{T_x} = CG_{w_x} + b = 3.039" + 25lbs(17" - 3.039")/(25lbs + 205lbs) = 4.557"$$

$$CG_{T_y} = CG_{s_y} + a = 0.5" + 205\ lbs(10.413" - 0.5")/(25lbs + 205lbs) = 9.336"$$

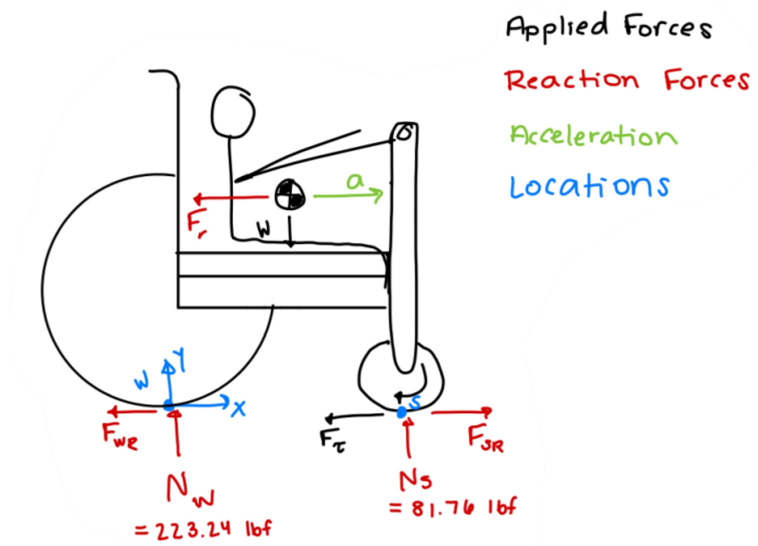
$$CG_T = (4.557", 9.336")$$

To get the coordinates of the total CG with respect to point B:

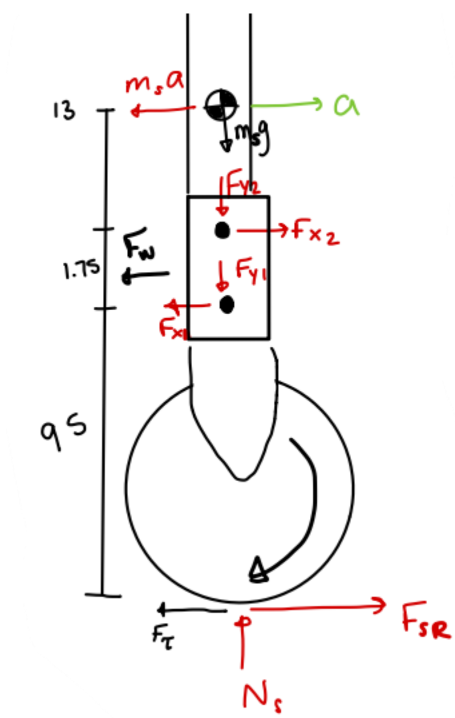
$$CG_{T_y} = CG_{T_y} + \ AB = 9.336" + 12" = 21.336"$$

$$CG_T = (4.557", 21.336")$$

Appendix F: Analysis of Forces on the Attachment Components



Freebody diagram of the wheelchair, propulsion-aid system while a user drives forward.



Freebody diagram of the power-column and collar as the user drives forward

The forces that will directly act on the latch mechanism are those that act on the pegs of the power-column collar. To analyze the attachment strength through simulations, F_{X1}, F_{X2}, F_{Y1}, and F_{Y2} must be found.

Known values and locations:

$$w = wheelchair = (0, 0)$$

$$COG = center\ of\ gravity = (4.557, 21.336)$$

$$s = powercolumn\ (scooter) = (17, 0)$$

$$m = mass\ of\ the\ system = \frac{305\ lb_f}{32.2\ \frac{ft}{s^2}} = 9.47\ slug$$

$$m_s = mass\ of\ powercolumn = \frac{20\ lb_f}{32.2\ \frac{ft}{s^2}} = 0.62\ slug$$

$$a = acceleration\ of\ powercolumn = 3.38\ \frac{ft}{s^2}$$

$$v = maximum\ velocity\ of\ the\ powercolumn = 15\ mph = 22\ \frac{ft}{s}$$

$$r = radius\ of\ the\ powercolumn\ wheel = \frac{1}{3}\ ft$$

Solve for F_r, the force caused by acceleration of the system:

$$F_r = ma = 9.47 slug \left(3.38 \frac{ft}{s^2}\right) = 32.0 lb_f$$

Solve for F_w, the force on the power-column by the wheelchair:

$$F_w = (m - m_s)a = (9.47 - 0.62)\ slug \left(3.38\ \frac{ft}{s^2}\right) = 29.91\ lb_f = F_{X1} + F_{X2}$$

Solve for F_{sR}, the force of rolling resistance (friction):

$$power = mav = 9.47\ slug \left(3.38\ \frac{ft}{s^2}\right)\left(22\ \frac{ft}{s}\right) = 704.19\ \frac{lb_f\ \cdot ft}{s}$$

$$\tau = torque = \frac{power}{angular\ velocity}$$

$$\omega = angular\ velocity = \frac{v}{r} = \frac{22\frac{ft}{s}}{\frac{1}{3}ft} = 66\frac{rad}{s}$$

$$\tau = \frac{704.19\ \frac{lb_f\ \cdot ft}{s}}{66\frac{rad}{s}} = 10.67\ lb_f \cdot ft$$

$$F_{sR} = \frac{\tau}{r} = \frac{10.67\ lb_f \cdot ft}{\frac{1}{3}ft} = 32\ lb_f$$

Solving for the forces acting on the collar pegs:

$$\sum F_X = m_s a = 32\ lb_f - F_{X1} + F_{X2}$$

$$\sum M_{COG} = 0 = 32\ lb_f(1.083\ ft) - F_{X1}(0.292\ ft) + F_{X2}(0.146\ ft)$$

$$F_{Y1} = F_{Y2} = F_Y$$

$$\sum F_Y = 0 = -m_s g - 2F_Y + N_s = -81.76\ lb_f + 0.62\ slug\left(32.2\frac{ft}{s^2}\right) = -61.796\ lb_f = -2F_Y$$

$$\boldsymbol{F_{X1} = 207.8\ lb_f}$$

$$\boldsymbol{F_{X2} = 177.9\ lb_f}$$

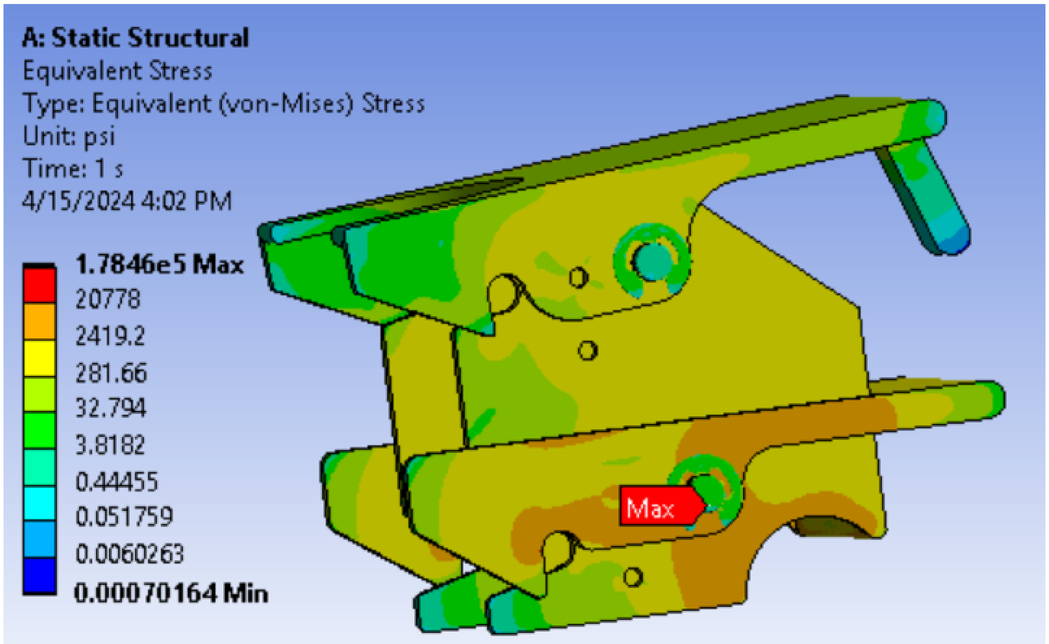
$$\boldsymbol{F_{Y1} = F_{Y2} = 30.898\ lb_f}$$

Note: The forces listed are distributed across two pegs on the final collar. The force that each peg will experience is ½ of the calculated force.

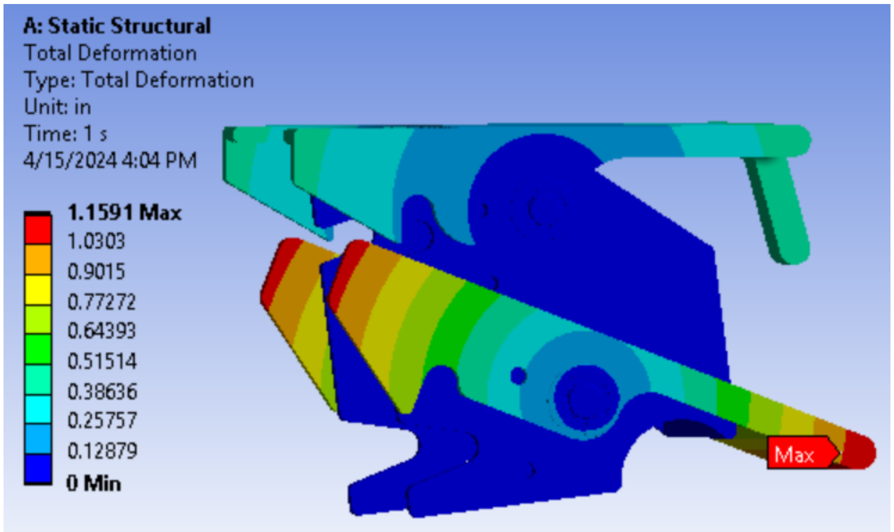
Appendix G: Ansys Simulation Results

The double latch mechanism and collar were each tested in Ansys for three separate loading scenarios: stationary, moving forwards, and moving backwards. Von Mises stresses and deformation were checked for each simulation to ensure proper safety and function of the design.

Initial results of the original design illustrated that changes would need to be made to the design in order to reach proper safety factors. The deformation and stresses in this simulation are shown below. Changes made based on the failure of this design include the guiding path of the bottom peg on the bottom latch, the diameter of the collar pegs and clevis pins, and the thickness of both latch tops and the latch bottom.



Logarithmic view of the stresses on the original design without deformation effects in forward loading

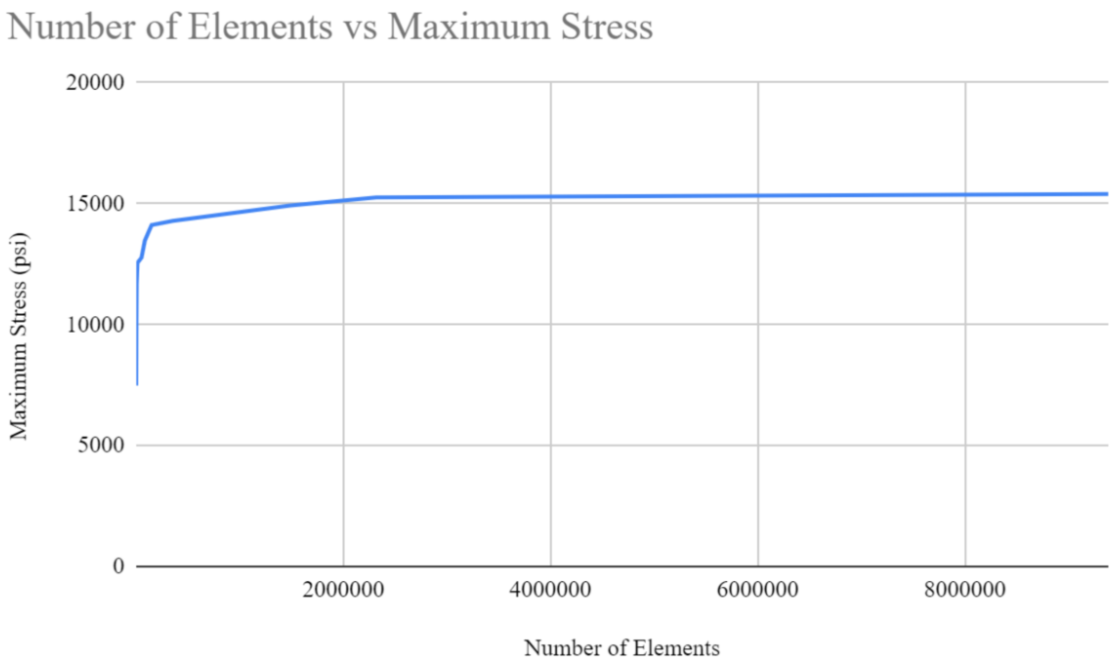


True scale deformation of original design in forward loading

After design changes were made, convergence was tested to ensure the proper element size was used in the final simulations. These results are detailed below. Based on the data, a mesh size of 0.015 was chosen.

DATA COLLECTED FOR MESH CONVERGENCE

Mesh Size (in)	**Number of Nodes**	**Number of Elements**	**Stress (psi)**
0.2	17728	8476	4706.8
0.1	36678	18494	6525
0.05	119193	63738	7905.7
0.025	494636	278597	15067
0.015	1397935	802386	16511
0.01	3208733	1862746	16795
0.009	4014293	2336882	17112
0.00875	4239053	2468176	17106
0.0075	5798413	3384748	17106



Graph of mesh convergence

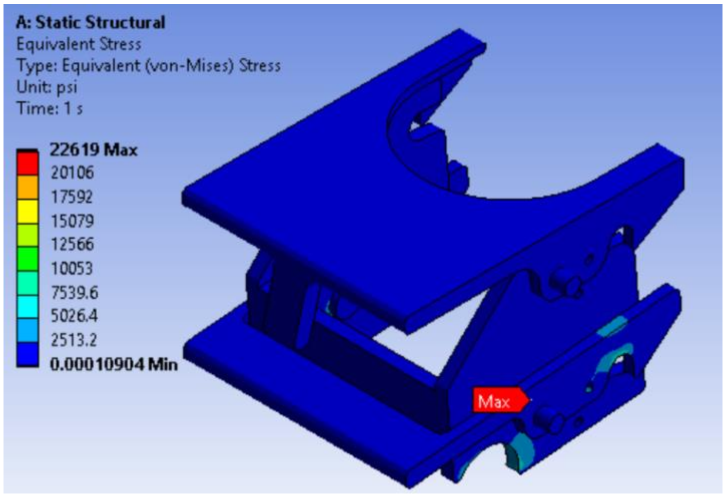
The element size and design changes led to the final results. The stresses on each component in each loading scenario is summarized in the table below.

SUMMARY OF MAXIMUM STRESSES ON EACH COMPONENT

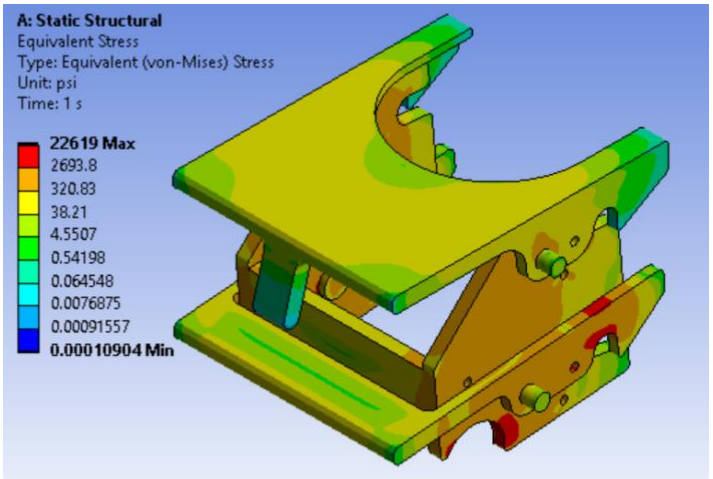
	Element Size	Nodes	Elements	Max Stress	FOS
Attachment Forward	0.015	1402178	804857		
Aluminum					
Aluminum (Weld)				5646.3	3.542142642
1045 Steel				22619	2.886953446
Top Latch 1 Forward	0.015	259210	147260		
Aluminum				14111	2.83466799

Attachment Backward	0.015	1406519	807664		
Aluminum					
Aluminum (Weld)				2802.1	7.137504015
1045 Steel				20076	3.252639968
Top Latch 2 Backward	0.015	456247	263017	13075	
Aluminum				13075	3.059273423
Attachment Stationary	0.015	1406519	807664		
Aluminum				4462.5	8.963585434
Aluminum (Weld)				4462.5	4.481792717
1045 Steel				1734.9	37.63905701
Collar Forward	0.015	1779000	1046137		
Aluminum				12847	3.11356737
4140 Steel				16741	13.12346933
Collar Backward	0.015	1779000	1046137		
Aluminum				11892	3.363605785
4140 Steel				14331	15.33040262
Collar Stationary	0.015	1779000	1046137		
Aluminum				1376.6	29.0570972
4140 Steel				1651.9	132.9983655

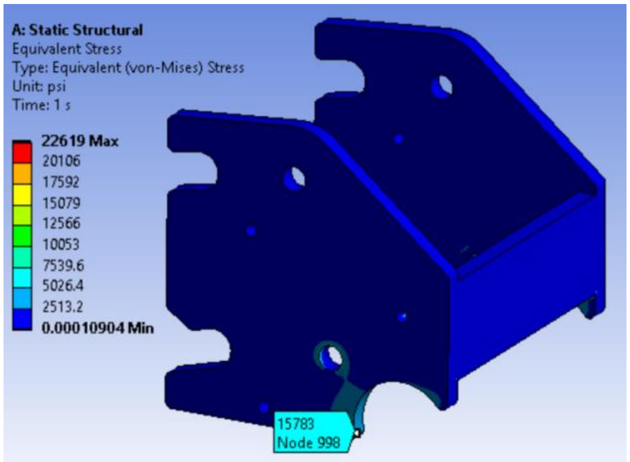
Images of the Von Mises stresses on each loading scenario are included below. These images come from simulations of both the entire attachment mechanism, and simulations of selected individual components.



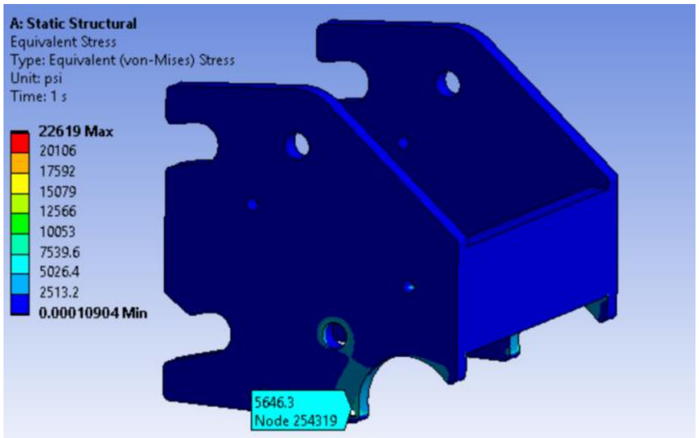
True scale view of the Von Mises stresses of the entire latch mechanism in forward loading with the marked maximum stress



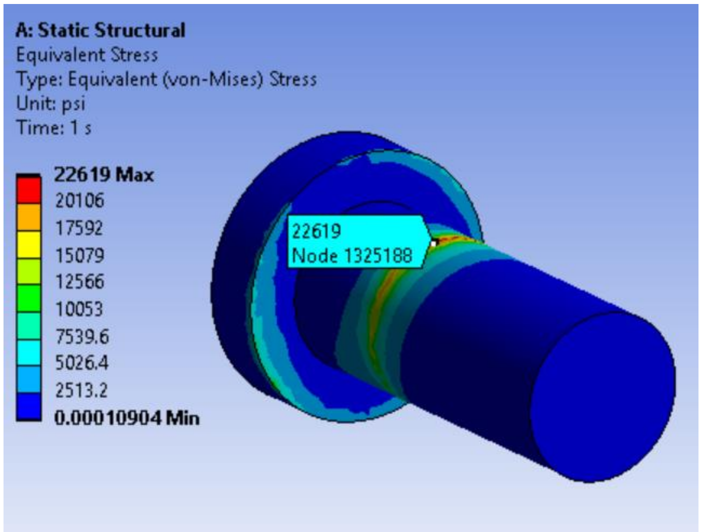
Logarithmic scale view of the Von Mises stresses of the entire latch mechanism in forward loading



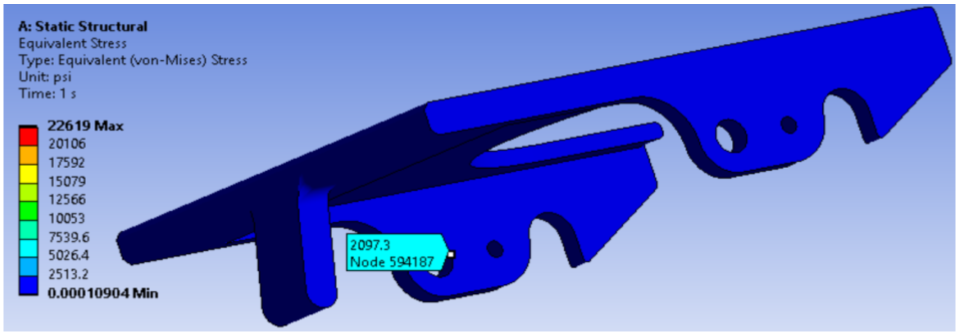
True scale view of the Von Mises stresses of the bottom latch in forward loading with the maximum stress marked



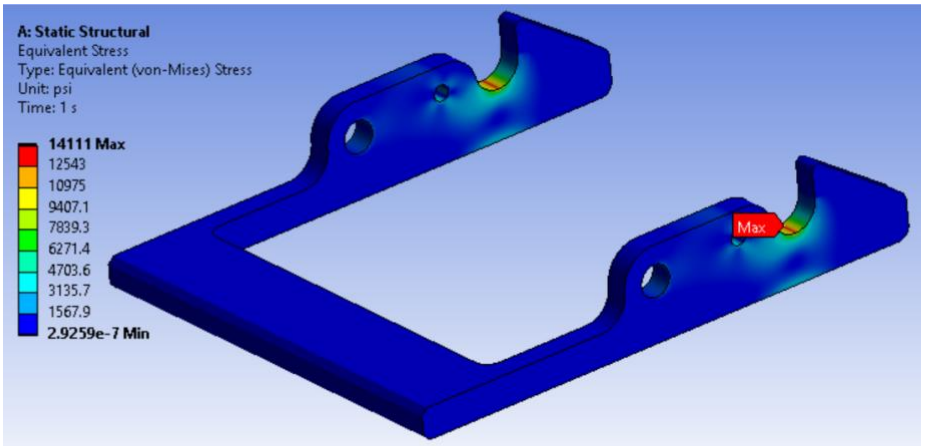
True scale view of the Von Mises stresses of the bottom latch in forward loading with the maximum stress experienced by the area surrounding the weld marked



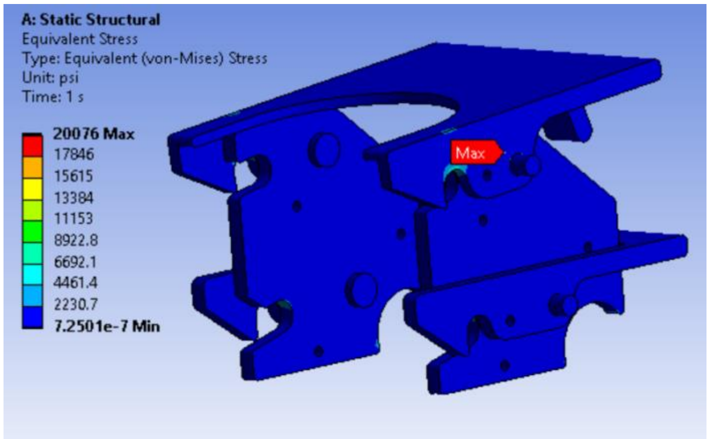
True scale view of the Von Mises stresses of a Clevis pin with the marked maximum stress on the pins in forward loading



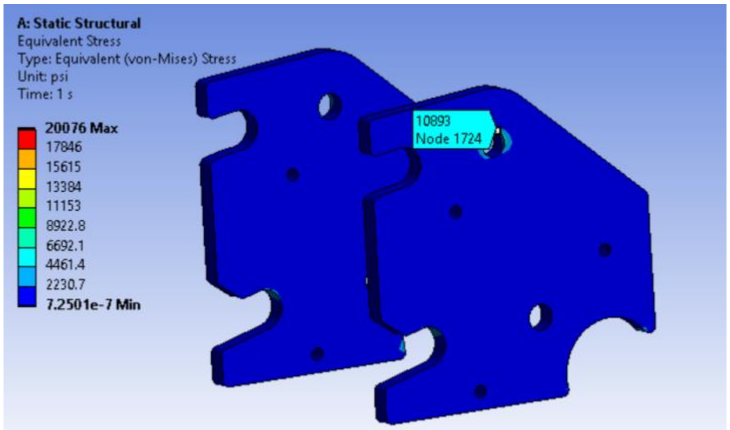
True scale view of the Von Mises stresses of Latch Top 2 with the marked maximum stress in forward loading



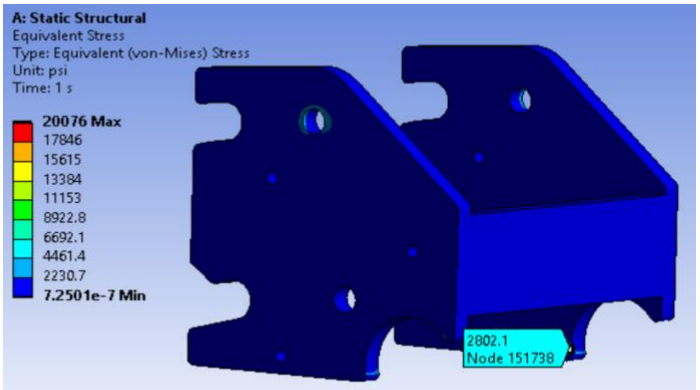
True scale view of the Von Mises stresses of Latch Top 1 with the marked maximum stress in forward loading



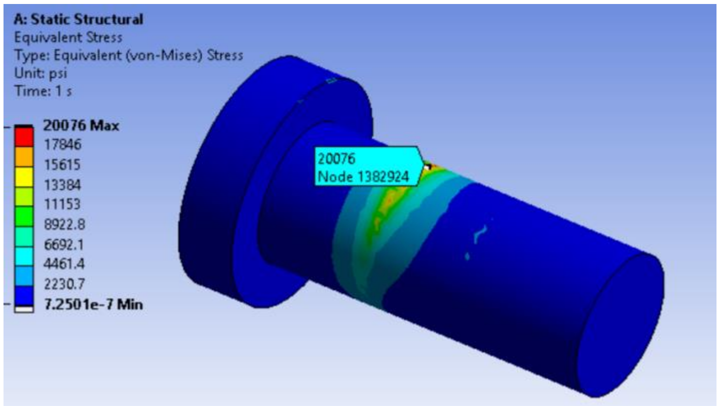
True scale view of the Von Mises stresses of the entire latch mechanism in backward loading with the marked maximum stress



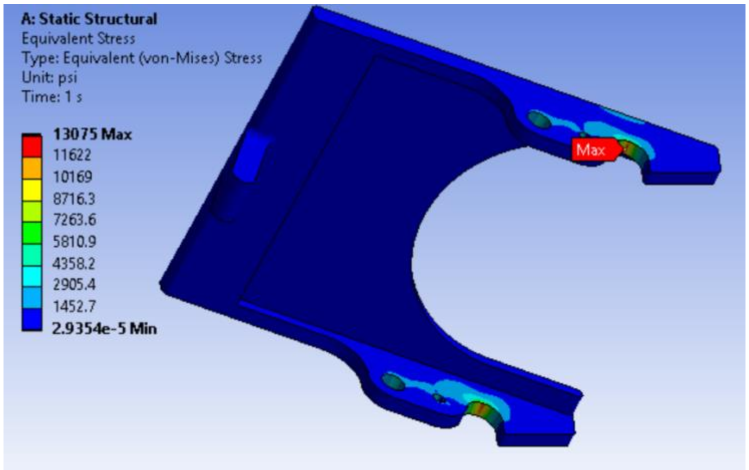
True scale view of the Von Mises stresses of the bottom latch in backward loading with the maximum stress marked



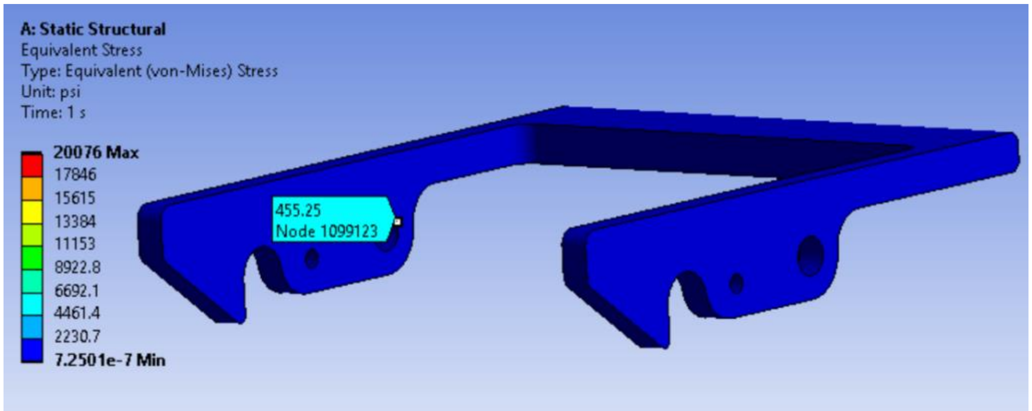
True scale view of the Von Mises stresses of the bottom latch in backward loading with the maximum stress experienced by the area surrounding the weld marked



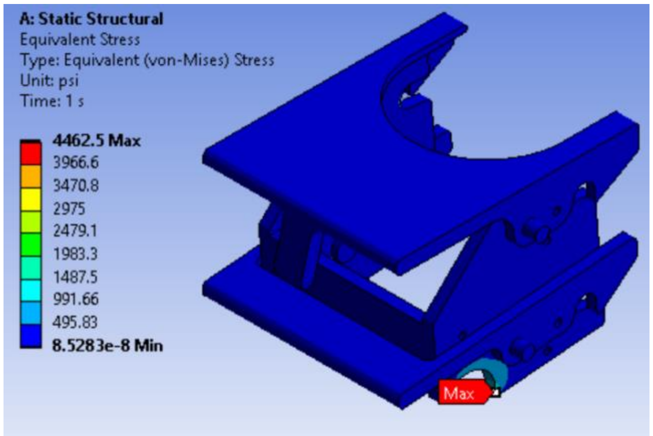
True scale view of the Von Mises stresses of a Clevis pin with the marked maximum stress on the pins in backward loading



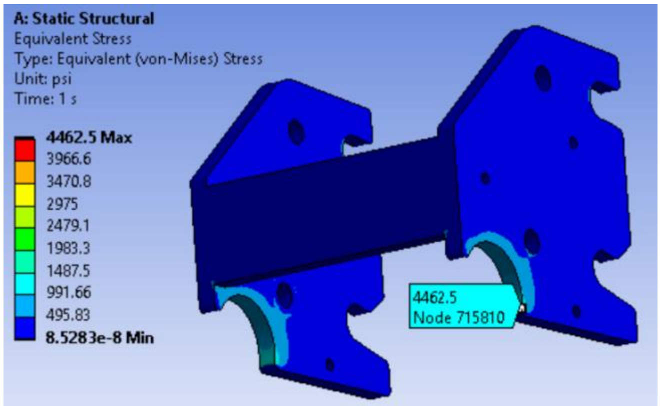
True scale view of the Von Mises stresses of Latch Top 2 with the marked maximum stress in forward loading



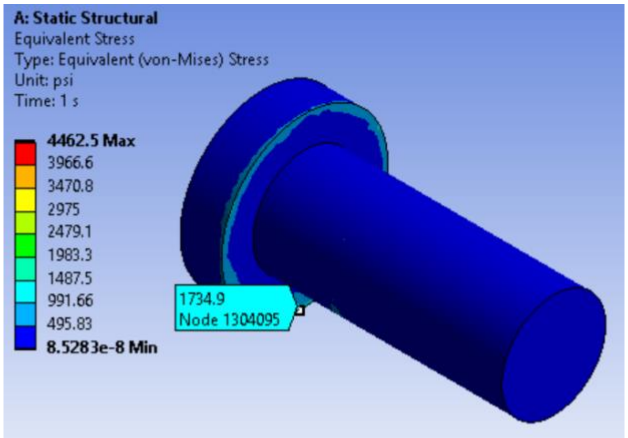
True scale view of the Von Mises stresses of Latch Top 1 with the marked maximum stress in backward loading



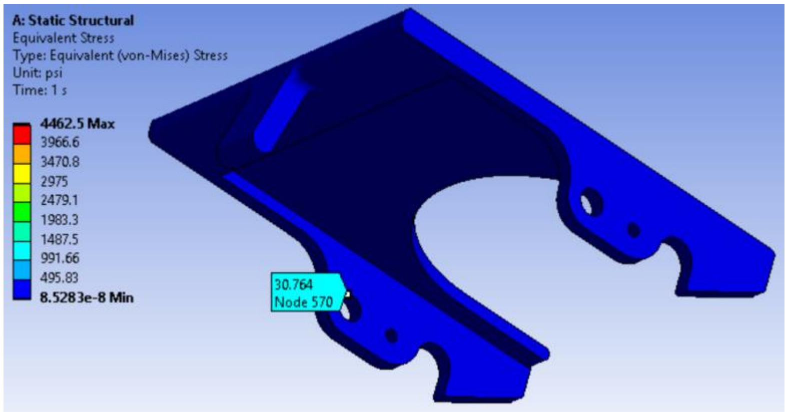
True scale view of the Von Mises stresses of the entire latch mechanism in stationary loading with the marked maximum stress



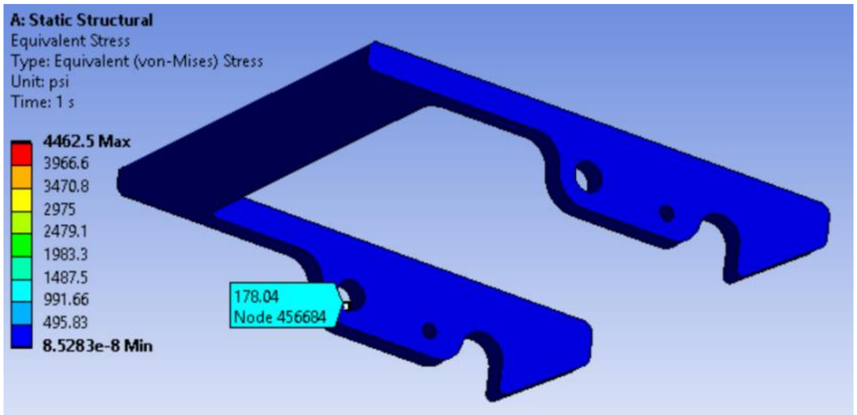
True scale view of the Von Mises stresses of the bottom latch in stationary loading with the maximum stress marked (for this loading scenario the maximum stress on the lower latch was used to approximate the load on the area surrounding the weld)



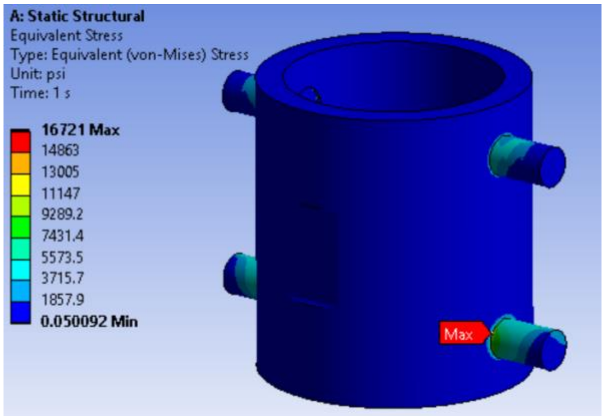
True scale view of the Von Mises stresses of a Clevis pin with the marked maximum stress on the pins in stationary loading



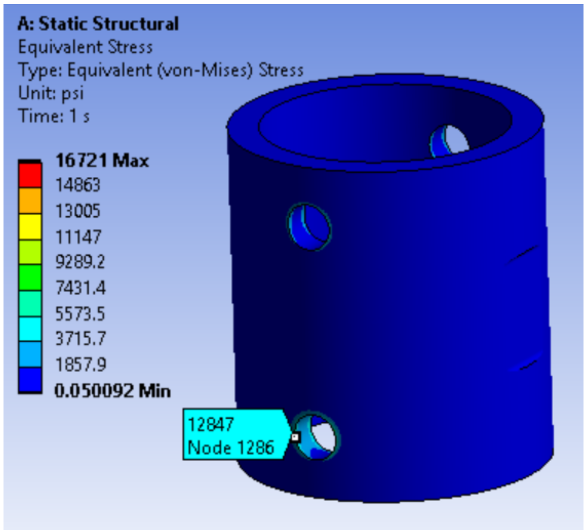
True scale view of the Von Mises stresses of Latch Top 2 with the marked maximum stress in stationary loading



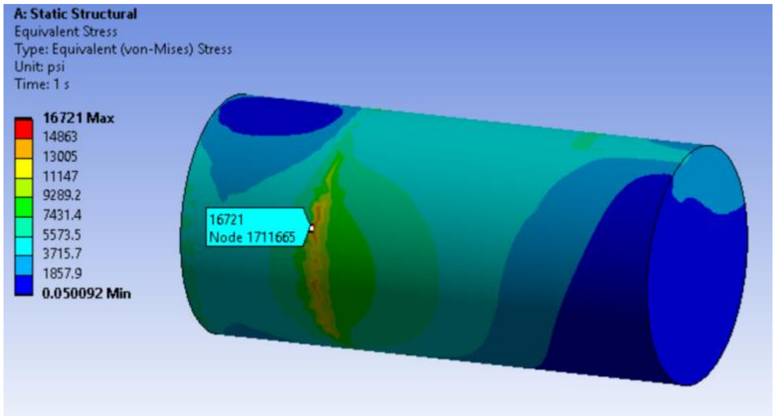
True scale view of the Von Mises stresses of Latch Top 2 with the marked maximum stress in stationary loading



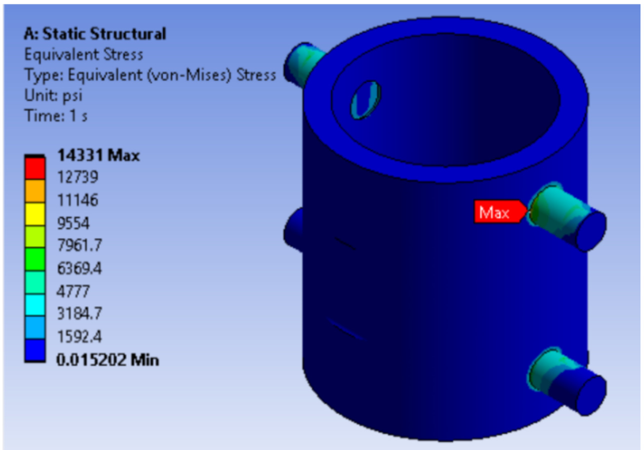
True scale view of the Von Mises stresses of the entire power-column collar in forward loading with the marked maximum stress



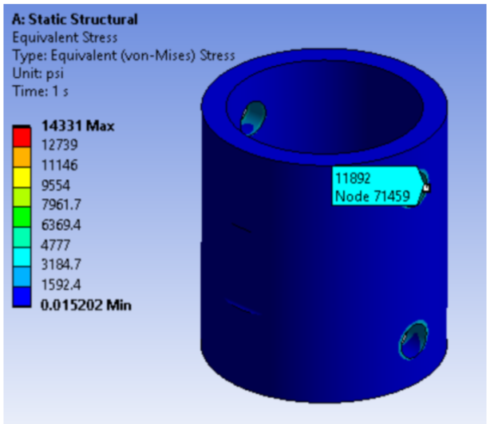
True scale view of the Von Mises stresses of the aluminum piece of the collar in forward loading with the marked maximum stress



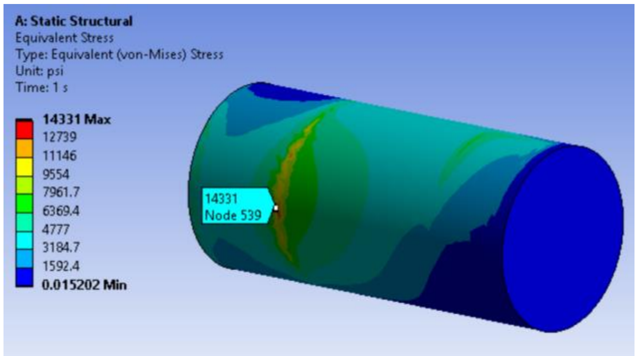
True scale view of the Von Mises stresses of a steel peg on the collar in forward loading with the marked maximum stress



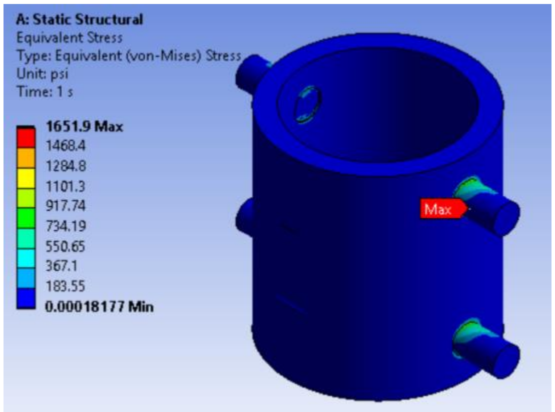
True scale view of the Von Mises stresses of the entire power-column collar in backward loading with the marked maximum stress



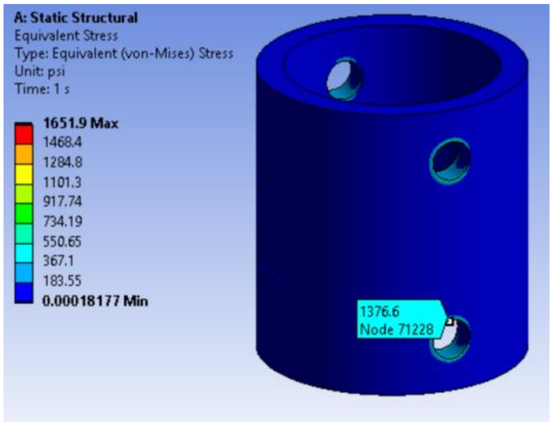
True scale view of the Von Mises stresses of the aluminum piece of the collar in backward loading with the marked maximum stress



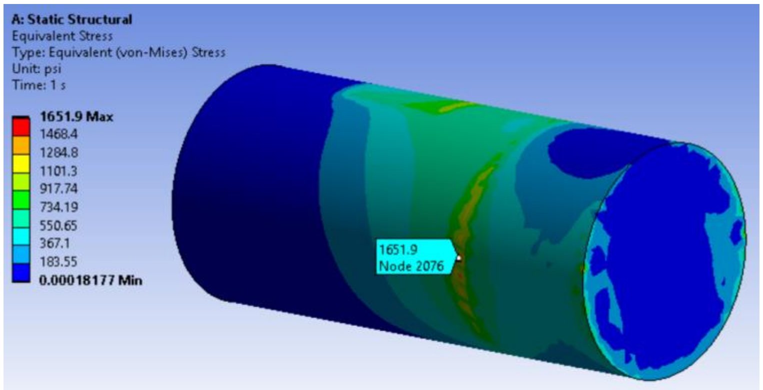
True scale view of the Von Mises stresses of a steel peg on the collar in backward loading with the marked maximum stress



True scale view of the Von Mises stresses of the entire power-column collar in stationary loading with the marked maximum stress

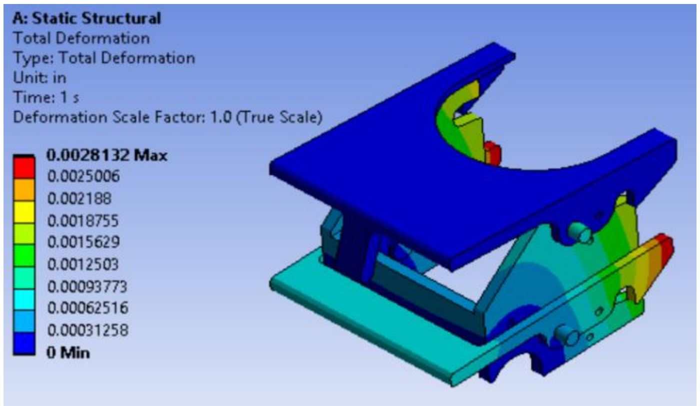


True scale view of the Von Mises stresses of the aluminum piece of the collar in stationary loading with the marked maximum stress

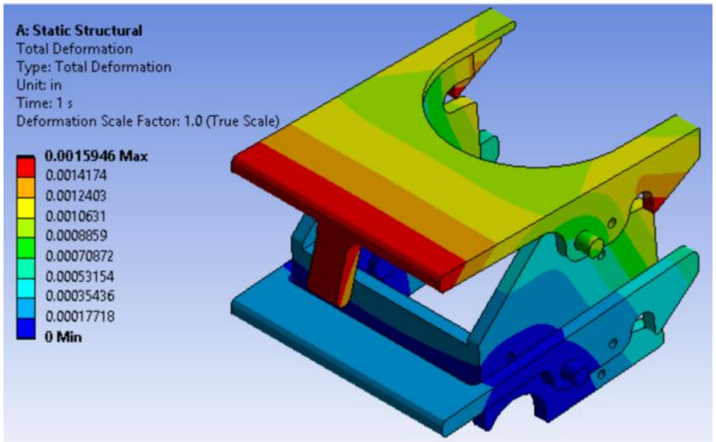


True scale view of the Von Mises stresses of a steel peg on the collar in backward loading with the marked maximum stress

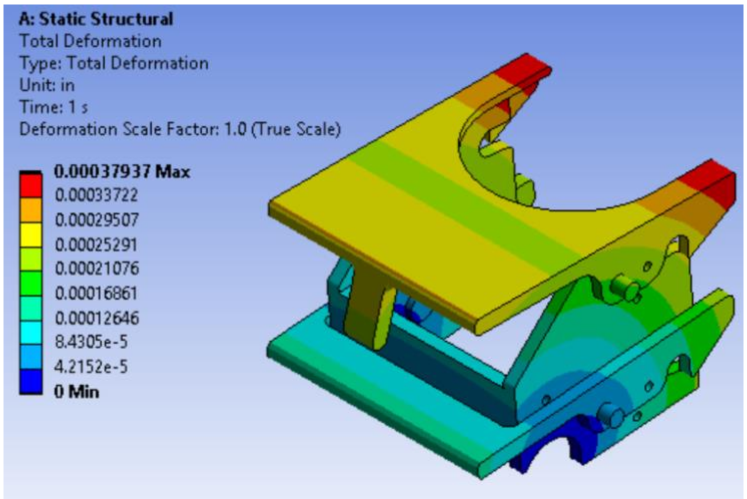
Images of the deformation for each loading scenario are included below.



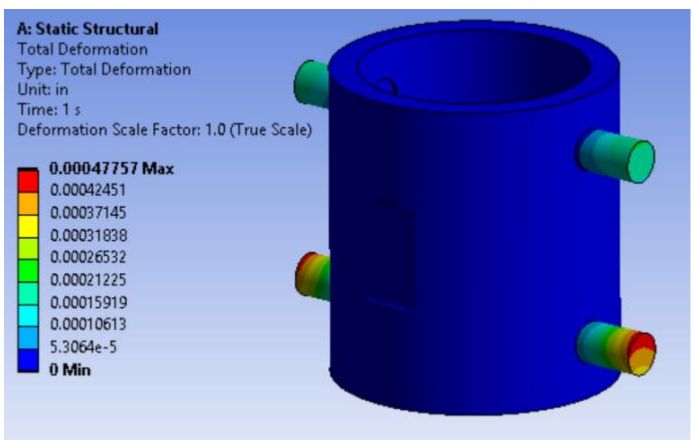
True scale view of the deformation of the entire attachment mechanism in forward loading



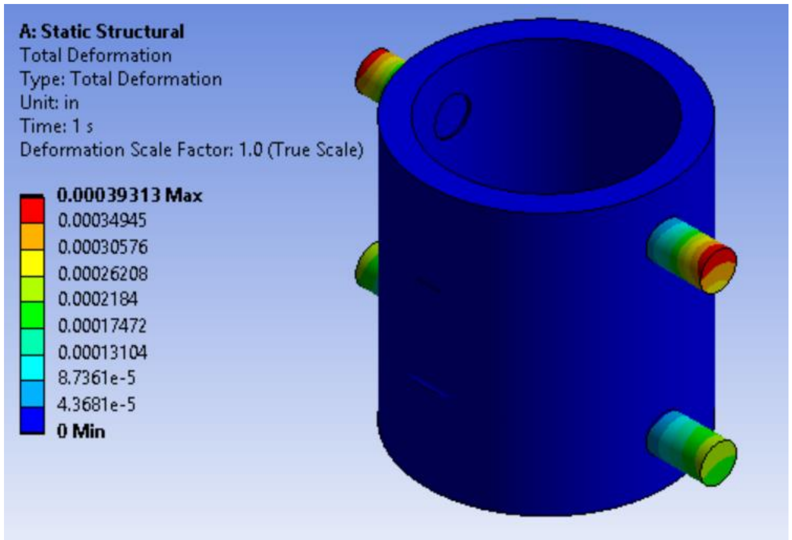
True scale view of the deformation of the entire attachment mechanism in backward loading



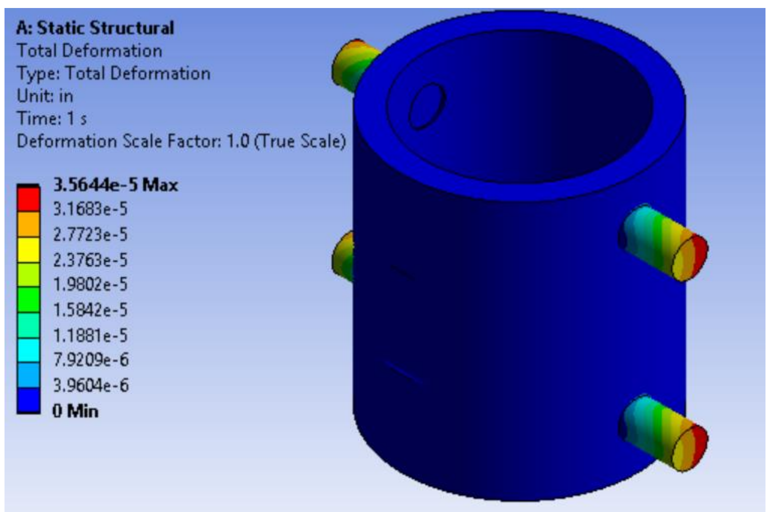
True scale view of the deformation of the entire attachment mechanism in stationary loading



True scale view of the deformation of the entire power-column collar in forward loading



True scale view of the deformation of the entire power-column collar in backward loading



True scale view of the deformation of the entire power-column collar in stationary loading