Final Report:

Curb Climbing System

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1.0 Introduction and Objectives

Navigating city streets can be difficult for powered wheelchair users due to physical barriers such as curbs. While ramps and curb cuts are simple and common solutions, they are not always implemented correctly. Curb-climbing wheelchairs are available to combat the problem, however, they tend to be costly. Thus, Tetra Society of North America (Tetra), a non-profit organization focused on finding solutions to challenges faced by people with disabilities, has enlisted Team Curby to design and build a curb climbing and descending powered wheelchair accessory. This accessory must have a maximum material cost of $500 CAD. After consultations with Tetra and Team Curby, the objectives of the project were narrowed to a fully-functional prototype, that integrates with a Torque SP 3200 powered wheelchair, which allows the user to climb a single, 90-degree, 4” (100 mm) curb. Furthermore, the proposed device must not interfere with user mobility and must function in normal weather conditions in Vancouver. The long-term goal is for Tetra to modify the proposed design for a variety of powered wheelchair models. Thus, more users can safely and independently navigate cities.

2.0 Final Design

The final design consists of a front wheel and back wheel lift system that allows the user to safely ascend a curb. The specifications of the final device are listed in Table 1.

Table 1. Summary of device performance

Metric	Final Device Performance
Cost [$]	$617.71[1]
User weight [kg]	100[2]
Curb Height [in]	4
Battery Capacity [mAh]	10,000
No. of operating cycles (before charge)	200
Operating Time [min]	3.00

These specifications are based on the requirements and evaluation criterias of the device, shown in detail in Appendix A: Requirements and Appendix B: Evaluation Criterion. The following sections will describe the key components and main features of each sub-system and their importance to the overall design. The assembly procedures for the front and back wheel lift systems can be found in Appendix C: Full Drawing Package, along with mechanical drawings for specific components of the device.

[1] Refer to Appendix D: Budget for a breakdown of the components costs
[2] The requirement as specified in Phase 5 was set at 190kg based on a maximum user weight of 100kg. While the device was only tested up to the maximum expected user weight, the actuators should be able to support much greater loads. Further testing should be conducted to re-evaluate this specification.

2.1 Major Components

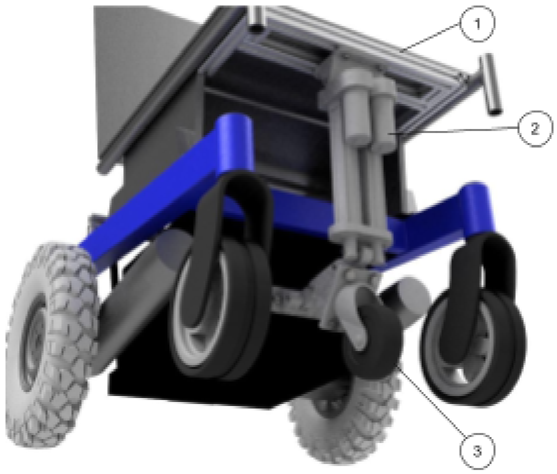


Figure 1. Front wheel lift system

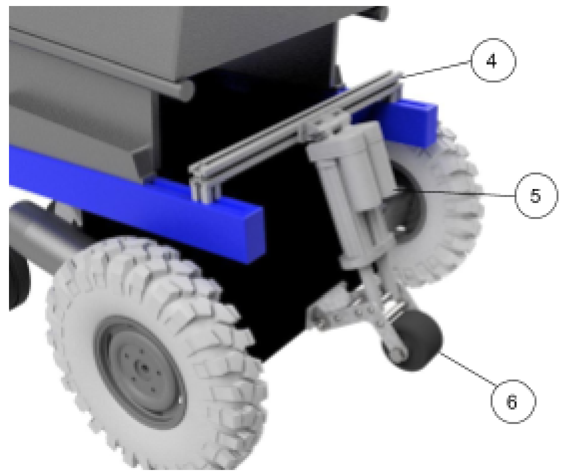


Figure 2. Back wheel lift system

The front wheel lift and back wheel lift systems, shown in Figure 1 and Figure 2, are made up of the components listed in Table 2.

Table 2. Major component specifications

Number	Name	Description
1	8020 Front Wheel Lift Mounting System	The 8020 frame mounts to the underside of the steel plate seating platform of the Torque SP 3200 Powered Wheelchair. The 8020 frame is easily adjustable and slides forwards and backwards to allow for repositioning of the actuators and caster system that attaches to it. This component allows for compatibility between different wheelchair models in ensuring that the casters' axis of rotation is perpendicular to the ground at the end of the actuators' extension.
2	6" Linear Actuators	These actuators are rated to a load of 270lbs each and provide enough extension to lift the front wheels of the Torque SP 3200 to a height of 4.5". The linear actuators are mounted in a pinned configuration to eliminate radial loading acting against the rod.
3	4" TPU Caster	This off-the-shelf caster is rated up to 300lbs and allows the wheelchair to drive when the front wheels are elevated off the ground. This is important as the front wheel of the wheelchairs need to be above the curb before the 6" linear actuators start retracting. In addition, the caster allows the user to make adjustments to the direction of the wheelchair once the front wheels are off the ground in case he/she has not perfectly aligned the wheelchair to the curb.

4	8020 Back Wheel Lift Mounting System	The 8020 frame mounts to the Torque SP 3200 Powered Wheelchair frame using a pair of t-nuts and bolts. The Torque SP 3200 has existing t-slots which allow for easy mounting and adjustability of the back wheel lift system.
5	4” Linear Actuators	The 4” linear actuators, like the 6” actuators, are also rated to 270lbs each. The actuators lift the back wheels (slightly) onto the curb and increases the grip of the back wheels of the wheelchair against the curb which allows it to climb using the drive system of the existing wheelchair. The back wheel lift system is designed such that the 3” polyurethane wheel only contacts the ground when the wheelchair is in its tilted state (in the process of climbing a curb).
6	3” Polyurethane wheel	This wheel is rated up to 900lbs and pushes against the ground to lift the back wheels of the wheelchair. It also allows for the wheelchair to continue to drive forwards and up the curb during this process.
7	Electronics	The device uses the following electronic components to control the actuators. Refer to Figure 3 for detailed flow charts of how the components interact with each other. ● **Arduino UNO**: microcontroller used to control the speed of the linear actuators ● **Voltage Divider**: converts the 12V output of the battery to a 5V input for the Arduino ● **DROK L298 Motor Driver**: controls the direction of the motor in the linear actuator based on voltages received from the Arduino ● **Lithium-ion Battery**: 12V battery with a 10,000mAh capacity used to power all the electronic components ● **Switch**: input device used by the user to extend/retract the linear actuators

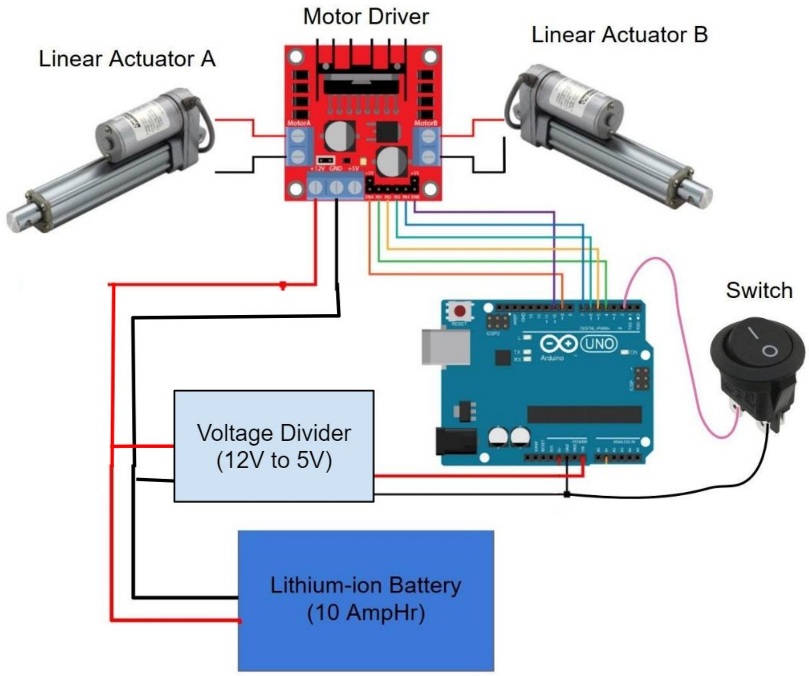


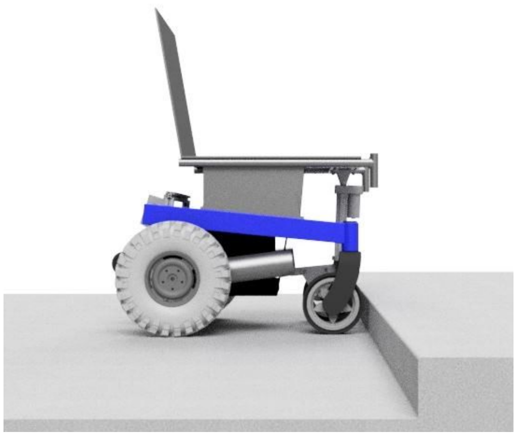
Figure 3. Electrical connections diagram

The electrical system does not use any of the powered wheelchair's existing electronics. The assembly time of the device is approximately 6 hours, 3 hours for the front wheel system and 3 hours for the back wheel system.

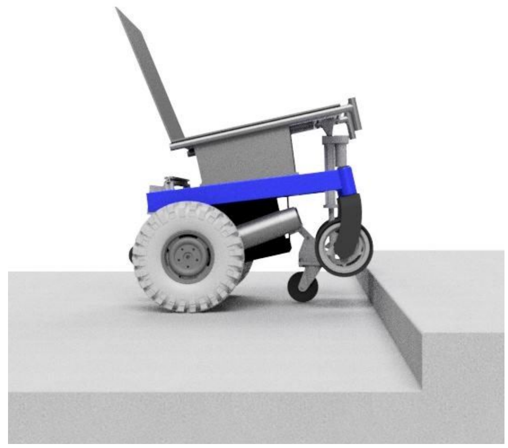
2.2 Device Operation

The following steps outline the operation flow of the device. A full animation of the operating procedures can be found here.

Step 1: User drives up to curb and stops.

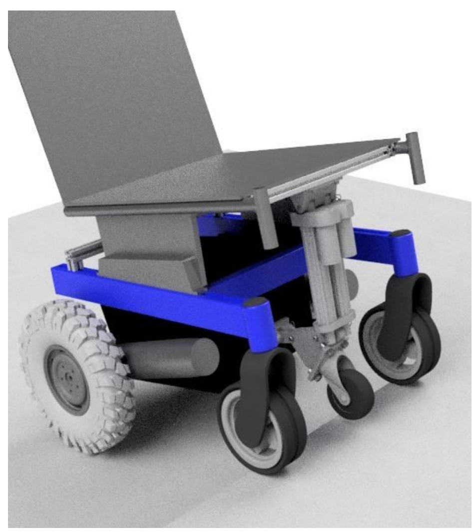


Step 2: User activates button to extend linear actuators in front wheel lift which tilts the wheelchair to raise the front wheels (of the wheelchair) above the curb.

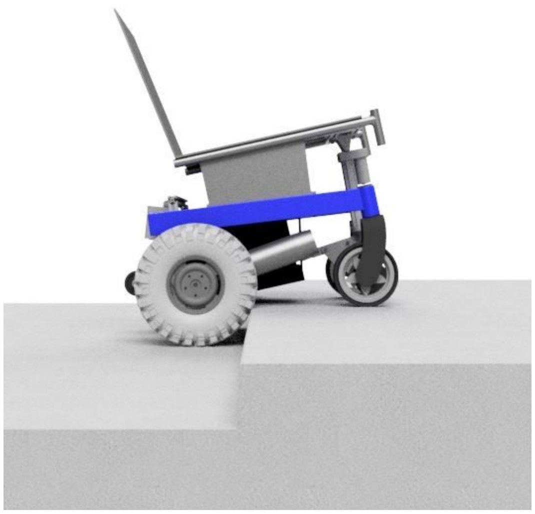


Step 3: User drives forward such that the front wheels are above the curb.

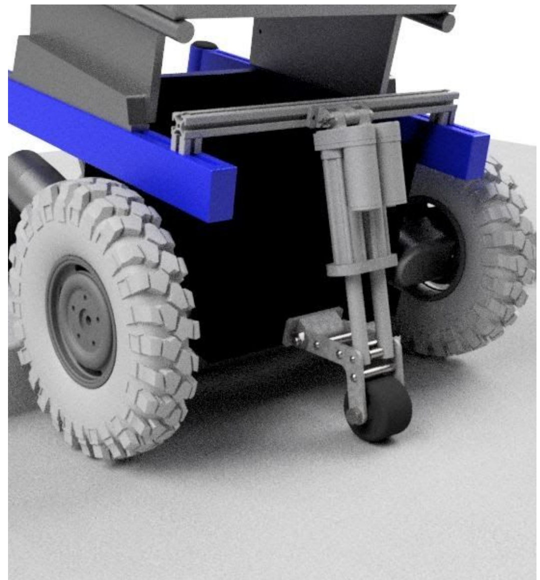
Step 4: User activates button to retract linear actuators in front wheel lift and place front wheels onto curb. User then drives forward until back wheels touch the curb.



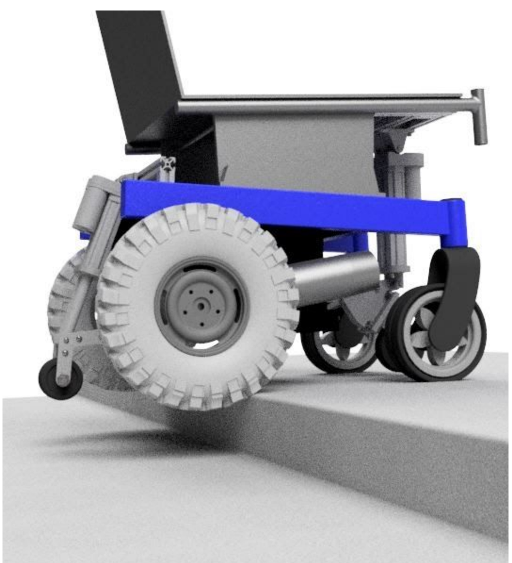
Step 5: User drives forward until back wheels touch the curb.



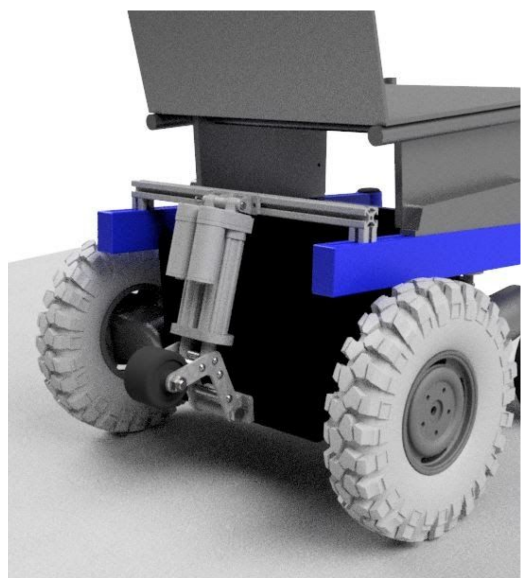
Step 6: User activates button to extend linear actuators in back wheel lift which lifts the back wheels to provide enough traction for back wheels to climb over curb.



Step 7: User drives up and over curb.



Step 8: User activates button to retract linear actuators in back wheel lift.



3.0 Validation and Verification

3.1 Engineering Calculations

Engineering calculations were done throughout the course of the project to provide estimates and approximations for requirements, the FMEA found in Appendix E: FMEA, and various component sizing. Testing was often completed to compliment these calculations. For each calculation, there is a corresponding explanation of the purpose, methods, and conclusions. The purpose outlines the relevance of each calculation and what it is intended to achieve. The methods section outlines the physics and mathematics principles behind each calculation, as well as any limiting assumptions. The conclusions outline how the results of the calculation were interpreted and used. Furthermore, only calculations relevant to the final design are included in this report. Table 3 contains a summary of the calculations and its conclusions. The details behind the purpose, methods, and scanned copies can be found in Appendix F: Engineering Calculations.

Table 3. Calculations Summary

Calculation Name	Conclusion
Front Wheel Linear Actuator Sizing	Provide front wheel linear actuator extension and spatial requirements
Front Wheel Operational Loads	Provide back wheel linear actuator and caster load requirements
Mounting Component Fatigue	Provide mounting component material and geometric requirements for fatigue
Pivot Arm Loads	Proof that addition of pivot arms eliminate bending stress in the actuator
Pivot Arm Sizing	Provide geometric requirements of the pivot arm
Front Wheel Linear Actuator Impact Loads	Provide linear actuator impact loads; select a damping material accordingly
Power Consumption	Provide the battery capacity requirement

3.2 Validation

Validation testing is an essential step for a design project.The testing outlined in this section will not be carried out, as discussed with the client. Instead, the information is intended as a guide for the client.

3.2.1 Methods

The validation methods outlined should be done with as many potential end users of the device as possible, see Appendix G: Validation Methods for details. A device user would be any powered wheelchair user that is interested in the ability to independently climb curbs of 4” in height. Using a large sample size of users that represent various demographics, within the device’s restrictions such as weight and range of motion, is important to obtain comprehensive feedback. Furthermore, since our device is designed for a specific model of powered wheelchair, adjustments must be made to adapt the device for users of different wheelchairs. We would recommend working in conjunction with a rehabilitation center such as GF Strong Rehabilitation Center for both user recruitment and execution of the validation testing. User feedback and researcher observations should be reviewed subsequent to the test.

3.3.2 Expected Results

Conducting a user evaluation is then essential as this information will be important in recommending next steps for our device such that it is compatible with a greater demographic. Validation testing will also aid in determining design performance in a more realistic environment, perhaps even uncovering new or re-prioritizing previous design considerations. The requirements and evaluation criteria should be revised to reflect any user preferences which are not adequately represented.

3.3 Verification

Verification tests were only completed for an older version of the front wheel subsystem design prototype, shown in Figure 4. Further testing was not possible due to the school closure. These tests verify the evaluation criterias and any associated requirements, see details in Appendix H: Completed Testing.

Figure 4. Old front wheel subsystem prototype

The evaluation criterias for the device are: Material cost, durability, user safety, operating cycle, and (design) risk. Out of these five criterias, the performance metrics that pertain to the physical prototype are the durability, user safety, and operating cycle.

3.3.1 Durability

The device must be able to withstand reasonably foreseeable forces without damage or hindering performance. The linear actuators are a critical component of the device and its corresponding SF should be determined to ensure it can withstand the expected forces. The ground reaction force on the actuators during operation was found using force plates, as shown in Figure 5.

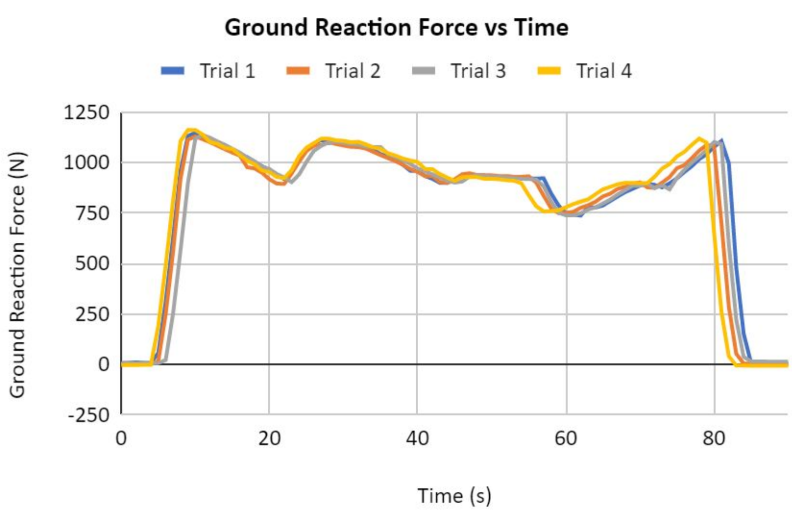


Figure 5. Ground reaction force acting on 6" linear actuators for 235 lb load for 4 trials

The average maximum load on the two linear actuators was 1143 N. Thus, the average maximum axial load on each actuator is 128.5 lbs. The linear actuators are rated to a maximum load of 270 lbs. This means that each actuator has a SF of 2.1.

The linear actuators in the older design were subjected to radial loads, which is damaging to the actuators. In the final design, the actuators are no longer subject to radial loads. Thus, we expect that the linear actuators will perform better with the final design so the actual safety higher should be the same if not higher than 2.1.

3.3.2 Operating Cycle

The operating cycle time is the total time it takes for the user to ascend a curb using the device. A shorter operating cycle is better. The time it takes to just lift the wheelchair front wheels onto the curb was measured to be 75s.

For the final device, this operating cycle should also include the time it takes for the linear actuators in the back to extend and retract, along with the time it takes the user to drive the back wheels onto the curb with the help of the deployed back wheel subsystem. Since the linear actuators used in the back wheel subsystem use the same motors as the ones in the front, we can assume that the back wheel subsystem will take approximately 75s as well. This brings the operating cycle to a total of 150s.

3.3.3 User Safety

User safety is a very important performance metric. The user is at a higher risk of tipping and/or falling whenever the center of gravity (COG) of the wheelchair is altered. The final device will alter the COG of the powered wheelchair during operation in order to ascend the curb. Thus, a design that does this for a shorter time should be safer for the user. After the front linear actuators first contact the ground, the powered wheelchair will be at an angle until the very end of the operation cycle, when both the front and back wheels are on top of the curb. The time the COG is altered is equal to the operating cycle time minus the time it takes for the front wheel linear actuator to contact the ground and start lifting the wheelchair. For the front wheel subsystem, the time COG is altered is the 60s.

The wheelchair will be in a tilted position throughout the operation of the back wheel subsystem. Therefore, the estimated time the COG is altered for the final device is 135s.

3.4 Requirements and Evaluation Criteria

Since the full design (the front and back wheel subsystems) cannot be assessed, the most up to date physical prototype, the front wheel subsystem, will be assessed based on the requirements and evaluation criterias. Although not all components of the front wheel system prototype are completed to the desired quality, the design currently meets many requirements and satisfies many evaluation criterias. The front wheel subsystem prototype fulfills 13 of the 19 stated requirements, see Table 4. “Satisfied” indicates that the current prototype fulfills the requirement. “Unverified” indicates that testing for requirement fulfillment has not begun. Future tests, to change the status of “Unverified” requirements to “Satisfied”, can be found in Section 4.1: Future Testing.

Table 4: Status of requirements for front wheel subsystem

Needs Category	Requirement	Status	Reference Material
Functional	The device functions as required for specified curb height (Min: 100mm or 4 inches)	Satisfied	Appendix H3
	Device functions as designed with an average net weight comprising of the user and their cargo (Min: 100kg/220lbs)	Satisfied	Appendix H1
	Device maintains the functional integrity of the surrounding when being used (Pass/Fail)	Satisfied	Appendix H3
	Device maintains the visual integrity of the surrounding when being used (Pass/Fail)	Satisfied	Appendix H3
Manufacturability	Device can be built quickly (Max: 100 hrs)	Satisfied	Section 2.1
Affordability	Device cost for the end user is within client specifications (Max: $500 CAD)	Satisfied	Appendix D
Compatibility	Device must be allow the total width of the chair to be able to fit through a standard door (Max: 32 inches/800mm)	Satisfied	Appendix H3
	Device is operable from a seated position (Pass/Fail)	Satisfied	Appendix H3
	Device requires only the upper body of the user to operate (Pass/Fail)	Satisfied	Appendix H3
	The device allows full maneuverability inside a small space (360° rotation in 68" x 51"/1730mm x 1295mm space) (Pass/Fail)	Satisfied	Appendix H3
	Device functions with the Torque SP 3200 Powered Wheelchair (Pass/Fail)	Satisfied	Appendix H3
Safety	Device operates without modifications to electronics on existing wheelchair (Pass/Fail)	Satisfied	Section 2.1
	Device does not cause harm to the user (Pass/Fail)	Unverified	Future Test F
Durability	Device withstands temperatures as experienced in Vancouver (Min/Max: [-20, 50 ℃])	Unverified	Future Test G
	Device withstands rain as experienced in Vancouver (IP54 rating) (Pass/Fail)	Unverified	Future Test H
	Device can be used an acceptable number of cycles before requiring maintenance (Min: 55 cycles)	Unverified	Future Test J
	Device can withstand typical impact forces without malfunctioning (Min: 5kN/1125 lbs)	Unverified	Future Test E

	Device's natural frequency is at least double typical vibration frequencies from travel of a powered wheelchair over a sidewalk (Pass/Fail)	Unverified	Future Test I
Regulatory	Device does not infringe any Canadian patents (Pass/Fail)	Satisfied	Appendix I
Project Development	Device's product development for the device is within budget	Satisfied	Appendix C
	Product development time is appropriate according to the scope of the project.	Satisfied	Footnote[3]

The performance of the completed subsystem was evaluated using five evaluation criteria (ECs) shown in Table 5. Refer to Appendix B for the determination of the weights and stakeholder satisfaction.

Table 5: Evaluation of front wheel subsystem performance

Evaluation Criteria	Metric	EC Weight	Performance	Stakeholder Satisfaction (of 10)	Weight x Stakeholder Satis.
Material Cost	Unit: Canadian dollars ($) Min/Max: [200, 300]	18%	$392 (Appendix D)	8.4	1.5
Durability	Unit: Lowest safety factor Min/Max: [1.5, 4]	11%	2.1	5.1	0.6
User Safety	Unit: Time center of gravity of chair is altered (s) Min/Max: [25, 180]	30%	60 s	8.4	2.5
Operating Cycle	Unit: Time (s) Min/Max: [60, 180]	7%	75 s	9.8	0.7
Design Risk	Unit: Hours required to complete device (hrs) Min/Max: [375, 600]	34%	480 hrs	5.8	2.0
			Net Score (of 10)		**7.2**

As shown, the front wheel subsystem scores 7.2 out of 10. It lacks performance in terms of durability, user safety, and risk. The durability of the device can be improved by using linear actuators that are rated for higher loads, thus increasing the safety factor. However, linear actuators that can lift more weight tend to cost more. User safety can also be improved by using linear actuators that extend and retract at a faster speed, as this would reduce the amount of time the center of gravity of the chair is altered. This means that there is a trade off between higher user satisfaction, in terms of durability and user safety, and material cost. This is a consideration that the client should be aware of.

[3] The time required to improve the as-built state of the front wheel subsystem so that it reaches the desired state is estimated to be minimal because the two states are very similar. Thus, the requirement can be deemed 'satisfied'.

4.0 Recommendations

All components designed, but not prototyped, are recommended to be built as specified in Appendix C. The back wheel subsystem should be made first out of 3D printed parts to test the functionality of both the front and back wheel subsystems working in tandem. Necessary modifications to all the components should be made prior to machining the final parts. Further testing to validate and verify the final design are needed, as detailed below.

4.1 Future Testing

The majority of future tests require the back wheel lift assembly. The following tests are required to validate the requirements of the final device. All target values referenced within Table 6 are taken directly from the device requirements in Appendix A.

Table 6: Descriptions of future testing

Test Name	Description
A. Front wheel subsystem loads test	Measure the ground reaction forces tested on the updated front wheel subsystem. The resulting forces should be used in finite element analysis for the additional design components. See Appendix J: Linear Actuator Forces and Power Test for the equipment needed and procedures.
B. Back wheel subsystem loads test	Measure the ground reaction forces at the back wheel subsystem to determine the safety factor of the linear actuators, similar to Test A. The resulting forces should be used in finite element analysis of all additional parts of the design. Modify Test A for the back wheel subsystem.
C. Final device functional test	Verify if the device can successfully ascend both front and back wheels of the wheelchair onto a 4” curb by going through the entire operating cycle.
D. Current during operating cycle test	Measure the current-draw for the final device to better estimate the number of operating cycles that can be completed before the battery needs to be recharged. Refer to Appendix J for the equipment needed and procedures.
E. Final device impact test	Verify that the final device can withstand a 5 kN impact force. Testing methods should follow ISO 7176-8 Wheelchairs - Part 8: Requirements and test methods for static, impact, and fatigue strengths, see Appendix K: Relevant Standards.
F. Stability test	Test the static and dynamic stability of the wheelchair when the device is in use following ISO and ANSI standards, see Appendix K.
G. Temperature test	Verify the device can operate normally in temperatures ranging from -20°C to 50°C using a temperature controlled chamber.

H. Electronics water-resistance test	The device must operate in the rain which requires all electronics to be housed in a weather-sealed and water-resistant enclosure. The electronics enclosure must be tested to ensure IP54 rating, which states that the enclosure is dust protected and able to withstand water splashes from any direction without harmful effects. Further details of the IP rating system can be found in the IEC 60529 standard.
I. Final device natural frequency test	Calculate the natural frequency of the final device using FEA software. Then, measure the operational frequencies through a field test. This would entail the analysis of data from accelerometers attached to the device as the chair is operated normally. Verify that the device's natural frequency is at least two times that of the normal vibrating frequency of the wheelchair.
J. Durability and stress test	Repeated operation cycles of the front and back wheel subsystems under expected loading conditions up to 55 times.

4.2 Relevant Standards

Relevant standards could not be accessed due to their high cost. Research on the standards relevant to curb climbing devices are summarized in Appendix K. These standards should be further investigated to determine device compliance. If the proposed design does not comply with standards, alterations may be necessary. If compliance is not possible, non-compliance should be disclosed to the user so that they are aware of the risks of operation.

5.0 Conclusion

Team Curby has successfully designed a device that will allow powered wheelchair users to ascend 4" (100mm) curbs. The front wheel subsystem of the intended design has been built, which enables the front wheels of a powered wheelchair to ascend curbs. Next steps are to build the back wheel subsystem so that the back wheels of the wheelchair can also ascend the curb. Once both subsystems are built, optimization and testing of the entire device will ensure verification and validation of Team Curby's design. Thus, the major accomplishments of Team Curby consist of:

1. Building a physical prototype that allows the user of the SP Torque 3200 to independently ascend the front wheels of the wheelchair over a 4" (100 mm) curb.
2. Creating a design that will allow the user of the SP Torque 3200 to independently ascend the back wheels of the wheelchair over a 4" (100 mm) curb.
3. Obtaining a functioning powered wheelchair (a SP Torque 3200) through a generous donation by GF Strong Rehabilitation Centre. Tetra is welcome to take and use the powered wheelchair for future projects.

Further communication with the MECH Capstone Instruction Team will be required to coordinate the handover process of the physical prototype because it is currently stored at the Rusty Hut at UBC.

Appendices

Appendix A: Requirements

Detailed requirements derived from stakeholders can be found here. Metrics for requirement evaluations and their justifications are also included. See WDM & AHP for the entire spreadsheet.

Figure A1. Complete requirements table

Needs Category [1]	Relevant Stakeholders	Requirement	Metric	Units	Criterion	Justification for Numerical Parameters
Affordability	Tetra, Team Curby, Powered Wheelchair Users	Device cost for the end user is within client specifications	Device cost	CAD	Max: 500	$500 max as stated by client
Compatibility	Powered Wheelchair Users	Device must be able to fit through a standard door	Width of the total wheelchair	inches	Max: 32	An average adult wheelchair, according to ANSI (American National Standards Institute), can be up to 50 inches long and up to 32 inches wide (https://www.1800wheelchair.ca/news/making-home-wheelchair-friendly/)
Compatibility	Tetra, Powered Wheelchair Users	Device functions with Torque SP 3200			Pass/Fail	It is impossible to design for all powered-wheelchairs - having a device that is compatible with one specific model would give confidence that it would work with additional designs while increasing the chance of a successful prototype. Compatibility with additional designs would be explored as a future consideration.
Compatibility	Tetra, Caretakers, Powered Wheelchair Users	The device is operatable from a seated position			Pass/Fail	The device should not require another person to assist the user in order to operate.
Compatibility	Caretakers, Powered Wheelchair Users	The device requires only the upper body of the user to operate			Pass/Fail	All users have impaired function of their lower extremeties; the device must be able to operate solely with the upper body
Compatibility	Tetra, Caretakers, Powered Wheelchair Users	The device allows full manuverability inside a small space with no added difficulty	360 degrees of rotation in 68" by 51" space	degrees of rotation	Pass/Fail	ADA (American with Disability Act) states that the minimum elevator floor dimensions are 68" by 51" for new and retrofitted elevators (https://www.elevators.com/ada-compliance/) Eric demonstrated a 360 degree rotation in the elevator at the Tetra head office
Durability	Tetra, Powered Wheelchair Users	Device withstands temperatures as experienced in Vancouver	Temperature	degrees C	Min/Max: [-20,50]	Based off an iPhone (https://www.apple.com/ca/batteries/maximizing-performance/)
Durability	Tetra, Powered Wheelchair Users	Device withstands rain as experienced in Vancouver (IP54)			Pass/Fail	Device is to be used outside, therefore must withstand typical Vancouver conditions. The IP54 code was chosen as many electrical devices use this and is a realistic goal for Team Curby
Durability	Tetra, Powered Wheelchair Users	Device can be used an acceptable number of cycles before requiring maintenance	Number of cycles before requiring maintenance	Operation Cycles	Min: 55	The device should last a year before maintenance. From stakeholder interviews, users encounter a curb that requires them to choose a different path about once a week.
Durability	Powered Wheelchair Users	Device can withstand typical impact forces without malfunctioning	Impact force	kN (kilo Newtons)	Min: 5	A 200lb person falling from a height of 2 ft produces a force of approximately 5kN (https://www.ehss.vt.edu/programs/FAL_gen_require.php)
Durability	Team Curby	Device's natural frequency is at least double typical vibration frequencies from travel of a powered wheelchair over a sidewalk	Natural Frequency	Hz	TBD	Ideal design parameter is to have the natural frequency as high as possible above the resonance (https://www.pioneer-engineering.com/resources/how-diagnose-and-prevent-resonance). Therefore, we are realistically assuming that a natural frequency double the resonance would be sufficient.
Functional	Powered Wheelchair Users	The device functions as required for standard curb heights	height of curb ascended	mm	Min: 100	Scope of the project was narrowed such that a 4" curb is being used (100mm)
Functional	Power Wheelchair Users	Device functions as designed with an average net weight comprising of the user, their wheelchair, and their cargo	Total weight to be lifted/lowered by the device	kg	Min: 190	The average total weight that the device must withstand is 415 lbs due to a wheelchair user's average weight (on the high end) of 225lbs, plus cargo which is an estimated 15lbs, and the wheelchair weight 175lbs (all values as stated from the client).
Functional	City Planning	Device maintains the functional integrity of the surrounding when being used			Pass/Fail	Destroying propety is illegal
Functional	City Planning	Device maintains the visual integrity of the surrounding when being used			Pass/Fail	Vandalism is illegal.
Manufacturability	Team Curby, Tetra Volunteer/Hobbyists	Device can be built under 100 hours	Time spent on building the device	hours	Max: 100	Stakeholder interviews indicated that projects take anywhere from 4 - 100 hours to build
Project Development	Tetra, MECH	Device's product development for the device is within budget	Product Development Cost	CAD	Max: 3250	Max funding provided by MECH is $3000 for development and Tetra is $250 for development
Project Development	Team Curby	Product development time is calculated according to the scope of the project.	Hours spent on project development	hours	Min/Max: [1200, 2400]	The course states that a minimum of 8 hours should be spent on the course, while we, as a group, have stated that we are not willing to spend 16 hours or more on a project that is only worth 3 credits a term. There are approximately 30 weeks including holidays in the school term that may be used for capstone work. There are 5 people on the Capstone team.
Safety	Tetra, Powered Wheelchair Users, Caretakers, Regulatory body	Device does not cause harm to the user			Pass/Fail	Device should not harm the user in any way.
Safety	Tetra, Powered Wheelchair Users	Device operates without modifications to electronics on existing wheelchair			Pass/Fail	Device cannot void wheelchair warranties, therefore must not modify wheelchair. (https://goldentechnologies.ca/wp-content/uploads/2012/09/Power-Chair-Warranty.pdf)
Regulatory	Regulatory body	Device does not infringe any Canadian patents			Pass/Fail	

Appendix B: Evaluation Criterion Table

See below for a detailed table demonstrating the calculation of raw scores for each evaluation criteria and the corresponding satisfaction curves. The raw scores were inputted into the satisfaction models for a value out of 10. A ‘0’ value represents that all design requirements were met and 0% additional satisfaction from the stakeholders was gained. A ‘10’ value represents that all design requirements were met and 100% additional satisfaction from the stakeholders was gained. This score was then multiplied by the weight of the EC to get a final score of 7.2/10.

Figure B1. Weighted decision matrix (WDM)

Evaluation Criteria				*Concept 2: Linear Actuators*			
	Purpose of EC	Weighting (%)	*Equation (y = score, x = EC)*	EC (x)	Rating Justification	Score	Weighted Score
Material Cost	Device accessibility is governed by the material costs as this is the main component of the burden that must be taken on by the end user **Unit: Canadian dollars**	18	(x<300) 10 (300<x<500) 62.3-0.448x+1.31E-3x^2-1.33E-6x^3 (x>500) 0	392	Material cost of the front-wheel lift subsystem was calculated based on the updated BOM to be $391.79.	7.9	1.4
Durability	Device must be able to withstand reasonably foreseeable forces without damage or hindering performance **Unit: Lowest safety factor**	11	(x<1.5) 0 (1.5<x<4) -32.5+32.9x-8.54x^2+0.741x^3 (x>4) 10	2.1	The lowest safety factor on the device is likely to be from the linear actuator. The actuators that are ideal for the design have a safety factor of around 2.1 based on tests. Max average load on each actuator is 128lbs, max load each actuator can lift is 270 lbs.	5.8	0.6
User Safety	Device operation may accentuate certain safety risks to the user even if the risk is still within the safety requirement. **Unit: Time (s) center of gravity (COG) of chair is altered**	30	(x<25) 10 (25<x<180) 9.93+0.0208x-9.3E-4x^2+2.77E-6x^3 (x>180) 0	60	The linear actuator needs to extend about 2 inches before it engages with the ground and starts lifting, this takes about 15s. The rest of the time of the total operating cycle the device's COG is altered. Total time is 60s.	8.4	2.5
Operating Cycle	The full operating cycle of the device should be within a reasonble period of time **Unit: Time (s)**	7	(x<60) 10 (60<x<180) 14.3-0.162x+2.01E-3x^2-8.63E-6x^3 (x>180) 0	75	Based on tests, the linear actuator takes 70s to extend and then retract while the wheelchair is loaded with 235 lbs (close to max. load of 100 kg). Add another 5s to drive to the curb. The total time is 75s	9.8	0.7
Risk	Design complexity results in a larger amount of manhours dedicated to the development of the device, which contributes to the risk of not completing the project **Unit: Total hours required to complete device**	34	(x<375) 10 (375<x<600) -130+0.919x-1.93E-3x^2+1.26E-6x^3 (x>600) 0	480	This design is straight forward and uses components that can be bought from local suppliers that are readily available. It is estimated that a total of 480 hours (see Risk sheet) will be needed in total to bring the design to completion.	5.8	2.0
Net Score		100					7.2

Figure B2. Analytical Hierarchical Process (AHP) for determining WDM weights

Analytical Heirarchial Process — # of criterion 5

Less Important

Criterion	Material Cost	Durability	User Safety	Operating Cycle	Risk	Row Total	Weight
Material Cost	1.00	5.00	0.20	5.00	0.20	11.40	2.28
Durability	3.00	1.00	0.33	1.00	0.20	5.53	1.106666667
User Safety	5.00	3.00	1.00	3.00	1.00	13.00	2.6
Operating Cycle	0.2	1.00	0.33	1.00	0.20	2.73	0.5466666667
Risk	5.00	5.00	1.00	5.00	1.00	17.00	3.4
Column Total	14.20	15.00	2.87	15.00	2.60		

Relative Criteria Ranking

Value	Ranking
1	equally important
3	slightly more important
5	moderetely more imporant
7	much more important
9	absolutely more important

Normalized Values — # of criterion 7

Less Important

Criterion	Material Cost	Durability	User Safety	Operating Cycle	Risk	Row Total	Weight
Material Cost	0.07	0.33	0.07	0.33	0.08	0.88	18%
Durability	0.21	0.07	0.12	0.07	0.08	0.54	11%
User Safety	0.35	0.20	0.35	0.20	0.38	1.49	30%
Operating Cycle	0.01	0.07	0.12	0.07	0.08	0.34	7%
Risk	0.35	0.33	0.35	0.33	0.38	1.75	35%
Column Total	1.00	1.00	1.00	1.00	1.00		100%

Figure B3. Calculation of performance for the 'Risk' evaluation criteria

Risk Justifications

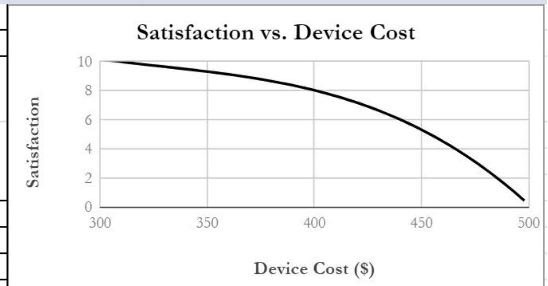
Metric	number of hours spent		
Available time for project	30	weeks	
Minimum time/person	8	hrs/ week	
Minimum Total hours	1200	hrs	
Additional time ppl on average can spend on project/week	2	hrs	
Additional time ppl on average can spend on project	300	hrs	
Average Total Hours	1500		
Max. additional hours for 0% team satisfaction per person	8	hrs/week	
Max. additional time	1200		
Max. Total Hours	2400		
Percentage time spent on documentation/dossier	75	%	*assuming the remaining 25% of the time is spent on design specific tasks
Number of ppl in team	5	ppl	
Max. time for design for 100% satisfaction	375		
Max. time for design to get 0% satisfcation	600		

UNITS IN HRS

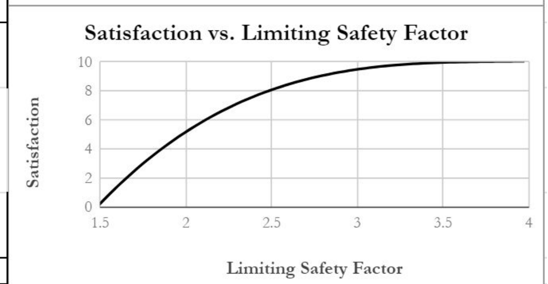
Estimated tasks	Pivot Foot	Linear Actuator	Notes
Concept Design	80	80	5 ppl * 8 hr/wk * 2 wk
Material Procurement	32	8	Pivot foot gas spring difficult to find so estimated it would take 4 times longer than linear actuator
Concept Feasability Testing	40	40	
Concept Re-Design	128	64	
Validation Testing	160	160	
Final Design	72	48	
Unexpected things	160	80	
SUM	672	480	

Figure B4. Satisfaction curves of all evaluation criterion

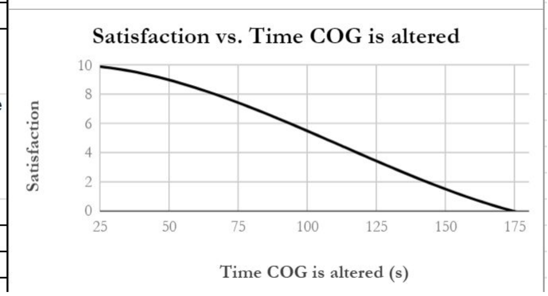
Device Cost		
Evaluation Criteria	**Satisfaction**	**Justification**
300	10	An estimated lower limit with an extreme assumption of lower costs dur to economies of scale.
350	10	
400	7	
450	6	A more affordable device increases accessibility.
500	0	Upper limit as specified by Tetra
62.3-0.448x+1.31E-3x^2-1.33E-6x^3		



Durability (limiting safety factor)		
Evaluation Criteria	**Satisfaction**	**Justification**
1.5	0	Having a safety factor higher than 1 is required in case the expected loading is higher than expected
2	6	
2.5	7	Higher the safety factor would be more durable and account for unexpected loading conditions
3	10	
3.5	10	
4	10	Having a FOS higher than 4 on the limiting component would be overkill for the application and result in an over-engineered device
-32.5+32.9x-8.54x^2+0.741x^3		

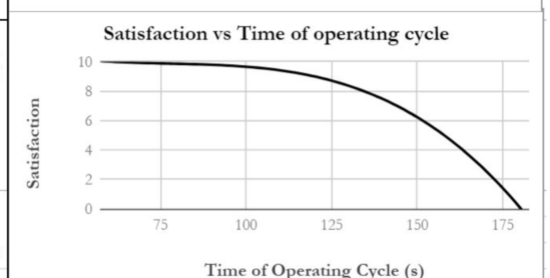


User Safety (time (s) COG is altered)		
25	10	Fastest plausible time to climb over a curb based on estimates of current curb-climbing wheelchair devices
75	7	The user is the most stable when all wheels of the chair are making contact with the ground.
125	5	Exposing the user to longer times of elevated
140	1	center or gravity makes the wheelchair more
160	0.5	prone to tipping, which is not desirable
180	0	Limited to three minutes by the operating cycle
9.93+0.0208x-9.3E-4x^2+2.77E-6x^3		

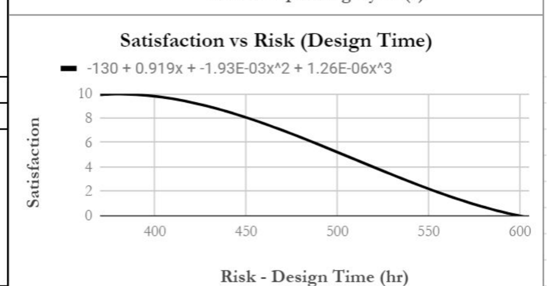


Time COG is altered (s)

Operating Cycle Length (s)		
Evaluation Criteria	**Satisfaction**	**Justification**
60	10	Traffic light cycle is between 60-90 seconds (https://nacto.org/publication/urban-street-design-guide/intersection-design-elements/traffic-signals/signal-cycle-lengths/). The minimum WALK time of 7 seconds is required (MUTCD 4E.06). Wheelchair moves at 12m/s, therefore, it takes, conservatively 2s for a wheelchair to cross one lane, leaving 5s for one cycle of use.
120	9.2	are exposed to oncoming traffic and more safe.
140	7	Stakeholder interviews show that the device
160	5	would not be useful if it's use cycle is greater than
180	0	An operating time longer than three minutes would require too much time and would disuade users from using the device and look for an alternate path
14.3-0.162x+2.01E-3x^2-8.63E-6x^3		



Risk (Design Time (hr))		
375	10	See Risk Sheet
425	9	
525	6	
530	1	
575	1	
600	0	
-130+0.919x-1.93E-3x^2+1.26E-6x^3		



Appendix C: Full Drawing Package

Below are the drawings for each machined component, sub-assembly, and the full assembly.

Figure C1. Full assembly

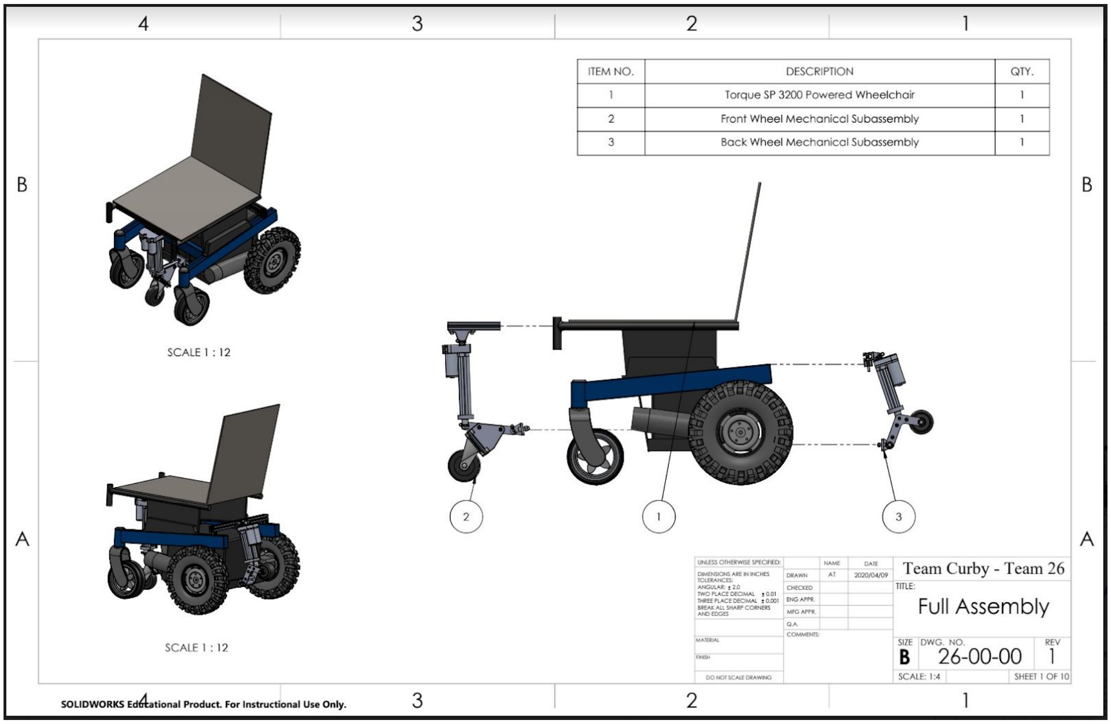


Figure C2. Front wheel mechanical subassembly

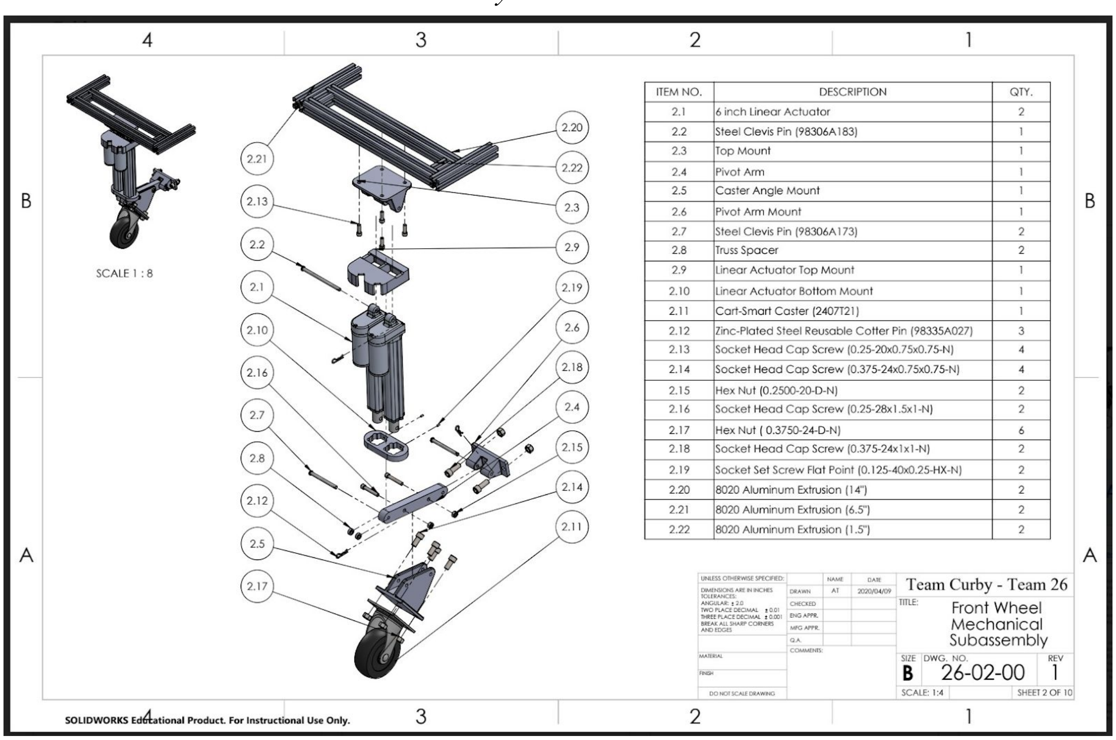


Figure C3. Back wheel mechanical subassembly

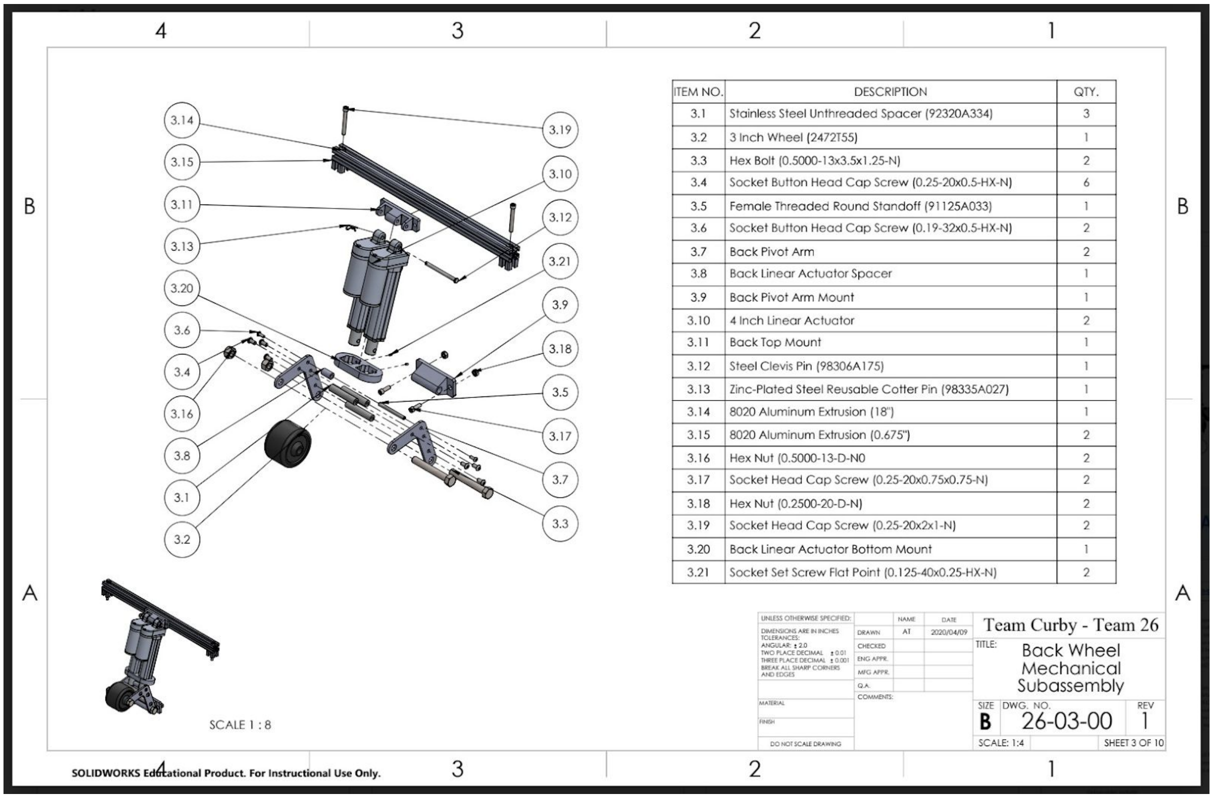


Figure C4. Top mount

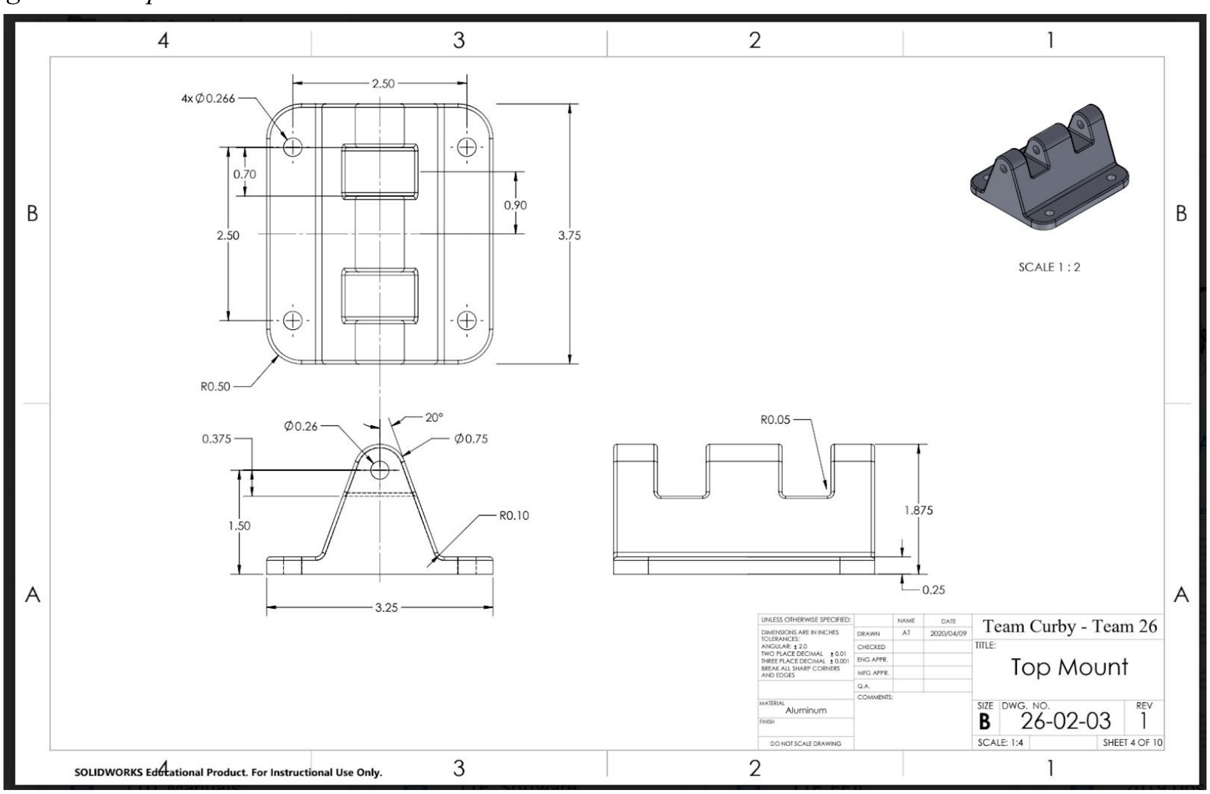


Figure C5. Pivot arm

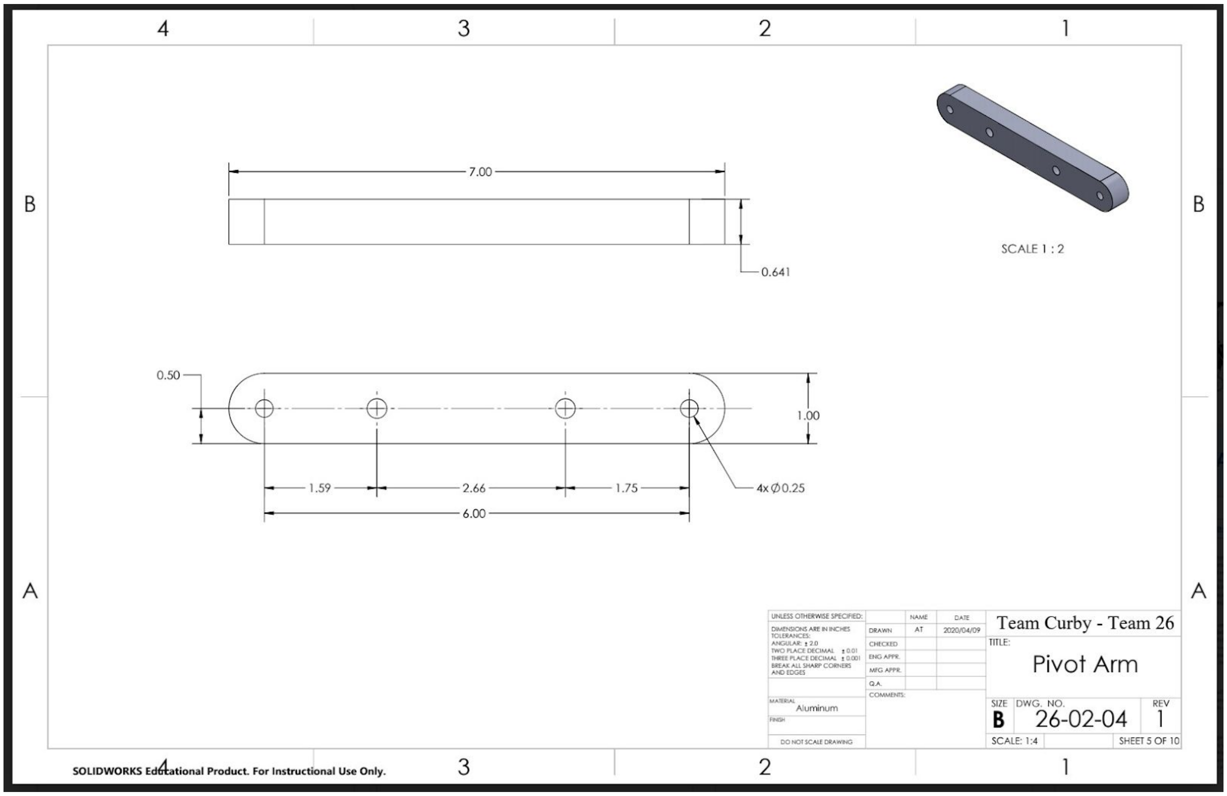


Figure C6. Caster angle mount

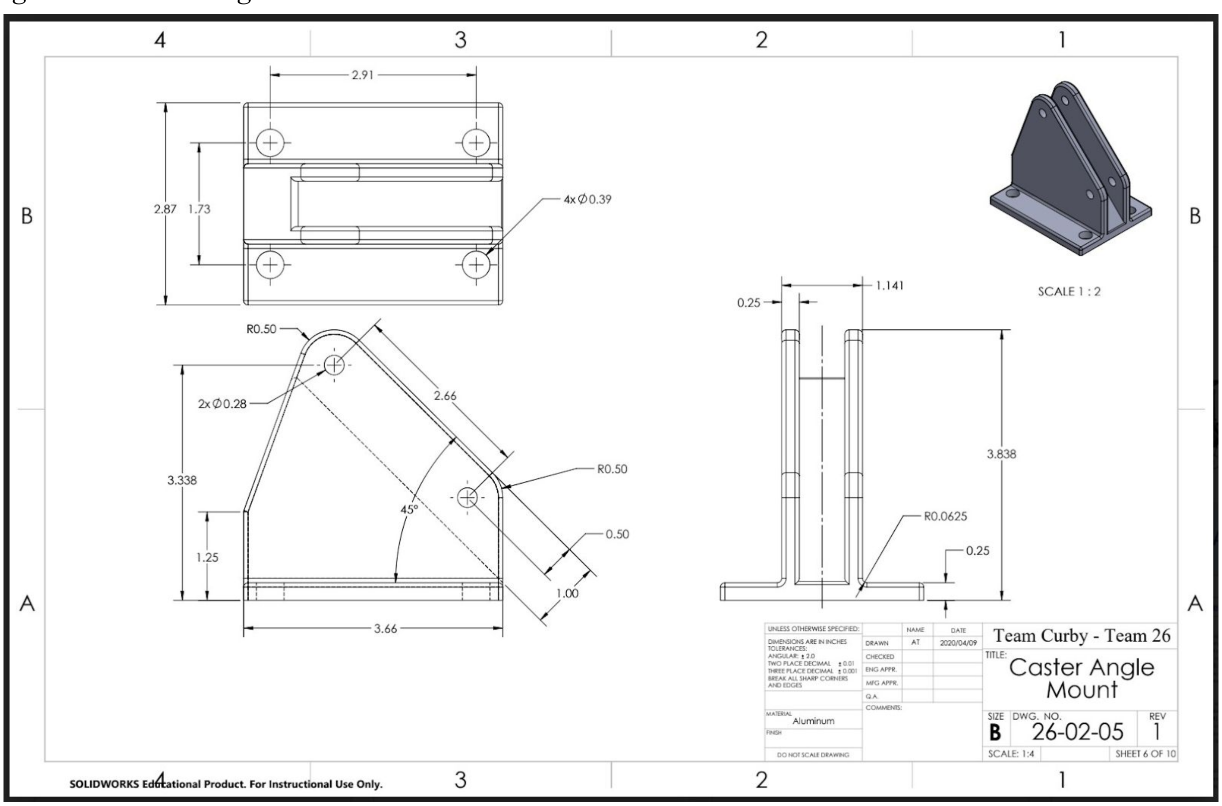


Figure C7. Pivot arm mount

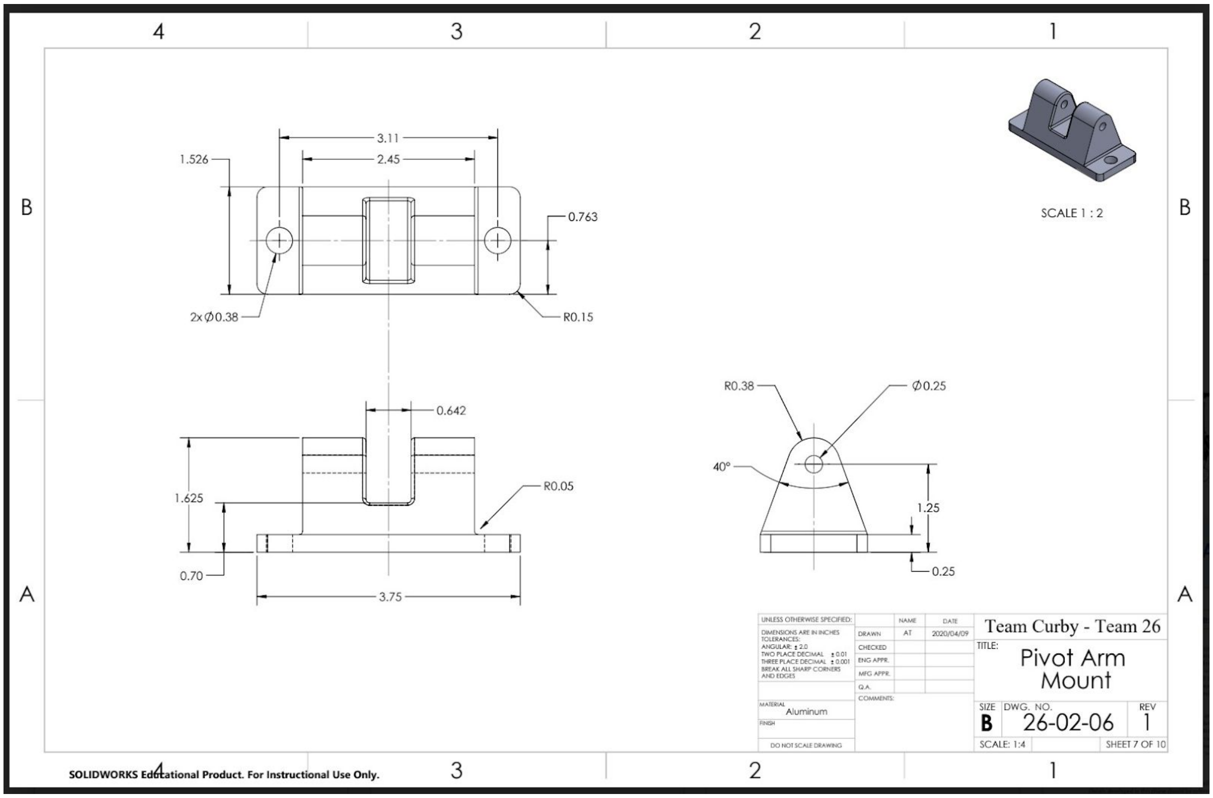


Figure C8. Back pivot arm

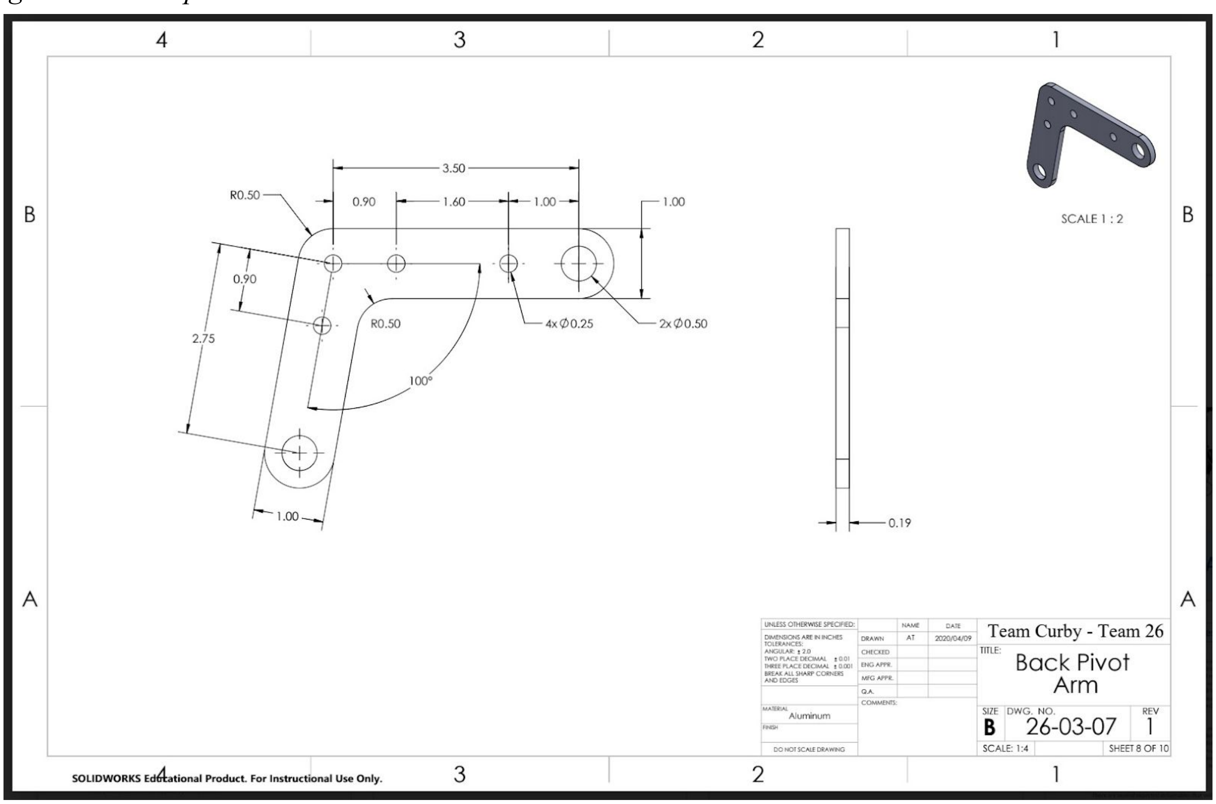


Figure C9. Back pivot arm mount

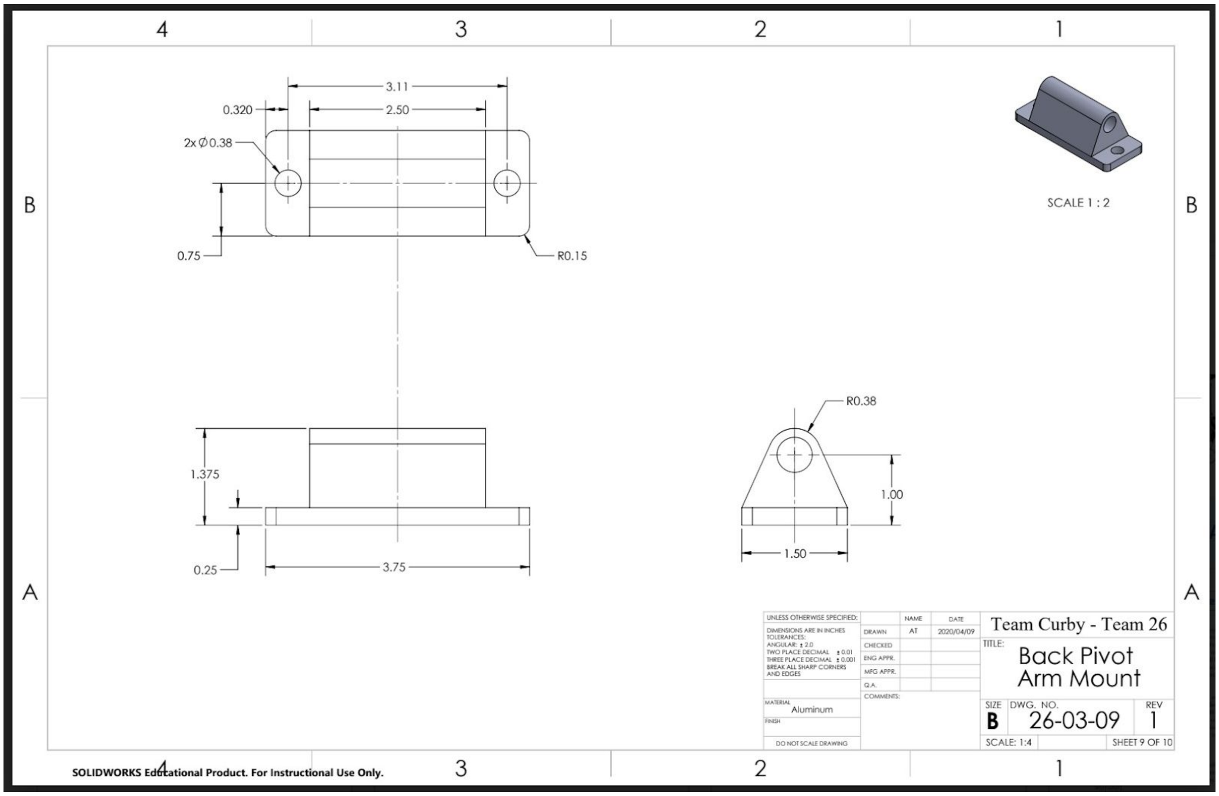
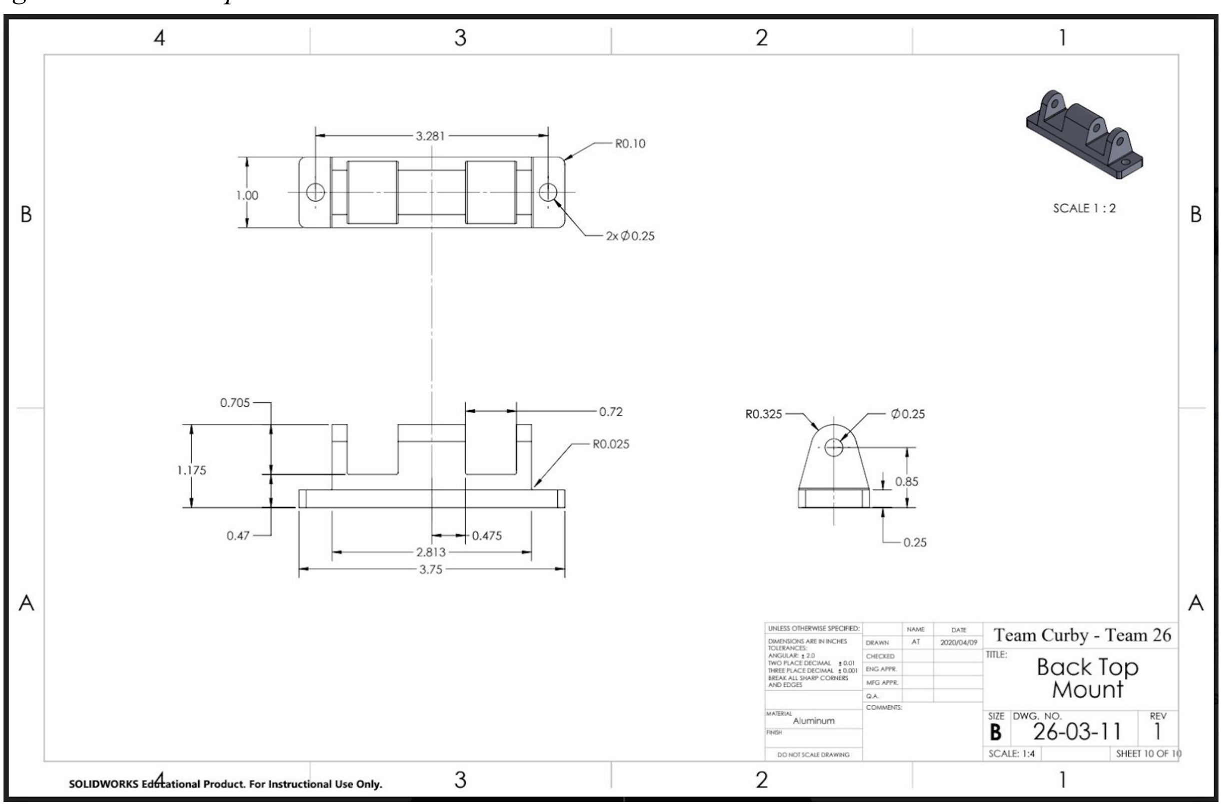


Figure C10. Back top mount



Appendix D: Budget

The costs for the front wheel subsystem is estimated below. This is a condensed version from our total project costs spreadsheet. Design phase refers to when in the design phase these components were used. Since the arduino uno was donated and no actual cost associated with it, a second motor driver is used to represent this arduino uno cost.

Figure D1. Front wheel subsystem prototype estimated cost summary

Front Wheel Subsystem Components									
Item No.	Description	Design Phase	Sub-System	QTY	Source	SKU	Unit Cost	Shipping	Total Incl. Taxes [CAD]
3	Electronics Box, Plastic, Sealed	Final Prototype	Electrical	1	Lee's Electronics	109471	$9.25	N/A	$10.36
4	DC Power Jack, 2.1mm, Female	Final Prototype	Electrical	1	Lee's Electronics	21009	$2.00	N/A	$2.24
6	Motor Driver, L298N	Final Prototype	Electrical	1	Amazon	N/A	$24.99	N/A	$24.99
1	Battery, Rechargeable	Test Prototyping	Electrical	1	Lee's Electronics	81038	$16.50	N/A	$18.48
2	Motor Driver, L298N	Test Prototyping	Electrical	1	Lee's Electronics	20162	$21.00	N/A	$23.52
5	Battery, Rechargeable, Lithium Ion	Final Prototype	Electrical	1	Lee's Electronics	88351	$65.00	N/A	$72.80
14	Linear Actuator, 12V, DC, 6 in. Stroke, 270lb	Final Prototype	Mechanical	2	Princess Auto	8507824	$79.99	N/A	$179.18
15	Caster, 4" Diameter, Swivel Heavy Duty Orange	Final Prototype	Mechanical	1	Home Depot	1001030265	$12.37	N/A	$13.86
19	Pivot Truss Material + Waterjet	Final Prototype	Mechanical	1	UBC Mech Shop	N/A	$11.53	N/A	$11.53
20	Top Mount Material + Waterjet	Final Prototype	Mechanical	1	UBC Mech Shop	N/A	$20.35	N/A	$20.35
24	3D Printed Parts Final Prototype	Final Prototype	Mechanical	1	Chris' Printer	N/A	$14.48	N/A	$14.48
								SUM	**$391.79**

Figure D2. Total spending

Item No.	Description	Design Phase	Sub-System	QTY	Source	SKU	Unit Cost	Shipping	Total Incl. Taxes [CAD]
3	Electronics Box, Plastic, Sealed	Final Prototype	Electrical	1	Lee's Electronics	109471	$9.25	N/A	$10.36
4	DC Power Jack, 2.1mm, Female	Final Prototype	Electrical	1	Lee's Electronics	21009	$2.00	N/A	$2.24
6	Motor Driver, L298N	Final Prototype	Electrical	1	Amazon	N/A	$24.99	N/A	$24.99
1	Battery, Rechargeable	Test Prototyping	Electrical	1	Lee's Electronics	81038	$16.50	N/A	$18.48
2	Motor Driver, L298N	Test Prototyping	Electrical	1	Lee's Electronics	20162	$21.00	N/A	$23.52
7	Jumper Wires, 10cm and 20cm	Test Prototyping	Electrical	1	Amazon	N/A	$11.99	N/A	$11.99
5	Battery, Rechargeable, Lithium Ion	Final Prototype	Electrical	1	Lee's Electronics	88351	$65.00	N/A	$72.80
14	Linear Actuator, 12V, DC, 6 in. Stroke, 270lb	Final Prototype	Mechanical	2	Princess Auto	8507824	$79.99	N/A	$179.18
15	Caster, 4" Diameter, Swivel Heavy Duty Orange	Final Prototype	Mechanical	1	Home Depot	1001030265	$12.37	N/A	$13.86
8	Linear Actuator, 12V, DC, 4 in. Stroke, 270lb	Test Prototyping	Mechanical	2	Princess Auto	8507816	$69.99	$7.12	$164.75
9	Caster, 3-3/4" x 2-5/8" Mounting Plate, Swivel with Flat-Free 6" Diameter Rubber Wheel	Test Prototyping	Mechanical	1	Mcmaster Carr	4941T21	$30.91	$8.14	$53.30
10	Caster, 3-3/4" x 2-5/8" Mounting Plate, Swivel with Flat-Free 3" Diameter Rubber Wheel	Test Prototyping	Mechanical	1	Mcmaster Carr	4941T31	$11.03	$8.14	$26.17
11	Cardinal Caster, Swivel with 4" Diameter Polyurethane Wheel	Test Prototyping	Mechanical	1	Mcmaster Carr	2426T53	$20.86	$8.14	$39.59
12	Nylon Sleeve Bearing, Light Duty Dry-Running, 1-3/16" OD x 1/16" Thick Flange, 3/4" Shaft, 1" Housing ID	Test Prototyping	Mechanical	2	Mcmaster Carr	6389K556	$2.03	$8.14	$13.88
13	Linear Actuator, 12V, DC, 8 in. Stroke, 270lb	Test Prototyping	Mechanical	2	Princess Auto	8507832	$84.99	$7.44	$198.71
17	T-Bar Mount Material	Final Prototype	Mechanical	1	Rocky Mountain	Various	$82.54	$18.50	$113.16
18	T-Bar Machining Service	Final Prototype	Mechanical	1	Rocky Mountain	Various	$28.35	N/A	$31.75
19	Pivot Arm Material + Waterjet	Final Prototype	Mechanical	1	UBC Mech Shop	N/A	$11.53	N/A	$11.53
20	Top Mount Material + Waterjet	Final Prototype	Mechanical	1	UBC Mech Shop	N/A	$20.35	N/A	$20.35
24	3D Printed Parts Final Prototype	Final Prototype	Mechanical	1	Chris' Printer	N/A	$14.48	N/A	$14.48
16	Linear Actuator, 12V, DC, 6 in. Stroke, 270lb	Test Prototyping	Mechanical	1	Princess Auto	8507824	$79.99	N/A	$89.95
22	3D Printed Parts CFP	Test Prototyping	Mechanical	1	Chris' Printer	N/A	$12.24	N/A	$12.24
23	3D Printed Test Prototypes	Test Prototyping	Mechanical	1	Chris' Printer	N/A	$35.88	N/A	$35.88
27	Misc Hardware	Miscellaneous	Misc	1	Various	N/A	$88.55	N/A	$88.55
28	Pick-Up Costs Estimate (Gas, Mileage, Etc.)	Miscellaneous	Misc	1			$50.00	N/A	$50.00
24	Startup Costs (Logbook, 3D Printer Upgrades, Filament)	Startup	Misc	1	Various	N/A	$177.38	N/A	$177.38
21	36" Zip Tie	Test Prototyping	Testing	1	Home Depot	4715409150237	$10.66	N/A	$11.94
25	Demo Curb, Raw Materials	Test Prototyping	Testing	1	Home Depot	Various	$35.93	N/A	$46.73
26	Snow Tire Chains, 10 Pcs	Test Prototyping	Testing	1	Amazon	N/A	$22.99	N/A	$22.99
								Sub-Total	$1,580.75
								Contingency (15% of Sub-Total)	$237.11
								Grand Total	$1,817.86

Appendix E: FMEA

Some engineering calculations were used to verify some of the FMEA elements. Please see the screenshots below of our full FMEA. A higher resolution of these can be found in the spreadsheet uploaded in [Phase 9A: Technical Analysis Plan](#).

Figure E1. FMEA spreadsheet screenshots

Severity		Occurrence	Probability that the failure will happen	Detection	Probability that the onset of the failure will be discovered and acted on before it results in the effect
10	severe injury or death or major damage	10	certain	10	no chance of detection and action
9	serious injury or damage	9	extreme	9	almost no chance of detection and action
8	injury or major disruption	8	very high	8	very low chance of detection and action
7	very significant customer dissatisfaction	7	high	7	low chance of detection and action
6	significant customer dissatisfaction	6	moderately high	6	low- moderate chance of detection and action
5	customer requires immediate service	5	moderate	5	moderate chance of detection and action
4	customer inconvenienced by premature need for service	4	low	4	moderate-high chance of detection and action
3	customer annoyed but not enough to demand service	3	very low	3	high chance of detection and action
2	customer notices but is not annoyed	2	extremely low	2	very high chance of detection and action
1	effect not noticed by customer (benign)	1	almost never	1	almost certain to detect and correct

RPN	Description
≥250	Significant
100-249	Somewhat important
<100	Not important

Sub-system: Mechanical Components

Original date: 23-Mar-20 **Prepared by:** JC
Revision date: **Revised by:**

Part	Failure Mode	Severity: Effect	S	Occurrence: Cause	O	Detection: Control	D	RPN	Recommended Action	Action Results	Expected Results of Action: S'	O'	D'	RPN'
Linear Actuator	Shaft plastic deformation	Wheelchair tips over	10	Excessive operational loads or torque	6	Engineering calculations done in 11B to determine operational loads of the device	4	240	Remove the bending moments in the actuators	The addition of the pivot arm element removes the bending moments in the actuators (see engineering calculations in 11B)	10	5	2	100
			10	Impact loads	8	Engineering calculations done in 11B to determine impact loads experienced by device	3	240	Dampen the impact forces	Line hazardous areas with impact attenuating material (see engineering calculations in 11B)	10	4	3	120
		Damaged device; poor/no functionality	8	Excessive operational loads or torque	6	Engineering calculations done in 11B to determine operational loads of the device	4	192	Verify computer simulation results	The addition of the pivot arm element removes the bending moments in the actuators (see engineering calculations in 11B)	8	5	2	80
			8	Impact loads	8	Engineering calculations done in 11B to determine impact loads experienced by device	3	192	Dampen the impact forces	Line hazardous areas with impact attenuating material (see engineering calculations in 11B)	8	4	3	96
Linear Actuator	Shaft corrodes	Wheelchair tips over	10	External environment enables corrosion of components, compromises actuator integrity	4	Linear actuator components are corrosion resistant	2	80	No actions at this time					0
		Damaged device; poor/no functionality	8	External environment enables corrosion of components, interfere with operation	6	Linear actuator components are corrosion resistant	2	96	No actions at this time					0

Sub-system: Mechanical Components

Original date: 23-Mar-20 **Prepared by:** JC
Revision date: **Revised by:**

Part	Failure Mode	Severity		Occurrence		Detection		RPN	Recommended Action	Action Results	Expected Results of Action			
		Effect	S	Cause	O	Control	D				S'	O'	D'	RPN'
Linear Actuator	Shaft fatigue fracture	Wheelchair tips over	10	Crack propagation fracture from cyclic loads	4	Engineering calculations in 11B to determine operational loads of the device	6	240	Verify engineering calculations	Experimental testing to obtain load data under operating conditions; linear actuators specified have an above 2 safety factor	10	3	3	90
		Damaged device; poor/no functionality	8	Crack propagation fracture from cyclic loads	4	Engineering calculations in 11B to determine operational loads of the device	6	192	Verify engineering calculations	Experimental testing to obtain load data under operating conditions; linear actuators specified have an above 2 safety factor	8	3	3	72
Linear Actuator	Shaft fretting	Wheelchair tips over	10	Shaft deflection causes uneven wear of seals	6	Engineering calculations in 11B to determine operational loads of the device	3	180	Remove the bending moments in the actuators which makes shafts susceptible to deflection	The addition of the pivot arm element removes the bending moments in the actuators (see engineering calculations in 11B)	10	4	2	80
		Damaged device; poor/no functionality	8	Shaft deflection causes uneven wear of seals	6	Engineering calculations in 11B to determine operational loads of the device	3	144	Remove the bending moments in the actuators which makes shafts susceptible to bending	The addition of the pivot arm element removes the bending moments in the actuators (see engineering calculations in 11B)	8	4	2	64

Sub-system: Mechanical Components

Original date: 23-Mar-20 **Prepared by:** JC
Revision date: **Revised by:**

Part	Failure Mode	Severity		Occurrence		Detection		RPN	Recommended Action	Action Results	Expected Results of Action			
		Effect	S	Cause	O	Control	D				S'	O'	D'	RPN'
Linear Actuator	Bearing Failure	Damaged bearing; poor/no device functionality	8	Radial loading - abnormal wear to bearings	6	Engineering calculations in 11B to determine operational loads of the device	4	192	Ensure actuator bearings are replaced/serviced before damages	Maintenance instructions/schedule in user manual according to experiment results	8	4	3	96
				Shaft misalignment - abnormal wear to bearings	4									
		Noisy operation	4	Radial loading - abnormal wear to bearings	6	Engineering calculations in 11B to determine operational loads of the device	4	96	Ensure actuator bearings are replaced/serviced before damages	Maintenance instructions/schedule in user manual according to experiment results	4	4	3	48
				Shaft misalignment - abnormal wear to bearings	4									
Mounting Parts	Mounting parts plastic deformation	Wheelchair tips over	10	Excessive operational loads or torque	7	Computer simulations to obtain operational loads on mounting components (see FEA done in 11E)	4	280	Construct mounting components according to FEA results done in 11E	Final mounting parts will be machined out of 6061 aluminum	10	2	4	80
		Damaged device; poor/no functionality	8	Excessive operational loads or torque	7	Computer simulations to obtain operational loads on mounting components (see FEA done in 11E)	4	224	Construct mounting components according to FEA results done in 11E	Final mounting parts will be machined out of 6061 aluminum	8	2	4	64
Mounting Parts	Mounting parts fatigue fractures	Wheelchair tips over	10	Crack propagation fracture from cyclic loads	4	Engineering calculations in 11B to determine effects of fatigue on mounting components	6	240	Construct mounting components according to engineering calculations in 11B	Final mounting parts will be machined out of 6061 aluminum; endurance limit well under operational loads	10	3	3	90
		Damaged device; poor/no functionality	8	Crack propagation fracture from cyclic loads	4	Engineering calculations in 11B to determine effects of fatigue on mounting components	6	192	Construct mounting components according to engineering calculations in 11B	Final mounting parts will be machined out of 6061 aluminum; endurance limit well under operational loads	8	3	3	72

Sub-system: Mechanical Components

Original date: 23-Mar-20 **Prepared by:** JC
Revision date: **Revised by:**

Part	Failure Mode	Severity		Occurrence		Detection		RPN	Recommended Action	Action Results	Expected Results of Action			
		Effect	S	Cause	O	Control	D				S'	O'	D'	RPN'
Fasteners	Fastener shearing failure	Loose/missing connections alter tolerances; poor device functionality	8	Shear loads exceed shear strength of fasteners	6	Device designed such that fasteners loaded in tension	2	96	No further action required					0
Fasteners	Fastener corrosion	Loose/missing connections alter tolerances; poor device functionality	8	External environment enable corrosion	6	Selected fasteners are corrosion resistant	2	96	No further action required					0
			8	Dissimilar metals enable corrosion	6	All components are corrosion resistant	2	96	No further action required					0
Fasteners	Fastener galling	Loose/missing connections alter tolerances; poor device functionality	8	Incorrect fastener installation procedure	4	Low speed installation, lubricant use, avoid fastener misalignment	2	64	No further action required					0
Fasteners	Fastener overloading	Loose/missing connections alter tolerances; poor device functionality	8	Operational loads deform fasteners	4	Fasteners rated for application with a safety factor	2	64	No further action required					0
Caster Wheel	Bearings Overloaded	Excessive wear on the bearings	5	Bearings loaded beyond their rated specifications	5	Engineering calculations in 11B to determine the operational loads of the caster	4	100	Verify engineering calculation results	Experimental testing to obtain load data under operating conditions; caster selected accordingly	5	3	2	30
		Caster's motion is restricted; poor device functionality	7	Bearings loaded beyond their rated specifications	5	Engineering calculations in 11B to determine the operational loads of the caster	4	140	Verify computer simulation results	Experimental testing to obtain load data under operating conditions; caster selected accordingly	7	3	2	42

Sub-system: Electrical Components

Original date: 23-Mar-20 **Prepared by:** JC
Revision date: **Revised by:**

Part	Failure Mode	Severity		Occurrence		Detection		RPN	Recommended Action	Action Results	Expected Results of Action			
		Effect	S	Cause	O	Control	D				S'	O'	D'	RPN'
Electrical Circuit	Short Circuit	Damages to circuit; poor/no device functionality	8	Unintended connection(s) during fabrication	6	Check wiring connections during installation	3	144	Prevent damages to circuit when short circuit occurs	Circuit breakers induce open circuit when short circuit sensed	8	4	2	64
			8	Wire insulation degradation	4	Experimentally evaulate wire insulation quality after repeated operation	4	128	Periodic inspection of wire insulation for signs of degradation	O&M manual provides instruction for wire insulation inspection	8	4	2	64
		Sparking of circuit; fire or injury	10	Unintended connection(s) during fabrication	6	Check wiring connections during installation	3	180	Prevent damages to circuit when short circuit occurs	Circuit breakers induce open circuit when short circuit sensed	10	4	3	120
			10	Wire insulation degradation	4	Experimentally evaulate wire insulation quality after repeated operation	4	160	Periodic inspection of wire insulation for signs of degradation	O&M manual provides instruction for wire insulation inspection	10	4	2	80
Electrical Circuit	Open Circuit	Poor/no device functionality	7	Missed connection(s) during fabrication	6	Check wiring connections during installation	2	84	No further action required					0
			7	Damaged components from environmental conditions (humidity/moisture)	4	Experimentally evaluate circuit component under operating environmental conditions	4	112	Protect components from environmental conditions	Circuit is encased in box and placed away from external elements	7	3	2	42
			7	Damaged components from time degradation	4	Experimentally evaluate circuit component quality after repeated operation	4	112	Periodic inspection of circuit components for signs of degradation	O&M manual provides instruction for electrical component inspection	7	4	3	84
Wheelchair/User	Inadvertent Current Flow	Electric shocks user	10	Circuitry is exposed; conducts with wheelchair or user	6	Visual inspection of electrical components and wiring	3	180	Protect electrical components and wiring	Electrical components and wiring placed away from external elements	10	3	3	90

Sub-system: Electrical Components

Original date: 23-Mar-20 **Prepared by:** JC
Revision date: **Revised by:**

Part	Failure Mode	Severity		Occurrence		Detection		RPN	Recommended Action	Action Results	Expected Results of Action			
		Effect	S	Cause	O	Control	D				S'	O'	D'	RPN'
Linear Actuator Electric Motor	Electrical overload	Insufficient torque; poor/no device functionality	8	Motor's rated load is insufficient for operating parameters	6	Linear actuator motor specified based off design calculations	2	96	No further action required					0
			8	Linear actuators' operation not synchronized	6	Synchronicity tested for and programmed using PWM	3	144	Periodic inspection of actuator synchronicity	O&M manual provides instructions for synchronicity test	8	6	2	96
		Motor overheats; damages to motor components	8	Motor's rated load is insufficient for operating parameters	6	Linear actuator motor specified based off design calculations	4	192	Implement fail safe design into electrical architecture	Specified motor driver fails before electric motors	8	3	4	96
			8	Linear actuators' operation not synchronized	6	Synchronicity tested for and programmed using PWM	4	192	Implement fail safe design into electrical architecture	Specified motor driver fails before electric motors	8	3	4	96
			8	Contiminants enter motor housing, block cooling fan	6	Motor performance testing under operational conditions	2	96	Prevent contaminants from entering motor	Motor encased in housing	8	4	2	64
			8	Operation in hot ambient temperatures	6	Experimentally evaluate the effects of high temperature operation on motor insulation	4	192	Limit battery operation time in hot temperatures	Insulate the battery casing from external temperatures	6	4	4	96
		Excessive current draw; damages to motor or circuit	8	Motor's rated load is insufficient for operating parameters	6	Linear actuator motor specified based off design calculations	4	192	Implement fail safe design into electrical architecture	Specified motor driver fails before electric motors	8	3	4	96
			8	Linear actuator's operation not synchronized	6	Synchronicity tested for and programmed using PWM	4	192	Implement fail safe design into electrical architecture	Specified motor driver fails before electric motors	8	3	4	96
Linear Actuator Electric Motor	Motor winding insulation failure	Motor short circuits; no functionality	8	Loosened wiring connections	6	Check wiring connections during installation	3	144	Implement fail safe design into electrical architecture	Specified motor driver to fail before electric motors	8	3	4	96
			8	Low resistance; motor wire insulation degradation over time	4	Experimentally evaulate motor insulation quality after repeated operation	4	128	Periodic inspection of motor insulation for insulation degradation	O&M manual provides instruction for motor insulation inspection	8	4	2	64
		Motor overheats; damages to motor components	8	Operation in hot ambient temperatures	6	Experimentally evaluate the effects of high temperature operation on motor insulation	4	192	Limit battery operation time in hot temperatures	Insulate the battery casing from external temperatures	6	4	4	96
			8	Poor power supply quality	5	Experimental testing to determine required power per cycle	4	160	Ensure power supply is sufficient for operating conditions	Battery specified to provide sufficient power supply	8	3	4	96
			8	Low resistance; motor wire insulation degradation over time	4	Experimentally evaulate motor insulation after repeated operation	4	128	Periodic inspection of motor insulation for insulation degradation	O&M manual provides instruction for motor insulation inspection	8	4	2	64

Sub-system: Electrical Components

Original date: 23-Mar-20 **Prepared by:** JC
Revision date: **Revised by:**

Part	Failure Mode	Severity		Occurrence		Detection		RPN	Recommended Action	Action Results	Expected Results of Action			
		Effect	S	Cause	O	Control	D				S'	O'	D'	RPN'
Linear Actuator Electric Motor	Motor Vibration	Damages to motor; poor/no functionality	8	Linear actuator mounted on uneven or unstable surface	6	Tolerances enable level/tight fit; inspected during installation	4	192	Inspect for damages to device after repeated use	Fatigue test device for qualitative indications of vibration	8	6	2	96
			8	Loose/missing fasteners	4	Fasteners rated for operational loads, torqued according to specifications	4	128	Inspect for damages to device after repeated use	Fatigue test device for qualitative indications of vibration	8	4	2	64
		Noisy Operation	4	Linear actuator mounted on uneven or unstable surface	6	Tolerances enable level/tight fit; inspected during installation	4	96	Inspect for damages to device after repeated use	Fatigue test device for qualitative indications of vibration	4	4	2	32
			4	Loose/missing fasteners	4	Fasteners rated for operational loads torqued according to specifications	4	64	Inspect for damages to device after repeated use	Fatigue test device for qualitative indications of vibration	4	4	2	32
Power Supply	Insufficient power supplied to actuators	Poor/no device functionality	7	Battery capacity insufficient for application	5	Experimental testing to determine required power per cycle	4	140	Ensure power supply is sufficient for operating conditions, see 8D for optimization testing	Battery specified to provide sufficient power supply	7	3	4	84
			7	Batteries not charged adequately prior to use	8	Experimental testing to determine required power per cycle	2	112	Inform user when battery levels low	Include a battery level indicator with device	7	6	2	84

Sub-system: Electrical Components

Original date: 23-Mar-20 **Prepared by:** JC
Revision date: **Revised by:**

Part	Failure Mode	Severity		Occurrence		Detection		RPN	Recommended Action	Action Results	Expected Results of Action			
		Effect	S	Cause	O	Control	D				S'	O'	D'	RPN'
Lithium Ion Battery	Battery lithium plating	Irreversible battery capacity loss	6	Charging voltage above recommended upper cell voltage	6	Battery charger specified according to manufacturer's recommendation	2	72	No further action required					0
			6	Low temperature operation	6	Experimentally evaluate the effects of reasonably low temperature operation on the battery	4	144	Limit battery operation time in cold temperatures	Insulate the battery casing from external temperatures	6	4	4	96
			6	Physical damages to battery	8	Experimentally evaluate the effects/likelihood of foreseeable impacts to battery	4	192	Protect the battery from physical damage	Battery is stored in protective casing	6	4	4	96
			6	Manufacturer's defects	6	Battery visually and performance inspected prior to installation	2	72	No further action required					0
		Elctrode short circuit; no power supplied	8	Charging voltage above recommended upper cell voltage	6	Battery charger specified according to manufacturer's recommendation	2	96	No further action required					0
			8	Low temperature operation	6	Experimentally evaluate the effects of low temperature operation on the battery	4	192	Limit battery operation time in cold temperatures	Insulate the battery casing from external temperatures	8	4	4	128
			8	Physical damages to battery	8	Experimentally evaluate the effects/likelihood of foreseeable impacts to battery	4	256	Protect the battery from physical damage	Battery is stored in protective casing	8	4	4	128
			8	Manufacturer's defects	6	Battery visually and performance inspected prior to installation	2	96	No further action required					0
Lithium Ion Battery	Battery anode dissolves into electrolye	Battery short circuit; no functionality	8	Charging voltage below recommended lower cell voltage	6	Battery charger specified according to manufacturer's recommendation	2	96	No further action required					0
Lithium Ion Battery	Battery cathode degrades	Irreversible battery capacity loss	6	Charging voltage below recommended lower cell voltage for prolonged periods	4	Battery charger specified according to manufacturer's recommendation	2	48	No further action required					0
Lithium Ion Battery	Battery thermal runaway	Battery overheats; poor functionality	6	Physical damages to battery	8	Experimentally evaluate the effects/likelihood of foreseeable impacts to battery	4	192	Protect the battery from physical damage	Battery is stored in protective casing	6	4	4	96

Sub-system: Electrical Components

Original date: 23-Mar-20 **Prepared by:** JC
Revision date: **Revised by:**

Part	Failure Mode	Severity		Occurrence		Detection		RPN	Recommended Action	Action Results	Expected Results of Action			
		Effect	S	Cause	O	Control	D				S'	O'	D'	RPN'
Lithium Ion Battery	Battery thermal runaway	Battery overheats; poor functionality	6	Physical damages to battery	8	Experimentally evaluate the effects/likelihood of foreseeable impacts to battery	4	192	Protect the battery from physical damage	Battery is stored in protective casing	6	4	4	96
			6	High temperature operation	6	Experimentally evaluate the effects of high temperature operation on the battery	4	144	Limit battery operation time in hot temperatures	Insulate the battery casing from external temperatures	6	4	4	96
			6	Charging voltage/current above upper limits	6	Battery charger specified according to manufacturer's recommendation	2	72	No further action required					0
		Battery explodes/initiates fire; imminent injuries	10	Physical damages to battery	8	Experimentally evaluate the effects/likelihood of foreseeable impacts on battery	4	320	Protect the battery from physical damage	Battery is stored in protective casing	10	4	4	160
			10	High temperature operation	6	Experimentally evaluate the effects of high temperature operation on the battery	4	240	Limit battery operation time in hot temperatures	Insulate the battery casing from external temperatures	10	4	4	160
			10	Charging voltage/current above upper limits	6	Battery charger specified according to manufacturer's recommendation	2	120	Ensure user has correct charger	Charger supplied with device	10	4	2	80

Appendix F: Engineering Calculations

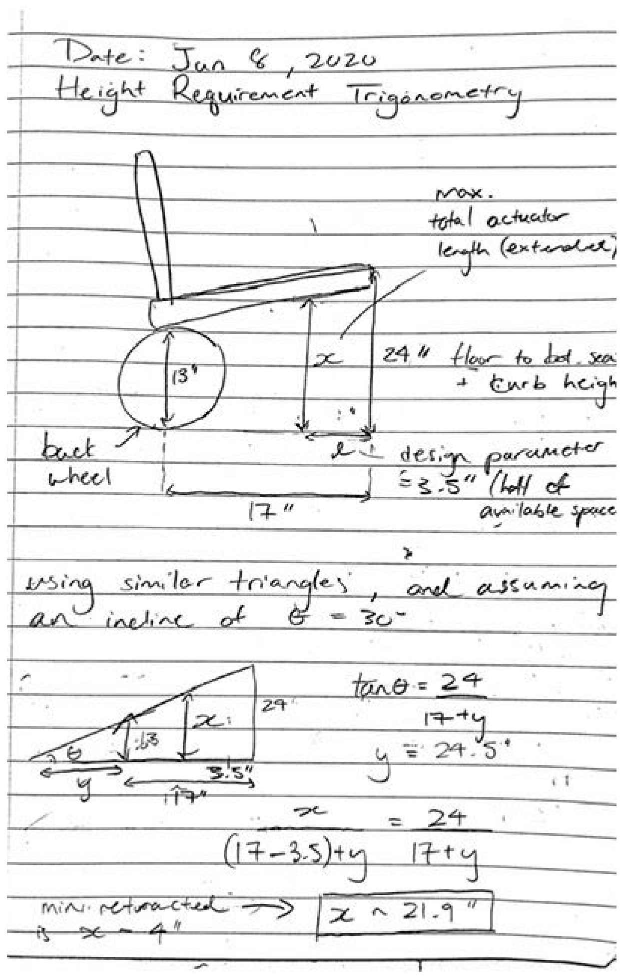
Engineering calculations that were done throughout the course to verify/guide the design according to requirements and also to verify the FMEA.

F.1 Front Wheel Linear Actuator Sizing

Purpose: Determine the required linear actuator extension to meet our height requirement of 4” curb lift.

Methods: Based on measurements taken for our wheelchair, we did simple trigonometry to determine a minimum amount of extension required for the actuators in order for the wheelchair to clear a 4” curb height.

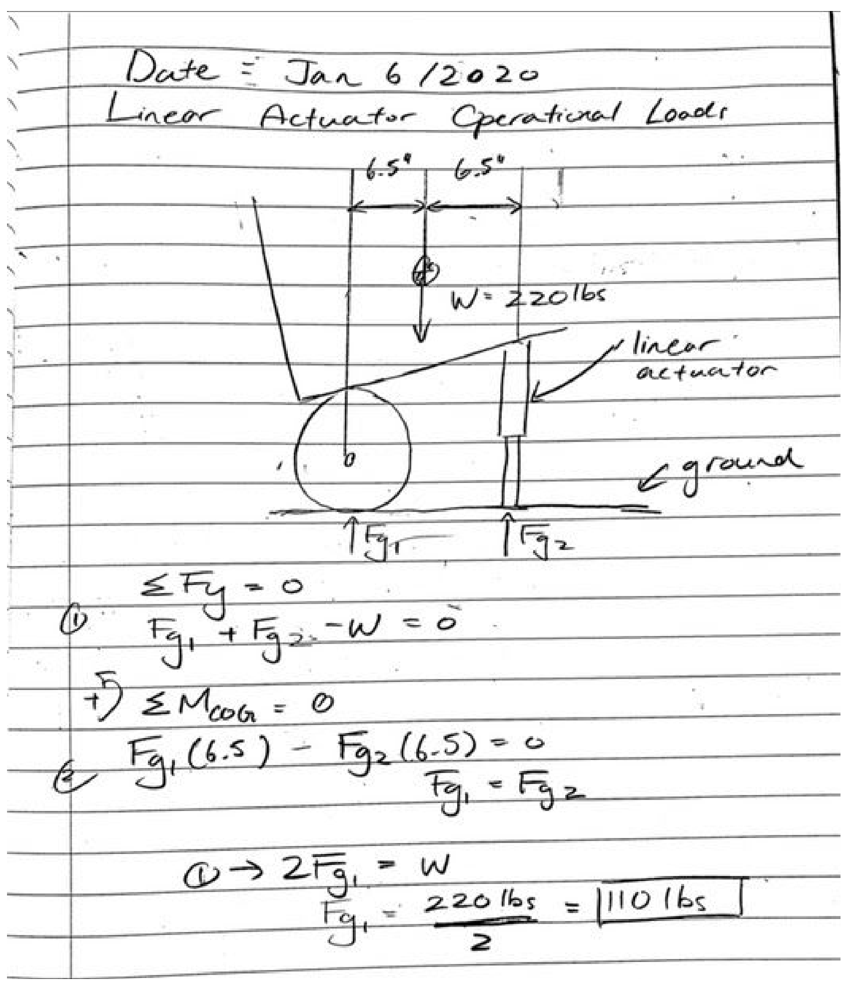
Conclusions: The height found was intended to be used as a starting point for the design of the actuators. It gave us insight into the available space for our design to achieve the height requirements. We selected 6” actuators based on these calculations and the other component sizing (mounting, caster, etc.) was detailed in Solidworks.



F.2 Front Wheel Operational Loads (Requirements)

Purpose: Determine the maximum expected operational loads experienced by the linear actuators and caster bearding during operation to verify specifications are sufficient for design.**Methods:** Based on weight requirement of 220lbs, completed a force analysis of the load to be carried by the actuator. The weight was assumed to act in the center of the wheelchair wheelbase (13"). This number will increase or decrease if the wheelchair weight acts off the center wheelchair wheelbase assumptions.

Conclusions: The system must support approximately 110lbs. Linear actuators and caster bearings were chosen accordingly with a safety factor margin. Note these calculations were done early in the design phase as a rough approximation and actual data was later obtained experimentally (see 8D. Optimization) which demonstrated that the forces are higher than these calculations indicate.



F.3 Mounting Component Fatigue (FMEA)

Purpose: Determine the cycles to failure, if applicable, of mounting components under expected operational loads.

Methods: Using the stress data obtained from the FEA analysis done in [Phase 11E: FEA]we compare these stresses to those seen on the S-N curve for 6061 aluminum.. It is important to note that all our tests completed to date have been completed with 3-D printed parts (PLA material) but the expected final design mounting components will be constructed from T-6061 aluminum.

Conclusions: Although aluminum does not have a fatigue limit, with a maximum expected stress of 5 MPa we see that the mounting components will surpass a million cycles. We do not expect the mounting components to fail from fatigue.

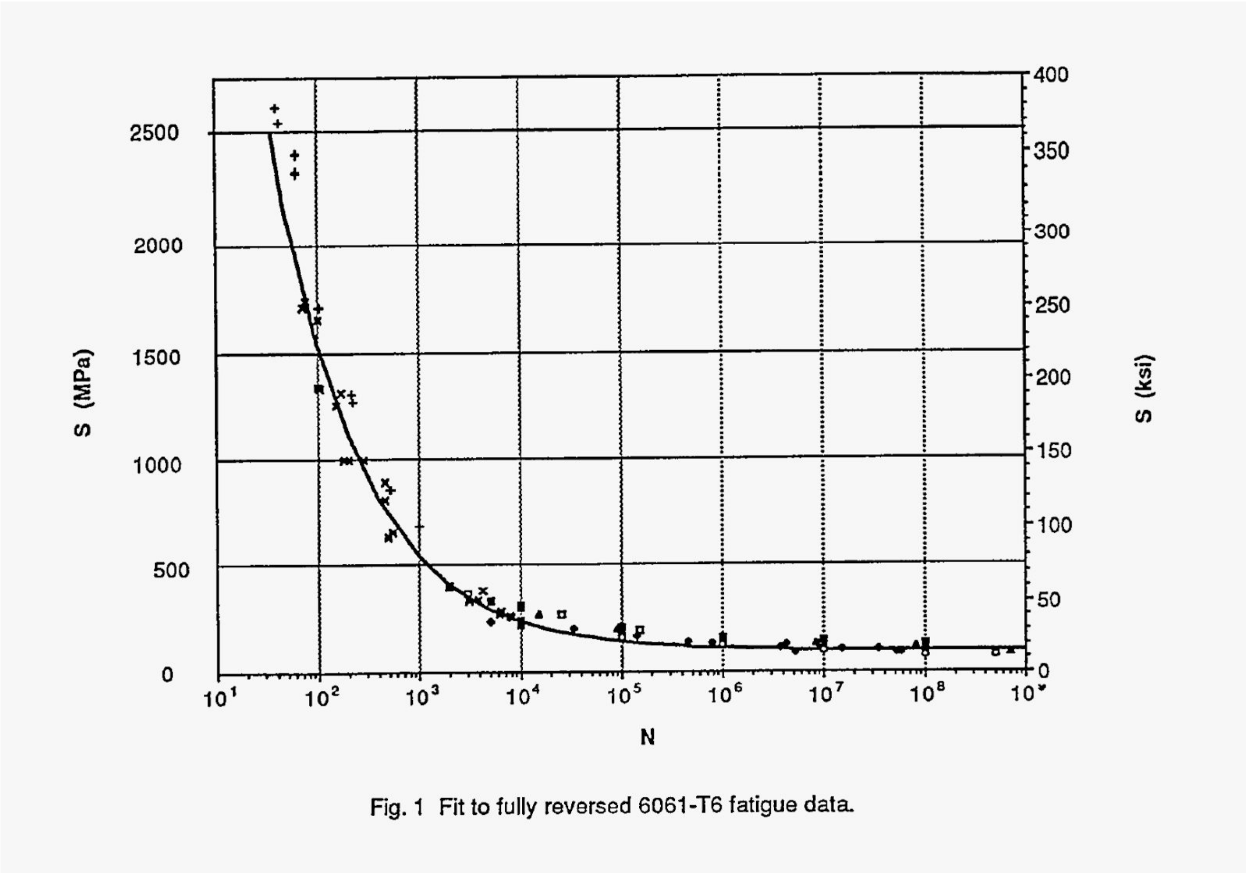


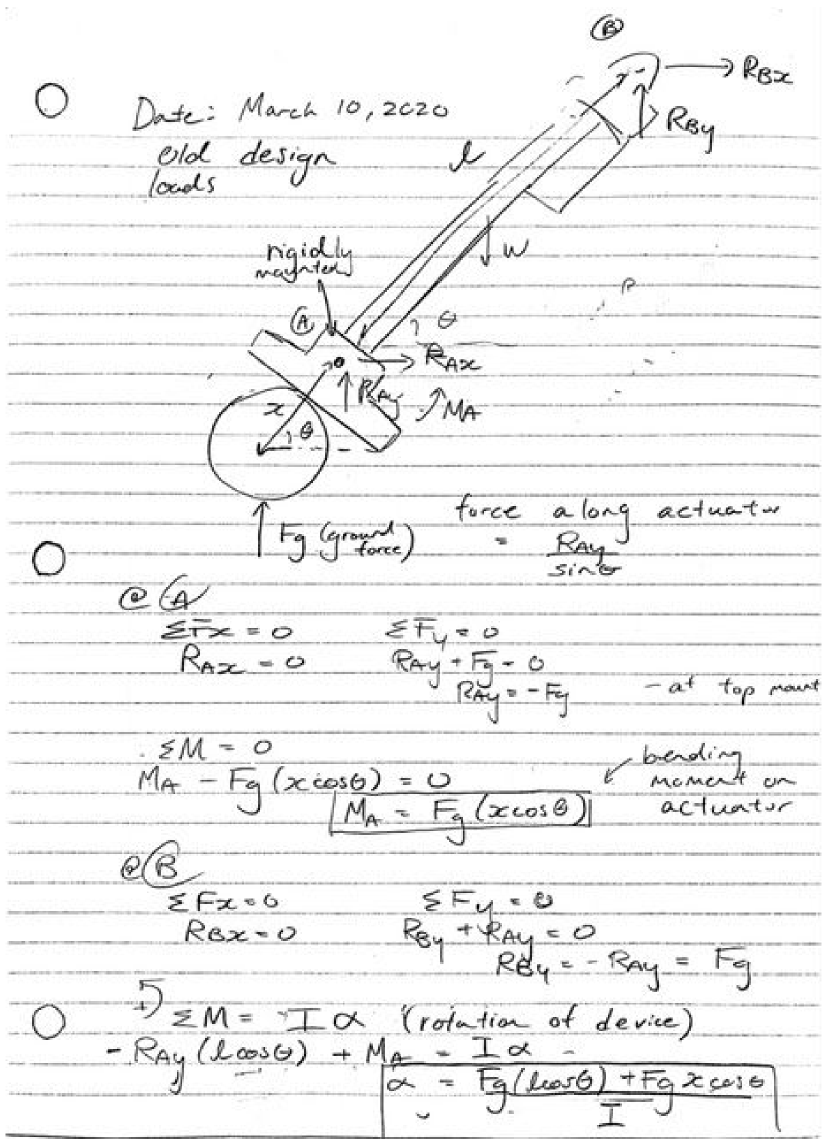
Figure F1. Taken from: T, Y. G. (1993). Fatigue Design Curves for 6061-T6 Aluminum. Oak Ridge National Laboratory.

F.4 Pivot Arm Loads (FMEA)

Purpose: A major revision to our design is the addition of the pivot arm element. This pivot arm, as suggested by our supervisor, Paul Winkelman, is intended to remove the concerns of bending stresses in the linear actuators. We did a simple force analysis to compare the experienced forces for the old design and the pivot arm design.

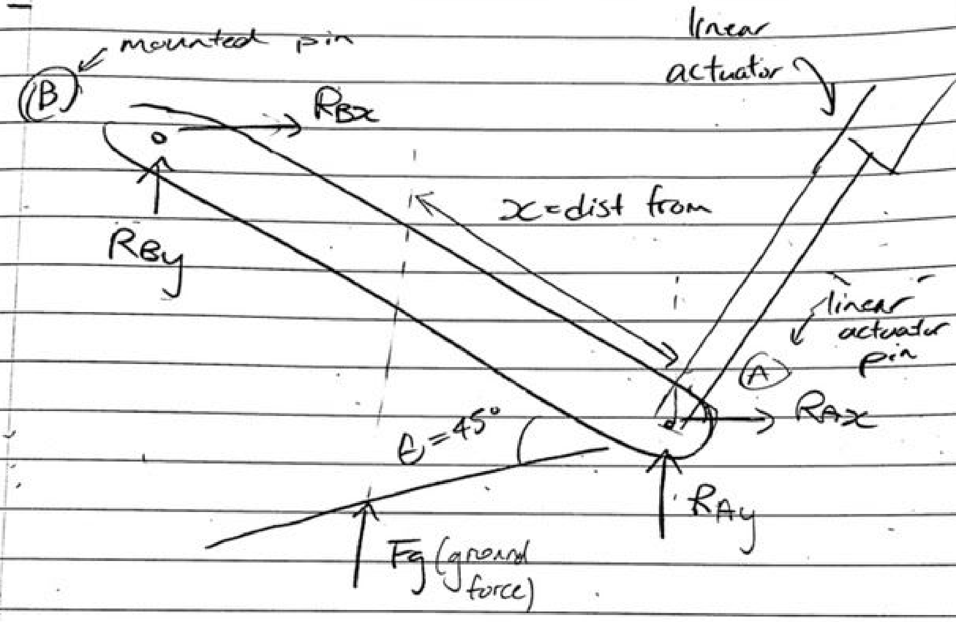
Methods: Do a force analysis of the device before and after the addition of a pivot arm. The calculations were kept high level using only variables

Conclusions: These calculations demonstrate a bending moment in our previous design, and in the FBD with the addition of the pivot arm, the linear actuator is pinned at both ends; thus removing the bending moment in the linear actuators. This confirms that the pivot arm is a crucial addition to the design.



Date: March 10, 2020

Pivot Arm Loads FBD



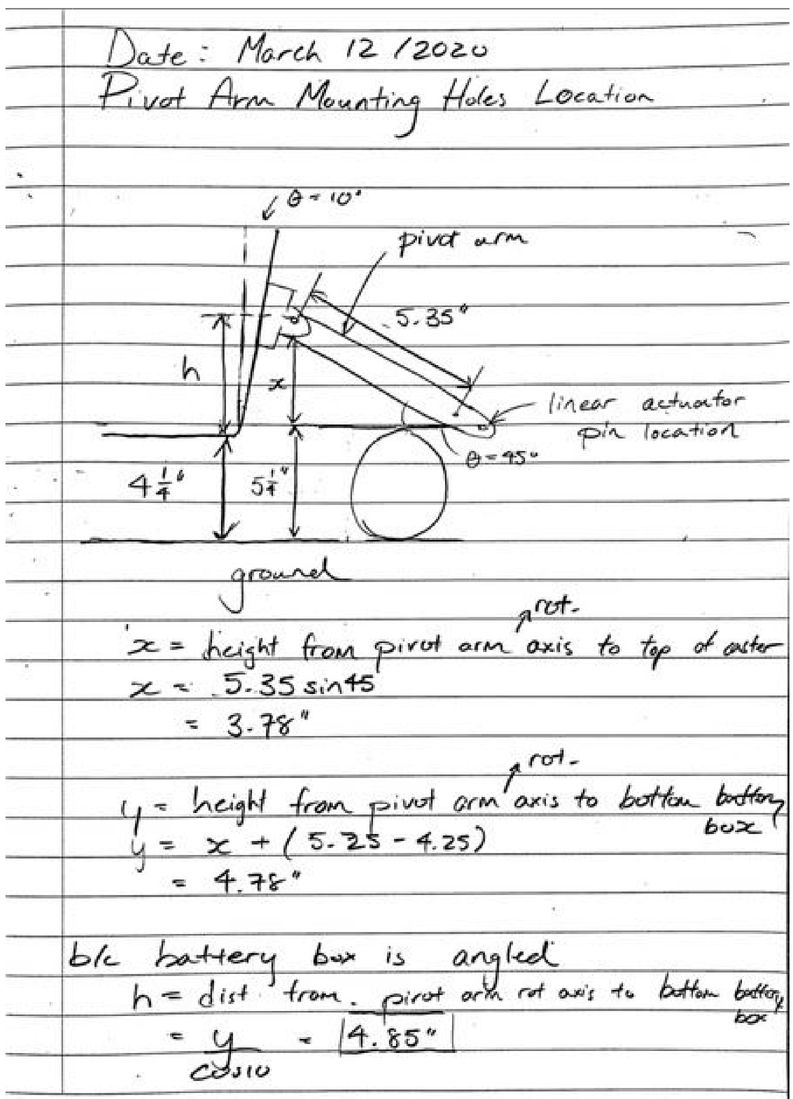
- since (A) is pinned, there is no longer a bending moment (M_A) on the linear actuators

F.5 Pivot Arm Sizing

Purpose: A major revision to our design is the addition of the pivot arm to eliminate the radial loads on the linear actuators. We had to trigonometrically determine the location of the mounting holes to be drilled into the wheelchair (Torque SP3200) battery box.

Methods: Using our previous prototype setup (without the pivot arm), we measured that the pivot arm length from linear actuator pin location to the pivot arm rotation had to be about 6” to obtain our desired curb height lift requirement of 4”. It was also important for the caster wheel axis of rotation to be parallel with the ground at the end of actuation to eliminate radial loads on its bearings. Using this we could determine the height that the mounting holes should be drilled at.

Conclusions: Drilled mounting holes at height of 4.85” from bottom of the battery box. During installation, slight adjustments were needed to the linear actuator top mount to ensure that the caster wheel axis of rotation was indeed parallel with the ground.

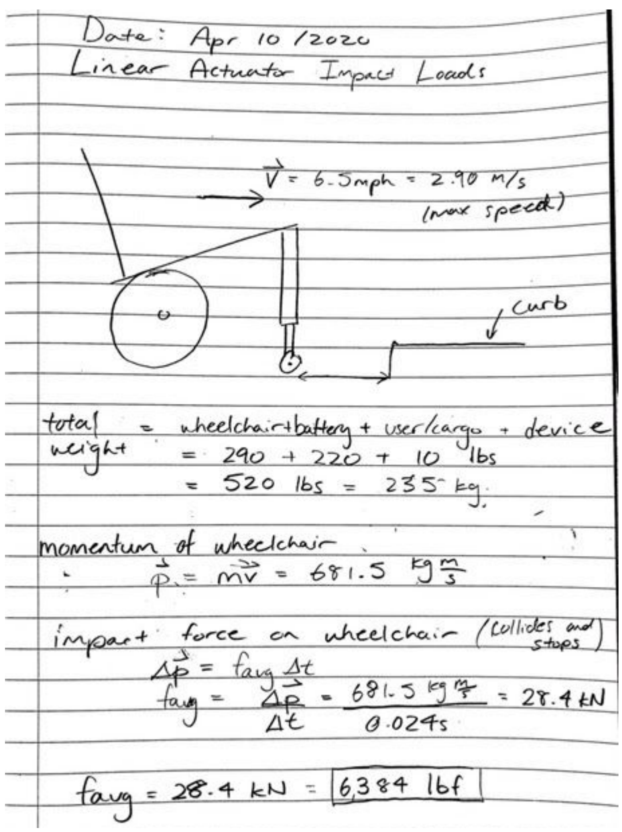


F.6 Front Wheel Linear Actuator Impact Loads (FMEA)

Purpose: During operation of the device when the wheelchair is tilted, there is a reasonable probability that the user will impact the curb with the extended linear actuators. These calculations provide insight into the approximate forces that would be experienced and impact attenuation/redesigns can be completed accordingly.

Methods: Using the max speed of the Torque SP 3200 of 6.5mph for a conservative estimate and the total expected weight, a momentum-force analysis was completed to estimate the average force during impact. A collision time of 0.024s was estimated from car collision data. [1]

Conclusions: The force estimated is a significant 6384 lbs. The max speed of the Torque SP 3200 was chosen on a worst case scenario basis, but more practical impact speeds will be a fraction of this. Furthermore, the collision time assumption for cars is likely an overestimate, actual impact time can be expected to be longer as the pivot arm and linear actuators move with impact. However approximate, these calculations indicate the need to dampen these impacts to prevent damage to the actuators. If the point of impact is lined with an impact attenuation polymer, such as Sorbothane, we can reduce the impact forces by upwards of 80% (See Appendix A.1)


Date: Apr 10 /2020
Linear Actuator Impact Loads

total weight = wheelchair+battery + user/cargo + device
= 290 + 220 + 10 lbs
= 520 lbs = 235 kg

momentum of wheelchair
$\vec{p} = m\vec{v} = 681.5 \ kg\frac{m}{s}$

impact force on wheelchair (collides and stops)
$\Delta\vec{p} = f_{avg} \Delta t$
$f_{avg} = \frac{\Delta \vec{p}}{\Delta t} = \frac{681.5 \ kg\frac{m}{s}}{0.024s} = 28.4 \ kN$

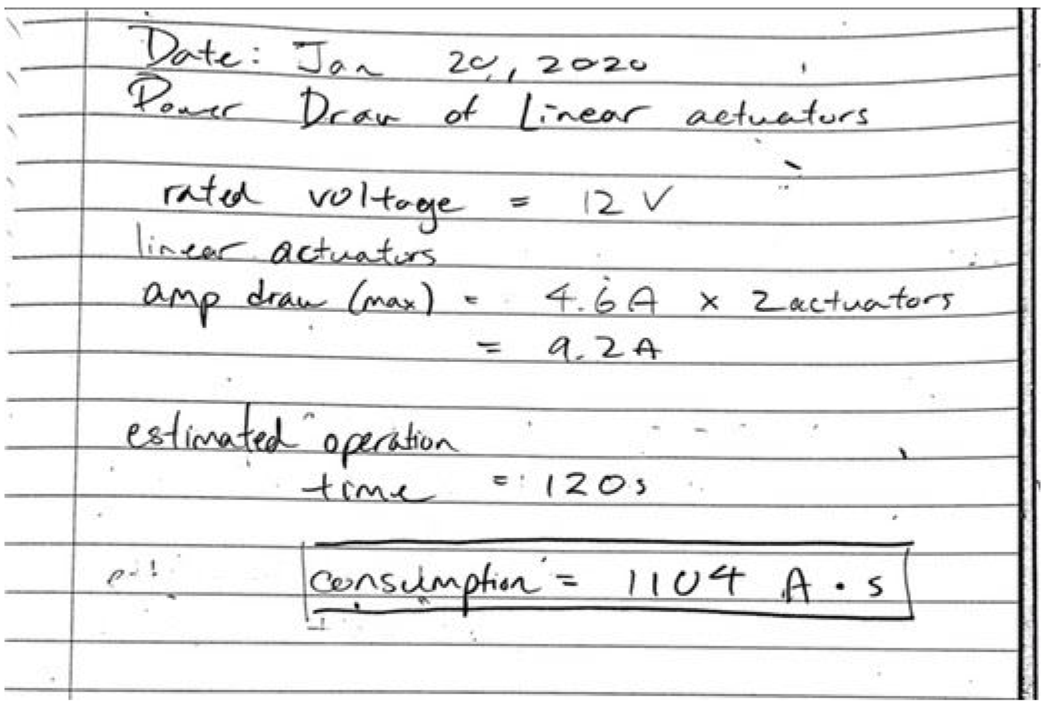
$f_{avg} = 28.4 \ kN = 6384 \ lbf$

F.7 Power Consumption (FMEA)

Purpose: Estimate the current draw per operating cycle of device on a worst case scenario.

Methods: Using the max amp draw of our actuators and the rated voltage, we estimated the operation time and found the amp-second draw of the linear actuators.

Conclusions: The consumption calculated was used to specify a battery for testing. Based on actual testing we obtained the actual current draw during the operation cycle and found the actual consumption per cycle. See Phase 8D: Optimization for the test summary.This value was much lower than what we calculated, due to the fact our design does not load the actuators at max load.


Date: Jan 20, 2020
Power Draw of Linear actuators

rated voltage = 12 V
linear actuators
amp draw (max) = 4.6A × 2 actuators
= 9.2A

estimated operation
time = 120s

consumption = 1104 A · s

Appendix G: Validation Methods

The method outlined in this section is to be done with as many potential end users of the device as possible. A device user would be any powered wheelchair user that is interested in the ability to independently climb curbs of 4 inches in height. It is ideal to have a large sample size of users that span across various demographics such as age, weight, familiarity with operating a powered wheelchair, range of motion, and more. However, be aware that users must be within the device's weight and potential range of motion restrictions unless appropriate modifications can be made. Because the device described in the previous section was designed for a specific type of powered wheelchair, significant effort must be made into adapting the device for the potential user prior to conducting validation testing regardless of these factors. The significant areas of modification include mounting of the device and user range of motion. Once a user has been recruited, it is important to characterize them through traits as mentioned above. An example of this would be to categorize users based on time elapsed conducting simple tasks such as turning corners, aligning themselves orthogonally to a curb, and navigating tight spaces. The following methodology will use this as the foundation for the validation testing.

Materials required for this validation testing are listed:

- Questionnaire
- Timer
- Computer (for recording results and observations)
- Camera (for visual observations)
- Release Form (for the ability to record results)

A set of tasks to be performed before and after the installation of the device will validate how well the device integrates with the user's current lifestyle. The tasks are irrelevant to the curb-climbing process, but indicate if the device presents obstacles to the user's current lifestyle.

Examples of tasks include:

- Ascending/Descending a ramp
- Turning a corner
- Rotating 360 degrees in a specific area (“61” x “51”)
- Going over a speedbump

In addition, a full functionality test will be conducted by the user multiple times. This full functionality test encompasses the whole operation cycle, from orthogonal alignment of the device with the curb, to the user being over the curb. Figure G1 contains an animation of what this is expected to look like.

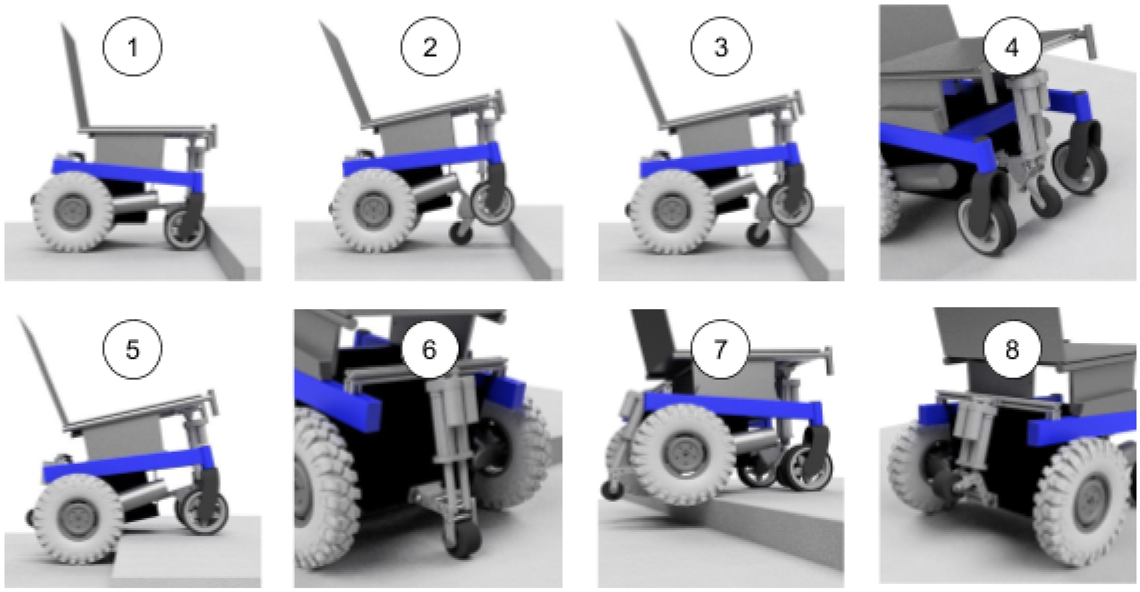


Figure G1. Animation of Full Device Operation

The researchers should keep the user talking throughout the trials to avoid biasing and to obtain time-dependent feedback. The user should respond to a set of statements with a numerical value between one (unacceptable performance) and ten (exceptional performance). In this way researchers are able to gauge the user's initial impression and determine any nuisances which develop as the user adjusts to the device. Beside each numerical rating, notes can be made on any elaborations that the user makes. Furthermore, to remove the influence of biases, different sets of statements should be alternated between users. If users bring up issues that are not suggested by the set of statements but are in another set of statements, this should be noted.

Suggested statements for the test includes:

- I notice a difference in performing this task with the device installed onto my chair.
- I notice a difference in stability during device operation.
- I notice the duration of device operation.
- I notice an effort put in to operate the device.
- I notice the weight of the device.

In addition to these methods evaluation, open-ended questions are also encouraged; ideally, they are asked throughout the test such that time-dependent feedback is collected.

Suggestions for these questions include:

- How do you normally navigate curbs?
- How frequently could you see yourself using this device?
- What are your first impressions about the device?
- What features are missing from this device?
- How many of your friends/family could you see using this device?

Appendix H: Completed Testing

This section details prototype testing that has been completed. Full documentation of the following experiments can be found in Phase 8: Technical Analysis. The main findings and conclusions are summarized below.

H1. Front wheel actuator loading

The purpose of this test was to quantify the axial and radial forces experienced by the actuators under loading. Finite element analysis was used to determine the safety factors for the different components of the system. This test was conducted on a previous version of the device with a very similar geometry, however, the magnitude of the ground reaction forces should be comparable between the two iterations of the design. As such, the results of this test continue to provide good insight on the forces experienced in the updated design.

A force plate was used to measure the ground reaction force (GRF) at the linear actuators under three different loads. The average results of three trials at each load are shown in Table H1.

Table H1. Ground reaction force on the actuators for different loading conditions

Load (lbs)	Avg Max Force (lbs)	Force per actuator (lbs)
110	183	91.5
185	212	106
235	257	128.5

The force profile over the stroke length is shown in Figure H1. The profile is categorized into 6 sections as explained in Table H2.

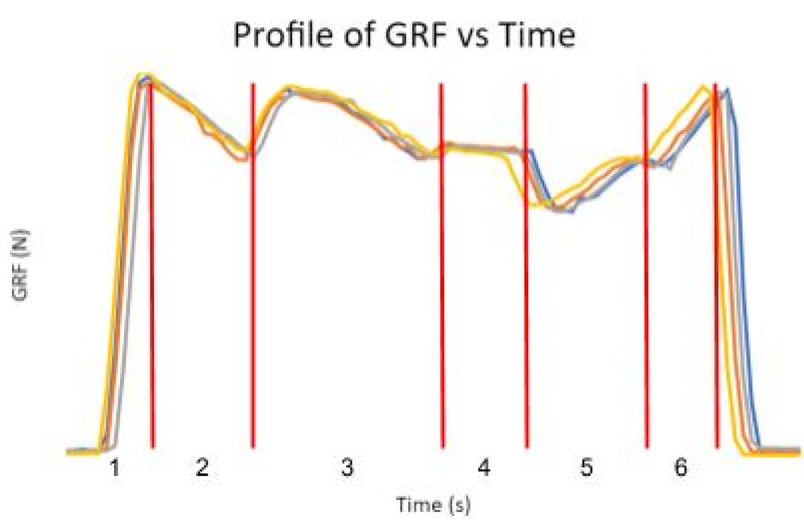


Figure H1. Force profile of ground reaction force over the operating cycle

Table H2. Force profile over the operating cycle

Zone	Comments
1	• Actuator extends and makes contact with the ground • The maximum observed force occurs at the initial contact point
2	• As actuators continues to extend, the center of mass is shifted backwards which decreases the GRF at the actuators
3	• Anti-tipping wheels contact ground causing increased GRF at the actuators as they need to work against the springs • Wheelchair starts pivoting about the anti-tipping wheels after fully bottoming out - GRF shifts away from the actuators
4	• Linear actuators are fully extended and there is a steady state force
5	• Linear actuators start retracting and center of mass shifts forwards, increasing the GRF at the actuators • In this zone, the anti-tipping wheels are supporting the majority of the load in the back, as opposed to the back wheels
6	• Linear actuators continue to retract and the pivot point shifts to the back wheels resulting in a change in force • Linear actuators reach the same peak force experienced in zone 1 and breaks contact with the ground

The data shows that the maximum GRF is experienced at the initial contact between the caster and the force plate. At this point, the actuator is also at its maximum angle from the normal of the ground, which results in the largest radial load experienced during the operating cycle. The maximum axial and radial forces applied on each actuator is summarized in Table H3. Since linear actuators are not designed to support radial loads, a truss element was added to eliminate radial loads on the actuators.

Table H3. Maximum forces and safety factor per actuator

	Maximum Force (lbs)	Actuator Safety Factor
Radial Force	33.3	n/a*
Axial Force	128.5	2.1

*actuators are not rated to support radial loads

H2. Current draw of linear actuators under load

The purpose of this test is to determine the power consumption and predict the number of operating cycles of the device.This test was conducted on the previous version of the device. However, it was observed during testing that the current draw was fairly consistent even when different loads were applied. As such, results from this test should be applicable to the new design.

The power consumed per actuator stroke was found to be 553 W at 15.6 Ah. The existing Lithium-ion battery in use can provide 10 Ah. Each operation takes 100s and the actuators draw an average of 1.77 A. This means that when the battery is fully charged, the device can be operated 203 times before a recharge is required.

H3.Operational Test

The full operating cycle of the front wheel lift was tested to validate several requirements. It was determined that the device could climb curbs up to a height of 4.5” (137 mm). In addition, the front wheel lift subsystem is confined under the seat of the Torque SP 3200 powered wheelchair and does not impede on the user's mobility. Lastly, operation of the device is easily activated through the use of an accessible button and the device does not damage the functional or visual integrity of the surroundings during use.

Appendix I: Regulatory Requirements

There are currently no regulatory bodies that govern the development, deployment, and implementation of a curb ascending and descending attachment for powered wheelchairs. However, there are multiple regulatory bodies that govern the accessibility of public infrastructures that powered wheelchairs must conform to; these accessibility standards must continue to be met with the addition of our device. In addition, there are existing technical standards regarding powered wheelchairs that would be of benefit to Team Curby for evaluation of the device performance.

Methods

- Regulatory bodies and standards related to wheelchairs were researched online - findings are summarized in the Results section.
- The majority of the standards published by standards organizations require fees for access to the standards. As such, standards that were deemed useful are listed below with a brief description. Should Team Curby require access to specific standards, communications can be made through MECH/UBC to acquire said standards.

Results

Regulatory Bodies

1. Canadian National Building Code (CNBC) - Building Accessibility Standards [1]
    - Wheelchair accessible ramp requires a minimum 1in of rise for every 12in of ramp
    - Turns must either be 90° or 180°
        - Turns of 180° require a wheelchair landing double that of a 90° turn
    - Ramp width must be at least 36in
        - Ramps accommodating two-way traffic should be approximately 120in wide
    - Landings (typically 60in by 60in of level surface) are required at the top and bottom of a ramp
    - Handrails are required if a ramp rises over 6in or a project extends over 72in horizontally
        - It is recommended that barrier of at least 2in tall be placed along the edges of the ramp

2. Insurance Corporation of British Columbia (ICBC) - Low-powered vehicles [2]
    - Motorized wheelchairs do not require registration, vehicle license, insurance or driver's license
        - Treated similarly to pedestrians and may be operated anywhere that pedestrians are permitted to walk
    - Permitted on sidewalks, walkways, crosswalks, and paths

3. Curb Heights
    - The curb height shall be 130 mm for local streets and 150 mm for major arterial streets. The curb height may vary between 100 and 170 mm to provide adequate drainage or to match existing grades. [3]

Wheelchair Standards

1. WC10: RF-WPS - Wheelchair containment and occupant retention systems for use in large accessible transit vehicles: systems for rearward-facing passengers [4]
    - Ensure adequate clearance space for wheelchair access
    - Provide head and back support for the wheelchair occupant

2. WC18: WTORS - Wheelchair Tiedown and Occupant Restraint Systems (WTORS) for Use in Motor Vehicles [5]
    - For users who cannot safely transfer from their wheelchairs to a seat in a vehicle and must use their wheelchair as the vehicle seat, in which case the OEM belt-restraint system cannot be used
    - Ensure proper frontal-crash protection for forward-facing wheelchair occupants comparable to that provided by OEM belt-restraint systems that comply with federal motor vehicle safety standards (FMVSS) and reduce serious and fatal injuries to wheelchair occupants in frontal vehicle crashes
    - Considers nominally worst-case 48kph frontal sled-impact test with 85kg surrogate chair, 78kg nominal crash-test dummy
    - Requires a pelvic belt and one or more shoulder belts and requires the wheelchair be constrained to the vehicle

3. WC19 - Wheelchairs Used as Seats in Motor Vehicles [6]
    - Establish design and performance requirements, and associated test methods for wheelchairs related to their use as seats in motor vehicles
    - Required key features:
        - Have at least four permanently labeled securement points that can withstand the forces of 30mph, 20g impact
        - Have specific securement point geometry that can receive a securement end fitting hook of a specified maximum dimension
        - Be equipped with anchor points for a wheelchair-anchored pelvic belt and recommendations for purchasing a belt if not provided, such that the wheelchair and pelvic belt will withstand a 30mph, 20g impact
        - Provide a standard interface on the pelvic belt to connect to a vehicle-anchored shoulder belt

4. WC19 - Wheelchairs Used as Seats in Motor Vehicles [7]
    - Establish design and performance requirements, and associated test methods for wheelchairs related to their use as seats in motor vehicles
    - Required key features:
        - Have at least four permanently labeled securement points that can withstand the forces of a 30mph, 20g impact
        - Have specific securement point geometry that can receive a securement end fitting hook of a specified maximum dimension

    - Be equipped with anchor points for a wheelchair-anchored pelvic belt and recommendations for purchasing a belt if not provided, such that the wheelchair and pelvic belt will withstand a 30mph, 20g impact
    - Provide a standard interface on the pelvic belt to connect to a vehicle-anchored shoulder belt

Technical Standards

1. ISO 7176-4:2008 [7]
    - Specifies methods for determining theoretical distance range of electrically powered wheelchairs

2. ISO 7176-5:2008 [8]
    - Specifies methods for the determination of wheelchair dimensions and mass
    - Specifies methods for the determination of outside dimensions when the wheelchair is occupied by a reference occupant and the required manoeuvering space needed for wheelchair manoeuvers commonly carried out in daily life
        - Pivot width, reversing width, turning diameter

3. ISO 7176-9:2009 [9]
    - Specifies requirements and test methods to determine the effects of rain, dust, condensation and the effects of changes of temperature on the basic functioning of electrically powered wheelchairs

4. ISO 7176-10:2008 [10]
    - Specifies test methods for determining ability to climb and descend obstacles

5. ANSI/RESNA WC-1:2009 [11]
    - Specifies test methods for determining the static tipping stability of wheelchairs

6. ANSI/RESNA WC-2:2009 [12]
    - Specifies test methods for determining the dynamic tipping stability of electrically powered wheelchairs

Conclusions

Many of the regulatory bodies specify standards for wheelchair accessible features such as ramps. Our device should not impede on these dimensions and should allow the powered wheelchair user to maintain the same level of mobility prior to attachment of the device. Furthermore, during transport, wheelchairs are required to be fixed relative to the vehicle. Wheelchairs have designated mounting locations which should not be blocked by the device. In addition many standards listed above provide specific test methods to determine and calculate important values, many of which may be pertinent to our device. Contact through UBC MECH to acquire these standards will be necessary should Team Curby decide to look further into these topics.

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[2] ICBC. “Vehicle Registration: Specialty-Vehicles - Low powered vehicles”. 2019. [Online]. Available: https://www.icbc.com/vehicle-registration/specialty-vehicles/Low-powered-vehicles/Documents/low-powered.pdf. [Accessed Oct. 26, 2019]

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[10] International Organization for Standardization. “ISO 7176-10:2008 Wheelchairs — Part 10: Determination of obstacle-climbing ability of electrically powered wheelchairs”. [2019]. Available: https://www.iso.org/standard/45984.html. [Accessed Oct 26,2019].

[11] American National Standard Institute. “RESNA American National Standard For Wheelchairs - Volume 1: Requirements And Test Methods For Wheelchairs (Including Scooters)”. [2019]. Available: https://webstore.ansi.org/standards/resna/ansiresnawc2009. [Accessed Oct 26,2019].

[12] American National Standard Institute. “RESNA American National Standard For Wheelchairs - Volume 2: Additional Requirements For Wheelchairs (Including Scooters) With Electrical Systems”. [2019]. Available: https://webstore.ansi.org/standards/resna/ansiresnawc2009-1510887. [Accessed Oct 26,2019].

Appendix J: Linear Actuator Forces and Power Test

This section outlines the materials and procedure for comprehensive testing to determine the axial forces, radial moments, and power consumption of the device under various loading conditions while the device is stationary.

Purpose

- Quantify the magnitude of forces experienced by the linear actuator when the device is in use
  - Forces can be used for FEA to optimize/test geometry of mount design
- Calculate the axial and radial forces experienced by the linear actuators
- Measure the current draw of the linear actuators at maximum load

Materials

- Biomechanics kit
  - Force plate
  - Angle finder
  - LabQuest 2
  - 4x 2”x6” wood blocks
- Multimeter

Procedure

<u>Part 1</u>

1. Connect force plate to LabQuest2 Display.
2. Set the following settings through in LabQuest2.
   a. Rate: 1 sample/s.
   b. Duration: 120s.
   c. Interval will automatically be set to 1s/sample.
3. Place the wood blocks under the back and front wheels to raise the wheelchair to the same level as the force plate. Make sure the wood blocks are underneath the anti-tipping wheels as well. Ensure that the motors of the wheelchair are set to drive so that it doesn’t roll off the blocks. Power off the wheelchair.
4. Place the force plate underneath the linear actuator.
5. Place the angle finder on the wheelchair parallel to the seat, oriented such that the angle (pitch) can be read.
6. Zero the force plate on LabQuest2.
7. Start data collection on LabQuest2 and activate the button to start extending the linear actuators.
8. Wait for force readings to reach steady state. Record the angle displayed on the angle finder.
9. Activate button to start retracting the linear actuators. You can manually stop the data recording on LabQuest2 or wait until the 120 second duration is completed.
10. Repeat 2 times to get at least 3 trials in total.

Part 2

1. Attach the multimeter in series with the power supply as shown.

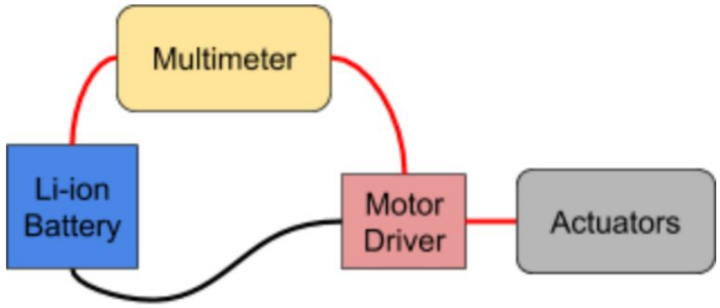

Figure J1. Multimeter connection diagram.

2. Perform tests outlined in Part 1.

Appendix K: Relevant Standards

Table K1 describes the standards relevant to the prototype design.

Table K1: Relevant standards

Relevant Standards		
Governing Body	**Standard**	**Description**
CAN/CSA	Z323.4.3-M89 (R1998)	- Adopted ISO 7176-1:1986 - Discusses determination of static stability for wheelchairs
CAN/CSA	Z323.4.11-94	- Adopted ISO 7176-2:1990 - Discusses determination of dynamic stability of electric wheelchairs
CAN/CSA	Z323.4.12-94	- Adopted ISO 7176-9:1988 - Discusses climatic tests for electric wheelchairs - Specifies methods for testing the effects of rain on the functioning of electric wheelchairs used outdoors and the effects of temperature changes on the functioning of wheelchairs taken outdoors after a period indoors - Does not cover the effects of splashes from puddles, nor the resistance to corrosion
CAN/CSA	Z323.4.7-M89 (R1998)	- Adopted ISO 7176-10:1988 - Specifies a method for determining obstacle-climbing ability of electric wheelchairs (matching a wheelchair's capabilities to the environmental conditions under which the wheelchair functions)
CAN/CSA	C22.2 NO. 107.2-01 (R2016)	- Discusses standards applicable to battery chargers for special applications such as wheelchairs and other medical applications
CAN/CSA	Z323.4.2-M86 (R1998)	- specifies methods for determining (a) the overall dimensions, both ready for occupation and folded; (b) the mass; and (c) the turning space of both manual and electric wheelchairs.
ISO	ISO 7176-5	- Determines overall dimensions, mass and manoeuvring space of wheelchairs
ISO	ISO 7176-8	- Specifies requirements and test methods for static, impact, and fatigue strengths for wheelchairs
ISO	ISO	- Specifies requirements and test methods for

	7176-21:2009	electromagnetic compatibility of electrically powered wheelchairs and scooters, and battery chargers
ISO	ISO/AWI 7176-32	- Specifies standard practice for wheelchair castor durability testing
ISO	ISO 7176-28:2012	- Specified requirements and test methods for stair-climbing devices
ISO	IEC 60086-4:2019	- Specifies safety requirements of lithium batteries
ISO	ISO 18243:2017	- Test specifications and safety requirements for lithium-ion battery systems

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