UC San Diego
JACOBS SCHOOL OF ENGINEERING

Design and Analysis of Rear-Support Assist Device for Extended Daily Use by Paraplegic Canines ("The Bodie")

Department of Mechanical and Aerospace Engineering
MAE 156B: Fundamental Principles of Mechanical Design II
University of California, San Diego

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Abstract

The Bodie was a project sponsored by Dr. Dave Yu and his pet bulldog Bodie. This project addressed a common occurrence of hind-leg paraplegia in dogs. The disability makes daily life difficult for both for the dogs and their caring owners. Current industry wheelchairs are stiff and disallow sitting. Sponsor Dr. Dave Yu reimagined the dog wheelchair as a device to restore mobility and the same independent functions, such as sitting and laying down, that dogs could perform prior to their disability. The objective for this project was to create a rear-support assist device for Bodie's extended use that returned his full range of physical functions, including running, standing, sitting and lying down. By introducing linear actuators, this design integrated electromechanical actuation to assist Bodie's sit-to-stand transition without requiring the strenuous physical effort from previous models. Performance tests were conducted throughout in order to use Bodie's eagerness, mobility, and satisfaction as critical user feedback for iterating designs and optimizing comfort and usability.

List of Figures

List of Tables

Chapter 1: Project Description

Background

Dog wheelchairs are used to assist dogs who suffer forms of paraplegia. Common causes of dog paraplegia are hip dysplasia, intervertebral disc disease, and spinal injuries which can all cause irreparable paralysis and/or immobility of the dog’s hind legs. A solution for caring pet owners who seek to improve the quality of life of their dogs are rear-support dog wheelchairs, which offer back-end support and mobility to enable happy, active lives.

Dr. Dave Yu is the pet owner of paraplegic English bulldog Bodie, who suffered spinal injuries several years ago. Bodie has lost complete control of his lower body, but still has sensation and will react to pinches or tickles on his hind legs. Despite his disability, Bodie loves being active. He attends physical therapy to maintain upper body strength, and enjoys swimming and running on his two front legs when his rear is supported by his owner.

Figure 1. Industry wheelchairs all feature rigid frames and attachable harnesses, but no system for sitting.

As seen in Figure 1, rear-support dog wheelchairs on the market typically use a rigid frame and attached comfort components, such as a saddle or belt strap, to provide support of the rear. The problem is all current models design for support and mobility alone. This means that dogs can move in the wheelchairs, but they cannot sit or lay down without the help of a caretaker.

Dr. Yu reimagines a dog wheelchair for extended use: one that enables activity and exercise, as well as downtime and pet relief. He proposes a wheelchair with the support frames seen in industry, but which also incorporates an assistance system to lower and lift the rear to allow walking, sitting/laying down, and standing up. This would enable full range of daily movement for paraplegic dogs, and also requires less assistance from owners.

Figure 2. Bodie in previous 156B wheelchair that includes folding frame to allow for sitting.

Dr. Yu has two wheelchairs for assisting Bodie: an industry wheelchair (Eddie's Wheels) and a previous 156B model wheelchair. The industry wheelchair is robust, fits well, but does not enable Bodie to sit without being removed from the cart. The previous 156B wheelchair folds upon itself to allow Bodie to sit and lay down, but observation of Bodie's behavior shows discomfort from the frame's weight distribution on his shoulder. The goal is to improve upon the previous team's wheelchair to design and develop a comfortable, supportive, sitting wheelchair solution for Bodie's daily use.

Review of Existing Design Solutions

There are several rear-support dog wheelchairs on the market. Leading pet wheelchair companies include Eddie's Wheels, Walkin' Wheels, and K9 Carts. Though there are variations in design, they are all designed custom-fit, and use a rigid frame and attached comfort components, such as a saddle or belt strap, to provide support. Some companies, like Walkin' Wheels and K9 Carts, have adjustable frames in case the dog grows or an injury develops.

Walkin' Wheels

Walkin' Wheels carts have two wheels attached to a telescoping push-button frame. This makes the carts easy for owners to adjust height and length for comfort or repositioning in case the dog or its disability changes. For customizing they only require two measurements: weight and the fold-of-flank (rear leg height). Dogs with insufficient rear strength but leg mobility require wheelchair support and can move their feet off the ground. But dogs with immobility require stirrups to lift their legs off the grown. The risk in this design in the cart rests its weight on the dog's shoulder harness and imprecise measurements can cause uncomfortable pressure points. Furthermore, the design does not allow sitting, and upon consultation it was revealed the design intentionally avoid collapsible carts that risk further injuring the users (dogs).

Figure 3. Walkin’ Wheelchairs rear-support cart with (left) and without (right) stirrups.

K9 Carts

K9 Carts wheelchairs feature wheelchairs with two or four wheels depending on the dog’s hind leg mobility. They recommend the 2-wheel “rear-support” wheelchairs for dogs that can swing their hind legs, or for small dogs that have paralyzed hind legs and need their legs lifted. They recommend the 4-wheel “full-support” wheelchairs for medium or large dogs that have paralyzed hind legs and need their legs lifted. For dogs paralyzed in the rear like Bodie, the number of wheels depends on size because of the weight distribution of the wheelchair’s frame. 2-wheel frames distribute the weight onto the dog’s shoulder harness, while 4-wheel frames distribute the weight across the back and front struts (wheel legs). Smaller paralyzed dogs can use 2-wheels because the frame is light enough and low enough to the ground that its weight is comfortably supported by the shoulder harness. However the larger paralyzed dogs must use 4-wheels because the larger, taller frame will exert a greater moment that can cause excessive and uncomfortable static load to the dog’s shoulder harness.

Figure 4. K9 Carts full-support cart (2 wheels) for small dogs that require hind leg elevation.

Figure 5. K9 Carts full-support cart (4 wheels) for medium dogs that require hind leg elevation.

Eddie's Wheels

Bodie's has a wheelchair from Eddie's Wheels, which is sturdy and snugly fit, but does not enable sitting or laying down. This cart features a thick, foam over-the-shoulder harness to distribute the weight of the hefty cart and avoid pressure points. This cart works well for waste disposal, as the area near his rear is unobstructed. Another advantage is loading for this cart is easy for Dr. Yu because the saddle is fastened to the frame and the wheelchair is standalone.

Figure 6. Bodie in his Eddie's Wheels rear-support wheelchair.

Previous 156B Model

The previous MAE 156B team designed a wheelchair with a folding frame that allows sitting and lying down. The weight distribution of the wheelchair is non-ideal as it concentrates excessive static load on Bodie's shoulders and causes uncomfortable pressure. This model's frame uses hollow aluminum tubes, which are strong and lightweight but extremely difficult to adjust for part positioning, as new holes had to be drilled every time a component needed to move. The sit-to-stand system uses springs to aid the transition from sitting to standing, but in testing still demands a visibly strenuous effort from Bodie to stand. Loading is difficult because the saddle and foldable cart must be held up while also maneuvering Bodie's body into it. Another problem was there was not enough clearance in his rear so the frame would obstruct Bodie's waste.

Figure 7. Previous 156B team's folding, rear-support wheelchair.

Statement of Requirements and Deliverables

Statement of Requirements

As defined by the sponsor, the wheelchair design must:

- **Be comfortable for every day extended use.** Factors to consider are the weight distribution of the frame and how load may be transferred to Bodie's body and the points of physical contact between the frame and Bodie.
- **Enable or assist transition between sitting and standing position.**
- **Allow easy loading/unloading by the owner.** Factors to consider are the amount of comfort components attached to Bodie as well as the frame's integrity. Poor design would make this task more difficult for the caretaker.
- **Allow for waste disposal.** Enough clearance must be accounted for in the rear design of the wheelchair so as to not obstruct Bodie from using the bathroom.

Statement of Deliverables

- Rear-support wheelchair.
    - Cart frame to support his weight and endure motion.
    - Comfort components with optimized positioning along frame.
    - Mechanism for enabling sit-to-stand transition.

- User manuals for intended use with final wheelchair product.
  - Instruction for owner on how to operate the switch-controlled motorized sit-to-stand mechanism.
  - Training advice for owner on how to train dog to independently operate the switch mechanism.
  - Safety manual detailing any potential risks or safety concerns of the wheelchair product.
- List of components, tools, and steps for replication or construction.
- Documentation of test procedures, results, and analysis for components and systems.
- Full report documenting the design process. This document includes relevant research, development, and analysis performed on the performance and overall model of the final product.

Chapter 2: Description of Final Design Solution

Figure 8. Early prototype of final wheelchair design featuring 4-wheel mobility design with linear actuated sit-stand system.

The final design incorporates two systems to address the primary objectives of mobility and a sit-stand feature. The **mobility system** includes the main outer frame and the four wheel struts mounted to it. Its primary function is mobility, and was designed with comfort and stability in mind for the user. The **sit-stand system** includes the inner frame that hinges, the cam lock, the comfort components (frontal harness and rear saddle), and the linear actuators and electrical components (power supply, wires, switch). Its primary function is to provide motorized assist that enables lifting and lowering of the rear. It was designed with safety, interface design, and electrical maintenance in mind for the owner and pet in mind.

Mobility System

- **Outer frame.** The main outer frame is fabricated from perforated aluminum tubing. Aluminum was selected for its lightweight strength. The perforation allows user to adjust positioning of wheels and comfort components. (see Figure 9 below).
- **Fixed back wheels.** The wheels are fixed directionally to allow for stable, controlled steering.
- **Swivel front wheels.** The wheels are swivel to allow for full range of motion and immediate response to direction change. Angled struts are used in the back to increase stability across uneven surfaces.

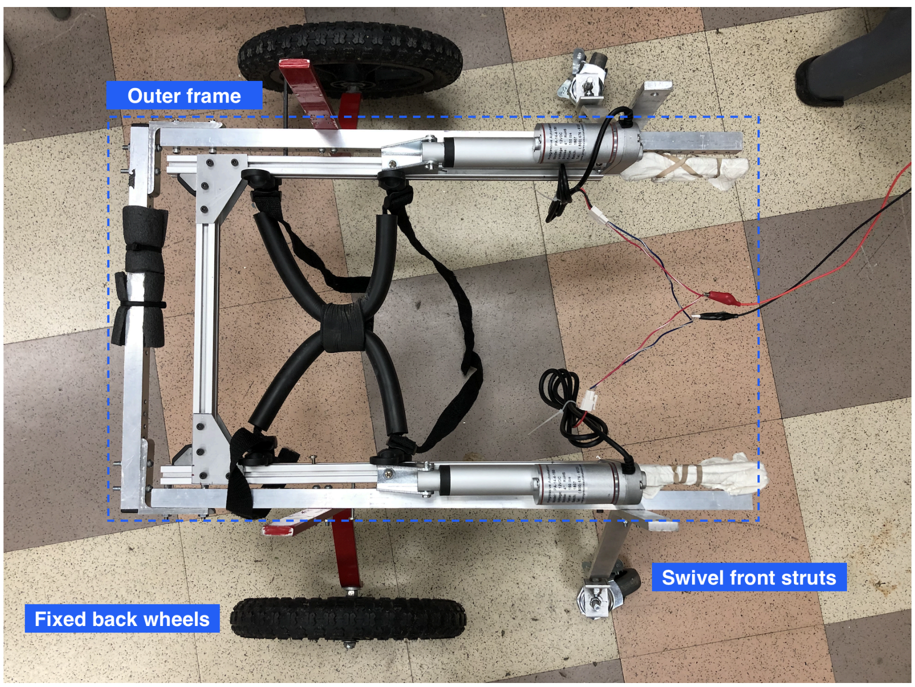


Figure 9. The mobility system.

Sit-Stand System (Hardware)

- **Comfort components.** This consists of the components that are in contact with Bodie's body: the front harness and back saddle. (see Figure 10 below.)
- **Inner frame.** The isolated inner frame is fabricated from perforated tubing and mounted inside the outer frame. (see Figure 11 below).
- **Brake lock.** The brake lock is mounted to the inner frame's pivot axis, and secures the retractable front harness when walking, and releases it when sitting. (see Figure 16 in Section 3 for more details).

Sit-Stand System (Electrical Components)

- **Linear actuators.** These provide the controlled linear force that lift and lower the inner frame to allow standing and sitting. An actuator is mounted on either side of the frame, each one supplying 667 N (150 lbs) of force with a 10.16 cm (4 inch) stroke.
- **Battery.** The 12VDC/1A battery supplies power to the linear actuators and DPDT switch.
- **Relay switch.** A double-pole, double-throw switch is used to control the linear actuators.

Figure 10. Comfort components that are in contact with Bodie's body.

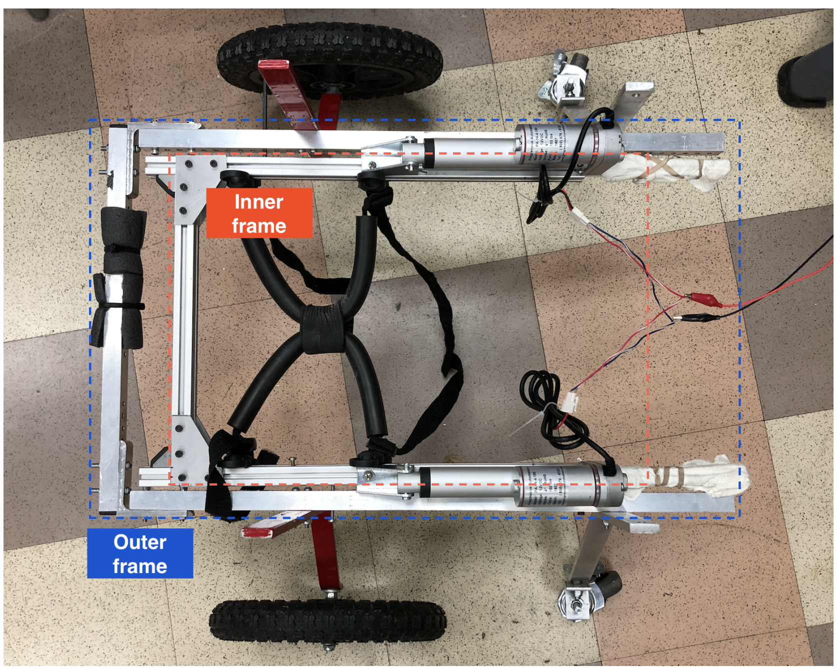


Figure 11. The inner frame mounts inside the outer frame.

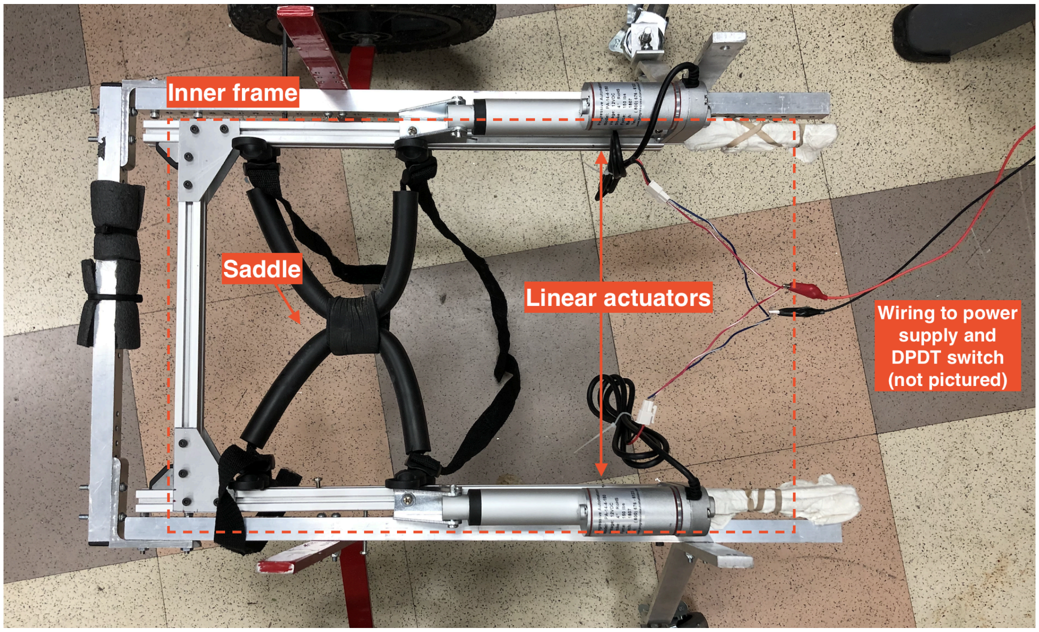


Figure __. The sit-stand system (brake lock and switch not pictured).

Chapter 3: Design of Key Components

Front Swivel Wheels

Overview

Two front wheels were incorporated into the design of the wheelchair in order to stabilize the cart and remove the issue of uncomfortable weight distribution. The front wheels feature swivel caster wheels with 360° mobility that are mounted on outward angled struts, which provide greater stability particularly over uneven surfaces.

Functional Requirements

- Support the weight of the frame
- Cannot interfere with quality and range of mobility afforded by 2-wheel design

Choice Justification

The previous 156B wheelchair is a 2-wheel design that collapses to enable sitting. With this design, the wheelchair does not stand on its own which makes it difficult to lift and load Bodie, and it also rests on Bodie's body which then requires precise harness positioning to prevent uncomfortable pressure points. As seen in Figure 12, the 2-wheel design's forward tilt adds load to Bodie's shoulders. Even when the frame sits parallel to the ground, half of the frame at minimum is loaded onto Bodie's front. As seen in Figure 13, 4-wheel design uses the two front struts to take the load of the frame off of Bodie's body to alleviate uncomfortable pressure points. It also stands alone which aids the owner in loading and unloading the dog. More detailed research of 4-wheel designs can be found in the Appendix.

Figure 12. Previous 156B team 2-wheel design applies load to Bodie’s harness.

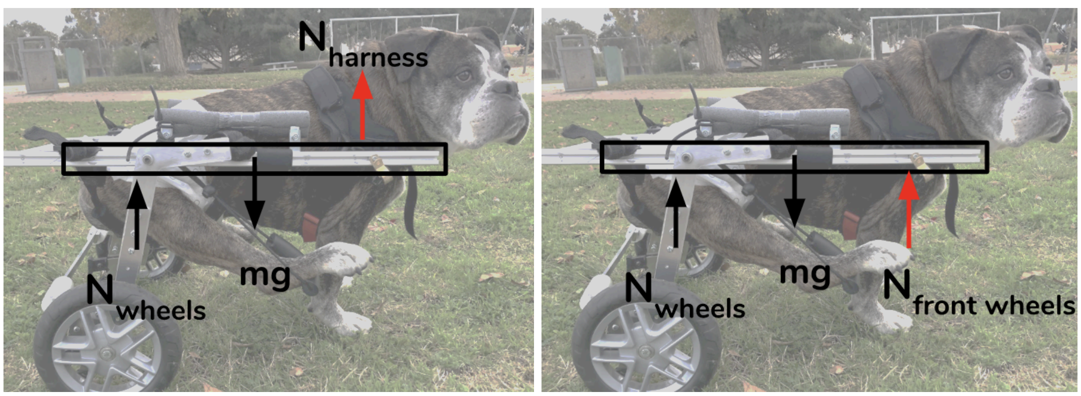


Figure 13. The frame weight distribution without (left) and with (right) two front wheels.

Swivel caster wheels with 360° mobility offer immediate response to direction changes, and are good for following the steering motion of the back wheels. They are mounted to outward angled struts rather than vertical ones in order to provide greater stability, particularly when running over uneven surfaces.

	Pros	Cons
2-Wheel Cart	• Lighter & compact	• **Weight distribution risk** • Requires precise fitting

4-Wheel Cart	• **Reduces load on Bodie/harness** • Standalone • Stable • Ease of loading	• Bulkier • Rigid

Table 1. Comparison of 2-wheel and 4-wheel design.

Linear-Actuated Sit-Stand System

Overview

The linear-actuated sit-stand system is used to assist Bodie in transitioning from standing position to sitting and laying down position. Two linear actuators each provide 667 N force along a single-axis distance (stroke) of 10 cm. They are mounted to a hinging inner frame (see next section *Isolated Inner Frame with Brake Lock)*. The mount design allows the frame to lower by a vertical displacement greater than the 10cm stroke of the actuators. Bodie's rear weighs approximately 11 kg which was taken to be the minimum force requirement.

Functional Requirements

- Support the weight of rear
- Enable controlled vertical motion of rear

Choice Justification

The previous wheelchair model pursued a mechanical sit-stand system that folded into sitting position via brake stops and springs. The issue with this design is that it did not offer easy transition between positions. Bodie exerts visible physical effort and strain to get up. To sit, Bodie must walk backwards to engage the wheelchair's sitting system. He then "falls" a great height before landing into a resting sit position. The effort required to operate this uncontrolled motion is excessive and exhausting for a feature that was intended for daily use.

An improvement was to have a sit-stand system that provides assistance. A challenge with mechanical assist systems is Bodie's heavy rear requires a large mechanical advantage to resume standing position, especially without external forces. Even capitalizing on Bodie's frontal strength is straining, as a detailed force analysis of a pulley-system shows in the Appendix. Motors supply external force that can be integrated into an assist system to provide controlled vertical motion for sit-stand.

	Motorized	**Mechanical**

Pros	● Electrical trigger (easier interface) ● Externally supplied force ● Controlled motion	● Easier to machine ● More mechanism options
Cons	● May require many electronic components (eg. power supply, motor, limit switch, sensor, actuator, etc.) ● Cost	● Physical trigger (requires Bodie to back up to sit) ● Requires physical force supplied by the dog ● Process is uncontrolled and can be ungraceful

Table 2. A comparison of motorized vs mechanical mechanisms for sit-stand system.

The first decision was what type of motor should be used for the this system. Electric motors had high costs for the target force range beyond the budget scope. Linear actuators are a less expensive but equally robust and reliable source of constant applied force.

Another advantage is linear actuators do not require a microcontroller for motion control. Internal limit switches program circuits to open after the actuator stroke has fully extended or retracted. This key feature eliminates the need to program, wire, and mount an additional electrical component like a mini Arduino onto the wheelchair.

The next step was defining the linear actuator specifications, including the stroke length and force supply, and the battery for supplying power. A more thorough documentation of research can be found in the Appendix.

Linear Actuators	
● 12V mini rod actuator: ○ extendable rod ○ specs: 5A, 156 or 222 N, 33 cm + stroke ○ price: $109 	● Mini track actuator: ○ sliding notch ○ specs: 5A, 222 N, 12 cm + stroke ○ price: $116 

Table 3. A comparison of the two linear actuator options considered.

Power Supplies	
● 12V, 5A power supply: ○ 1.81 kg in weight, 5A ○ dimensions: 8.89 cm x 6.86 cmx 10.16 cm ○ price: $40 	● 12V, 1A power supply: ○ 0.23 kg in weight, 1A ○ dimensions 13.46 cm x 2.03 cm x 3.05 cm ○ price: $21.50 

Table 4. A comparison of the two power supply options considered.

Linear rod actuators of 10.16 cm stroke supplying 667 N of force were selected. In deciding linear actuator specifications for the wheelchair, the greatest restriction was size. As seen in Figure 14 below, smaller actuators were used and mounted angled near the pivot point in order to create a geometric advantage to lowering the back end of the frame with a smaller stroke. Though this increases the necessary amount of force supplied, it enables a lighter, more compact actuator without affecting the price or required voltage supply.

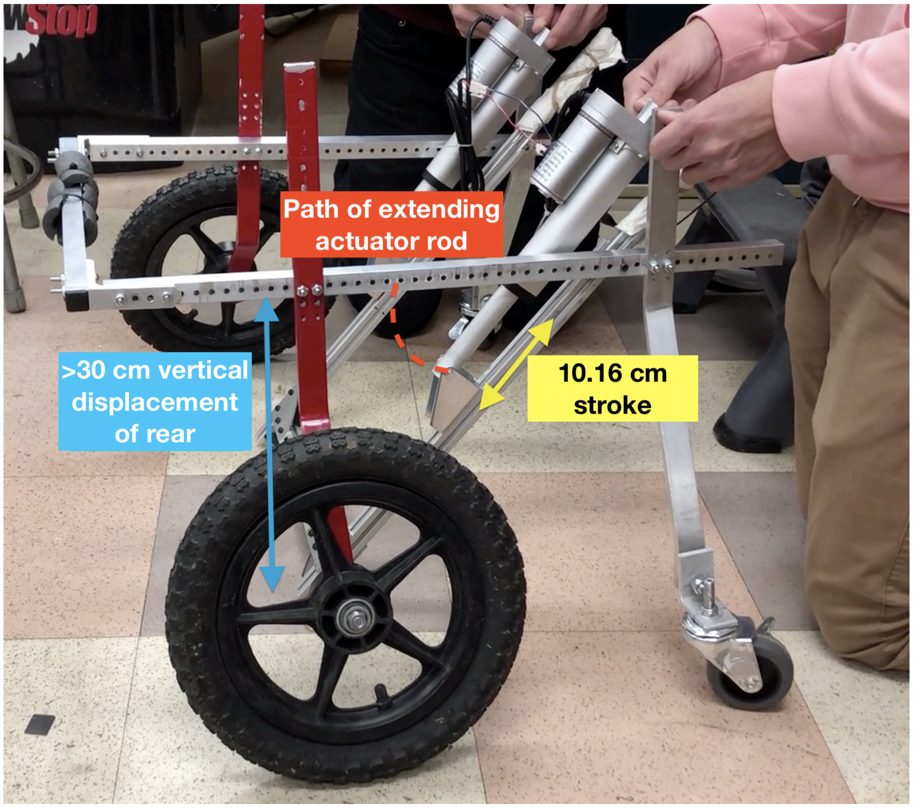


Figure 14. Mount design that achieves larger rear displacement using actuators with smaller stroke lengths.

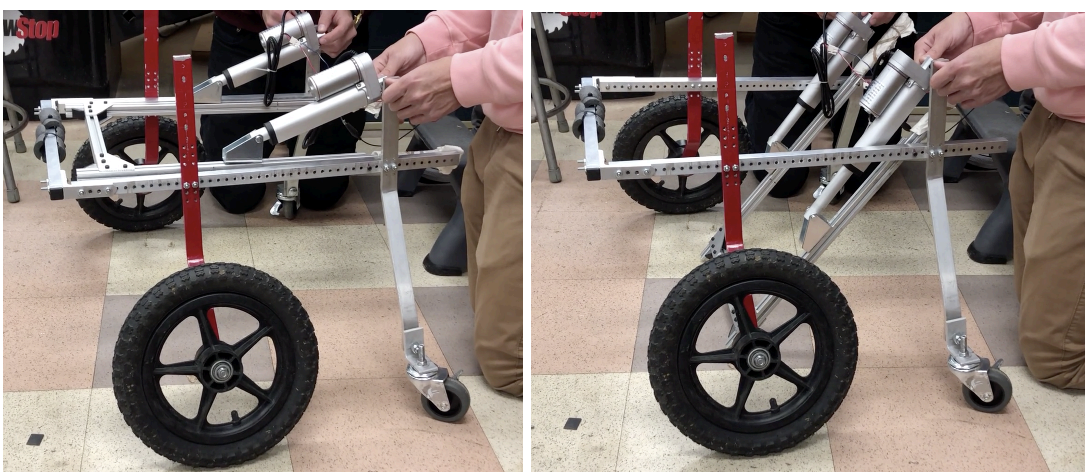


Figure 15. Linear actuated system in up (left) and down (right) positions.

Switch Control System

Overview

The switch control circuit is the *electrical component of the sit-stand system.* It consists of a power supply, a linear actuator, and a DPDT switch. The non-momentary rocker switch has an on-off-on switch operation that allows a simple interface: pushing the button either extends or retracts the actuator fully, to transition the wheelchair between sitting and standing positions. The circuit will be wired as in the following diagram:

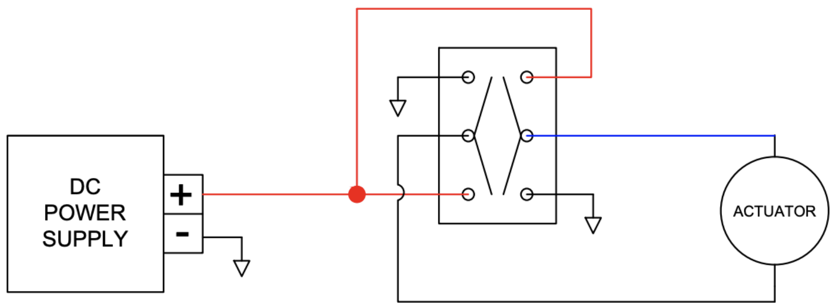


Figure 16. Basic rocker switch control of linear actuator.

Functional Requirements

- Activate sit-stand system
- Provide a simple interface for Bodie to learn and use

Choice Justification

The previous wheelchair model requires Bodie to walk backwards to engage the wheelchair's folding into sitting position. A problem with this model documented in the previous project report is that walking backwards is a non-intuitive motion for dogs, so training this command was challenging.

A switch still requires training but has a simple interface that requires less strenuous effort from Bodie. The switch also activates the linear-actuated assist system that provides vertical motion of rear in a controlled manner. A tradeoff between an electronic switch and mechanical cue-trigger is that it is not integrated into the frame, and requires mounting in an easily accessible location.

Adding to the usability is the use of a DPDT switch, which was recommended via consultation with industry engineer Frank at Progressive Automations (1-800-676-6123). When the DPDT switch is activated, it closes the circuit. After the actuator fully extends, or retracts, the internal limit switch automatically opens the circuit until it is activated again by the switch. This prevents passive draining of power to extend battery life and also reduces the risk of overheating.

Isolated Inner Frame with Brake Lock

Overview

The inner frame is the *hardware of the sit-stand system*. It supports the front harness and back saddle, and moves independently of the larger one. This frame hinges at a pivot point near the front of the wheelchair to lower in the back. The brake lock features the lock which controls the retractable straps attached to Bodie's harness. The lock is located at the pivot axis and pivots with the frame to unlock Bodie's frontal harness when his rear is lowered. The inner frame and brake lock are complementary features integrated together to allow for independent and total up/down motion in the front and back.

Functional Requirements

- Support the weight of Bodie and saddle
- Allow independent vertical motion in front and in back
- Secure harness in place when user is in wheelchair standing position
- Release harness when user is in wheelchair sitting position

Choice Justification

Earlier motorized design solutions featured sit-stand systems integrated into the main wheelchair frame. A viable model features a fixed flat-angle frame that is lifted/lowered up/down the back struts with actuators, while the front struts hinge forward to accommodate the shifting height. Results from the hardware testing of this model are detailed below in Chapter 4, but a key finding is that moving the entire frame required moving the front and back in unison, restricting Bodie to either standing (front up, back up) or laying down (front down, back down). The flat frame test revealed the front and back needed to be able to move independently of each other. Figure 17 below shows the relative harness and saddle positions required for Bodie to stand, sit, and lie down.

Figure 17. Positional requirements of harness and saddle

The front harness had to have a single axis degree of freedom: it must move up and down but cannot move forward or backward. One solution considered featured retractable cables (similar to those for clippable employee ID cards) but a concern was its durability of holding the harness in a single-axis, and securing it in place when running. Gate latches are strong, but also bulkier and require string or an additional method to unlatch/latch it exactly when the system went to sit/stand.

The brake lock mounted to a hinging inner frame integrates the two solutions for lowering the front and back. With the brake lock attached and rotating at the hinge, the frame and brake lock rotates downward, unlatching the retractable harness--as seen in Figure 18. This enables Bodie the freedom in his front half to either sit (front raises) or lie down (front lowered).

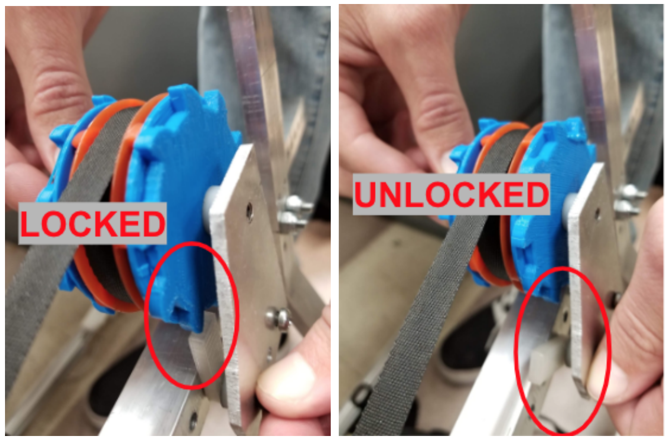


Figure 18. Brake lock system locking and unlocking retractable harness.

Due to the nature of the brake lock system, precision in spacing is crucial when mounting the brake lock assembly to the outer frame. To avoid interference from other components and ensure that the harness retracts with a consistent motion, the team created a casing to house the assembly with the appropriately placed spacers and guide the retractable leash back into place each time. As seen in Figure 19, the leash retracts back through the guide at the top of the casing, and all spool components are housed underneath inside the casing.

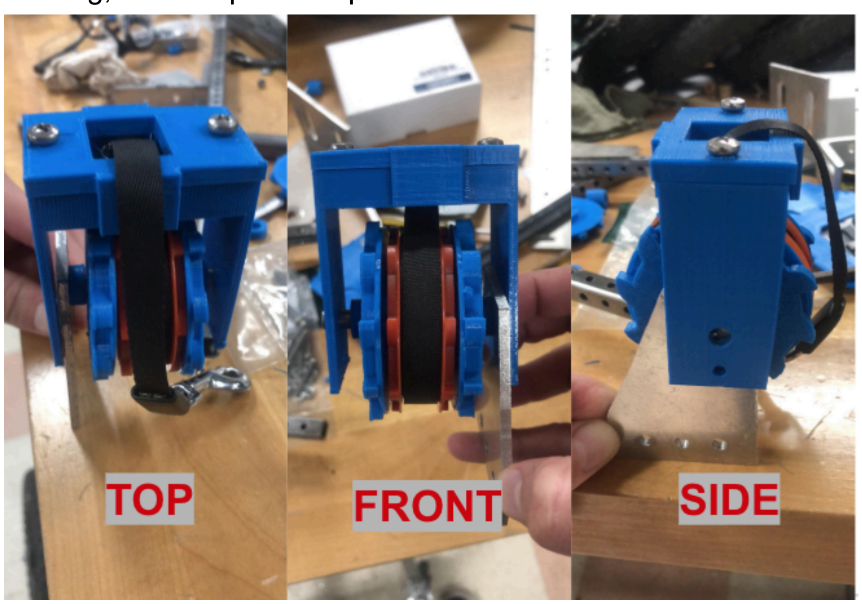


Figure 19. Brake lock casing guides the retractable harness.

Chapter 4: Prototype Performance

Theoretical Predictions

- 4-wheel design will significantly reduce the load on Bodie's shoulders.
- Caster wheels attached to front struts will allow similar maneuverability to 2-wheel cart.

- Bigger caster wheels perform better than smaller casters on uneven terrains.
- Flat frame lowering may be a simple solution to transition between sit-stand-lie down.
- Linear actuators providing less than 890 N (200 lbs) of force--the maximum force supplied by manufacturers under consideration--will be sufficient to lift Bodie's rear (estimated 112 N, or 25 lbs)

Test Conditions

80/20 Frame Test

A problem with the previous wheelchair model was uneven frontal weight distribution, with an uncomfortable pressure point on Bodie's shoulders from his harness. The objective of this test was to evaluate the potential usability of that wheelchair model, given a new frame that allowed adjustable comfort components. A frame was fabricated from 80/20 aluminum rods, enabling parts to be fastened and easily adjusted via screws and sliders. Bodie was placed in the cart and parts were fine tuned until the frame laid parallel to the ground indicating a more balanced frame. The placement along the frame and height of the saddle determined whether or not Bodie's spine would sit in its most natural, straight posture. The positioning of the harness and front wheel struts would determine the load that rests on Bodie's shoulders, and the resulting amount of discomfort.

4-Wheel Performance Test

The 4-wheeled cart design in Figure 19 below was introduced to address comfort. Prototype testing on the 4-wheel design focused on evaluating if the added front wheels on angled struts improved comfort without compromising mobility. The comfort testing was addressed in the 80/20 Frame Test, so this performance test observed the wheelchair's mobility over different surfaces and ability to support with Bodie, and Bodie's eagerness to move in it.

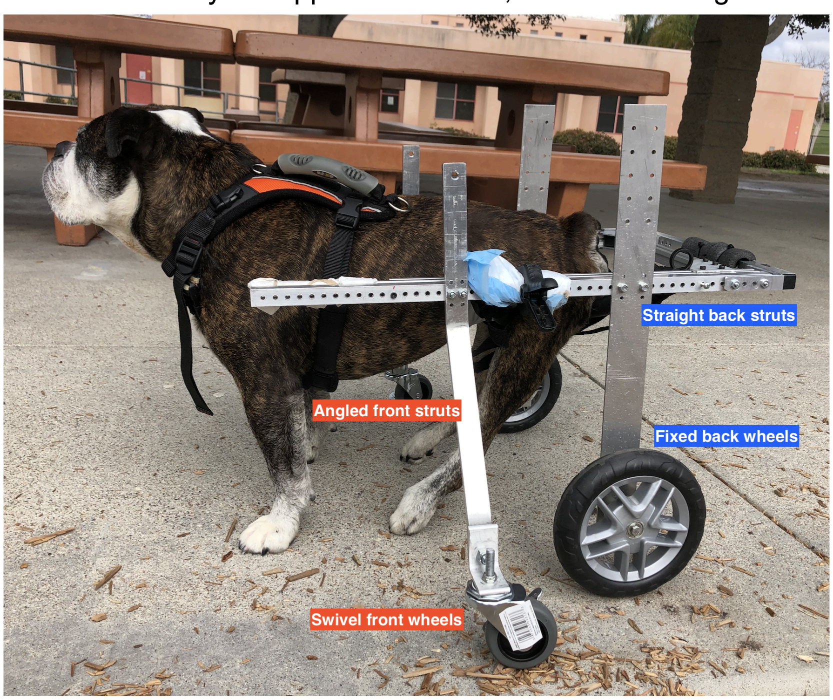


Figure 20. 4-wheel design prototype.

Flat Frame Test

An earlier wheelchair design featured the vertical lowering of the entire frame. The flat frame test was performed to assess the feasibility of vertically lowering the cart frame with the assistance of two 30.48 cm stroke linear actuators mounted on struts on either side. Hinging front struts would work in tandem with the actuator-assisted lowering along the back struts. The performance would be evaluated on the ability to lower Bodie's rear all the way to the ground, transition between sitting and laying down, and provide enough assist to lift back to a standing position.

Linear Actuator Specification Analysis

Free body diagram analysis was performed to determine the actuator range of motion (stroke) and strength (supplied force) specifications according to the wheelchair design. Force analysis was performed under several assumptions: the lifted weight was the sum of Bodie's rear and the frame, with the center of mass at the center of the saddle; the worst case scenario (or maximum force required from the actuator) occurs when the inner frame must be lifted from down position. Values used in calculations were body and wheelchair frame dimensions measured at sponsor meetings.

Rocker Switch Circuit Test

The purpose of electrical testing was to evaluate the performance of the actuator-switch circuit. Test objectives were to attempt wiring two actuators in parallel to a single switch with ON-OFF-ON switch configurations. A key performance evaluation was the speed of the actuators since the actuators draw 5A and the power supply outputs 1A. The smaller power supply was selected for its compact lightweight features so testing would determine whether 1A was sufficient current supplied for reasonable actuation speed. The circuit and components were isolated from the wheelchair for this test.

Linear Actuator Motion Test

In order to validate the final design of the electromechanical sit-stand system, both electrical and hardware tests were conducted. After the circuit was validated, it was mounted to the wheelchair to test the motion of the mechanism as seen in Figure __. The purpose of this test was to configure the actuators to the wheelchair, validate the mount design, and observe the stability of motion.

Linear Actuator Force Test

After the sit-stand mechanism motion and mount design were validated, a force test was conducted. The purpose was to experimentally validate theoretical force calculations by observing the lifting performance of the actuated system with applied load. The test bed was a box containing a 11.34 kg weight that was loaded to the wheelchair saddle.

Linear Actuator Mounting Analysis

Further rounds of mounting analysis were performed in response to results from the linear actuator motion test and force tests. Calculations addressed the final mount design and final actuator specifications, which improved the mathematical model. The purpose of this analysis was to derive the optimal mounting location of the actuator mount point relative to the inner frame hinge point, as denoted by X and Y in Figure 20.

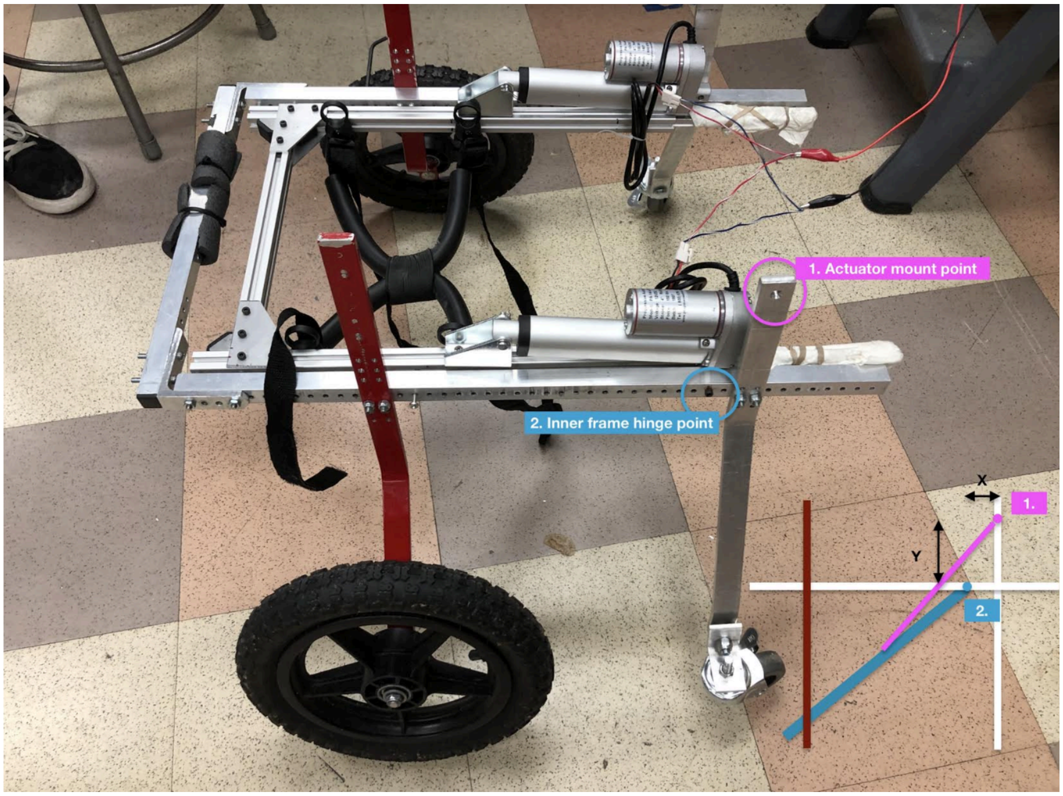


Figure 21. The position of the actuator mount and inner frame hinge point need to be specified in order for the actuator motion to work as intended.

Results

80/20 Frame Test

The results of this preliminary prototype test indicated that the reference position would be Bodie's hind legs, as the back wheel struts would be placed at around his hip joint to emulate his anatomy. The saddle would then be placed accordingly to have his hips lie in the same area. This prototype test also demonstrated that a tighter saddle sitting slightly higher up would bring up Bodie's rear and neutralize his spinal positioning. With the rear comfort components fixed, further testing determined that the optimal harness position would have the buckle of the harness sit 25.4cm (10 in.) from the mounting position of the back wheel strut, with the front wheel struts sitting right behind the harness buckle. This placement of components allowed the frame to sit parallel, provided neutral back posture for Bodie, and took the load of the cart off of Bodie's shoulders, as seen in Figure 21.

Figure 22. Before (left) and after (right) prototype testing on the adjustable 80/20 frame.

In order to further analyze the prototype, Table 5 below was developed to compare the relative strengths and level of desirability of the prototype to Bodie's most commonly used solutions. The industry wheelchair is the one manufactured by Eddie's Wheels, while the sling is a hand-held solution that requires the owner to follow Bodie while holding up his hind side. Speed and effort required to move are relative, while eagerness to move is also relative and indicative of how comfortable Bodie is in the corresponding assist device.

Performance standard	**Final adjusted 80/20 wheelchair**	**Industry wheelchair (Eddie's Wheels)**	**Sling (hand-held)**
Speed	Med	Low	High
Effort required to move	High	High	Low
Eagerness to move	Med	Low	High
Weight on front legs	19.23 kg	15.69 kg	19.23 kg

Table 5. Performance standards evaluated from preliminary prototype testing.

4-Wheel Performance Test

Preliminary performance tests on the 4-wheel design centered around caster wheels attached to the front struts. To assess their mobility over uneven terrain, a pair of 5.08 cm-diameter and a pair of 7.62 cm-diameter caster wheels were tested. While both sets of caster wheels were able to move effectively over tile, hardwood, and pavement, the smaller set of wheels had difficulty moving over grass. These results were consistent with information received from industry manufacturers, as they mentioned bigger caster wheels worked better over uneven surfaces. Otherwise, the caster wheels functioned as expected, providing the 4-wheel design similar maneuverability to the previous 2-wheel design. For secondary performance tests, focus will be on the effectiveness of angled front struts, and further testing may be conducted on different sized back wheels, should time permit.

Flat Frame Test

In order to validate the actuator design that vertically lowered the entire frame, two 30.5 cm (12 inch) stroke actuators each supplying 222.4 N (50 lbs) were ordered. While they met the sit-stand functional requirement of support the rear load, the actuators total length and weight were mistakenly unaccounted for. This made a mounting system difficult because the flat frame design assumed the actuators to stand vertically, but their weight made this unstable. The design was observed to be inefficient due to the the 1:1 actuator stroke to vertical displacement ratio.

Instead, the team modeled the flat frame design motion, specifically the hinging of the front wheels, by manually lifting and lowering the frame. An performance issue discovered from this testing was the even when the flat frame lowered all the way to the ground, Bodie's rear rested slightly above due to the saddle mount. Another issue was the struts were unstable as the actuators lowered and lifted the entire frame.

A more critical failure in the performance design was that it did fail the sit-stand transition functional requirement. Due to the frame's fixed flat position, lowering his rear forced the lowering of his front. This inhibited sitting position. A solution and insight for moving forward was to have the front harness move independently of the rear motion in order to allow transition between standing, sitting, and laying down.

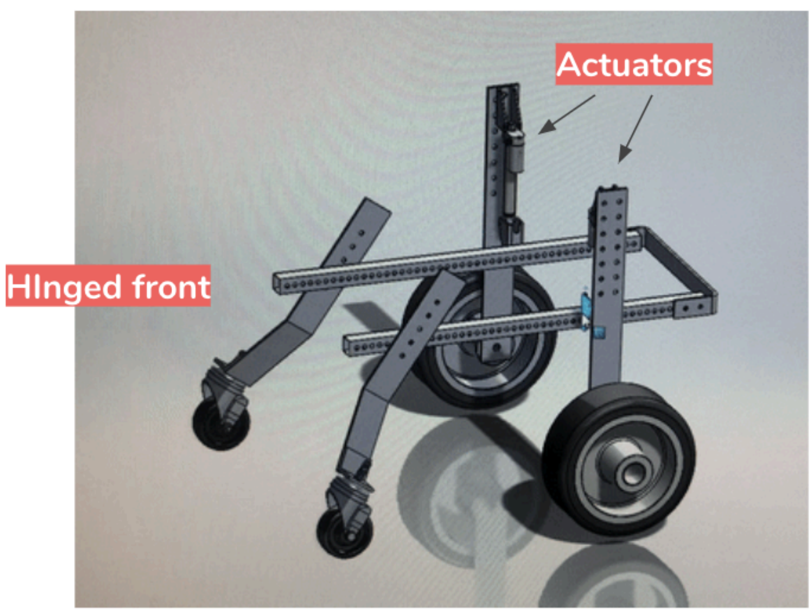


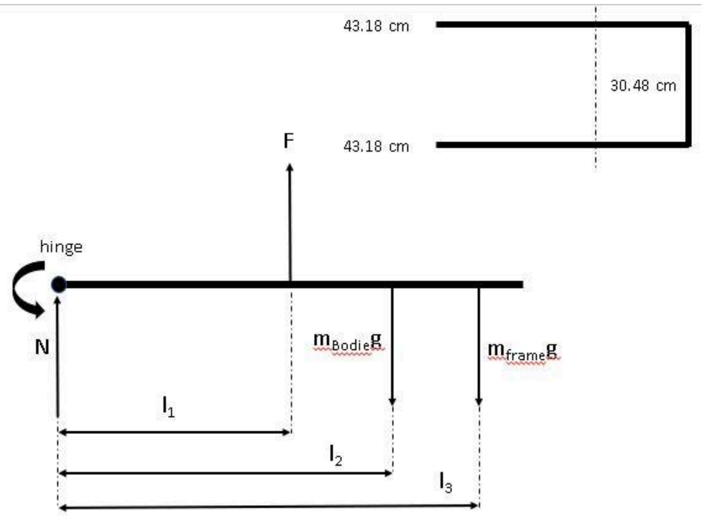
Figure 23. Flat frame prototype

Linear Actuator Specification Analysis

Bodie: m_{Bodie} = 50 lbs = 22.68 kg

Mini frame: $m_{frame} \cong .75$ kg

l_1 = variable (m)
F = required actuator force (N)
l_2 = 10 in = .254 m
l_3 = 10.72 in = .272 m



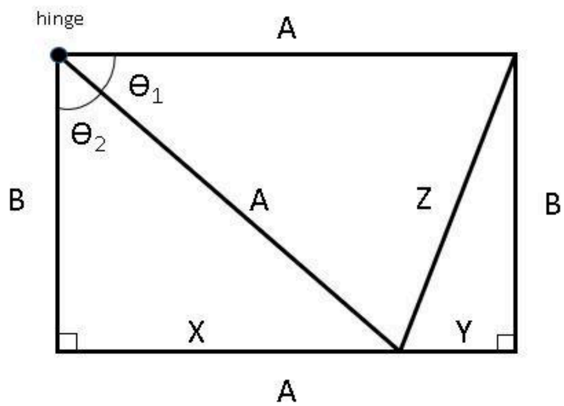
$$\Sigma F_y: N + F = g(m_{frame} + m_{Bodie})$$

$$\Sigma M_{hinge}: \boxed{Fl_1 = g(l_2 m_{Bodie} + l_3 m_{frame})}$$

Ex: l_1 = 8.5 in = .2139 m → F = 271.03 N = 60.93 lbf

Figure 24. FBD force analysis on mini-frame prototype

This free body diagram shows a side cross section of the mini-frame that would be used to lift and lower Bodie’s comfort components, and thus Bodie himself. The far left point of the frame is the hinge that connects the mini-frame to the larger frame around it, and therefore there will be a normal force vertically on the min-frame there. The last force in the FBD is the force supplied by the actuator and its corresponding location. The location and force of the actuator were left as variables, since the intention is to find an appropriate range of actuators that can supply our needed stroke and supplied force. The final equation can then be used in parallel with actuator research to see if a given stroke and force will work in a location on our frame. For the sample position of having the actuator at the center of the frame, approximately 271 N of force is required to lift Bodie and the mini frame.



$\Theta_2 = \cos^{-1}(\frac{B}{A})$

$\Theta_1 = 90^\circ - \Theta_1$

Ex: $\boxed{\Theta_1 = 55.44^\circ}$

Ex: A = 43.18 cm, B = 35.56 cm

$X = \sqrt{A^2 - B^2}$

$Y = A - X = A - \sqrt{A^2 - B^2}$

$Z = \sqrt{B^2 + Y^2} = \sqrt{B^2 + A - \sqrt{A^2 - B^2}^2}$

$$\frac{Z}{B} = \frac{\sqrt{B^2 + A - \sqrt{A^2 - B^2}^2}}{B} = \text{extension ratio}$$

Ex: $\boxed{\frac{Z}{B} = 1.1296}$

Figure 25. Geometric analysis of mini-frame motion

This secondary analysis serves to measure and calculate geometries of our design based on Bodie’s bodily constraints. The height B is the height of the frame off the ground, which should be related to his leg length. The length A is the distance from the mini frame hinge to the back end of the mini frame, which is the entire length that will rotate until the back of the frame touches the ground. Based on lengths A and B, two important values can be obtained. First, the angle theta 1 can be obtained, which will be the angular range of the mini frame; this will be important because our design will involve a locking CAM component that will unlock once the frame passes a certain angle. The second value obtained is the extension ratio, which is the extra travel distance that the actuator must traverse due to the fact that the actuator will travel at an angle rather than vertically. This value doesn’t need to be precise, as it just translates to how much extra stroke there must be, which can be accounted for by getting slightly oversize actuators for our purposes.

Rocker Switch Circuit Test

First the DPDT rocker switch was wired to a single actuator and a single 12VDC/1A power supply to understand how the switch and actuator worked together in opening and closing the circuit. The final circuit was simple to use and allowed for full extension in ___ seconds, which seemed reasonable for the process of sitting/standing. Next was adding the second actuator in parallel. This performed better than expected as the speed did not seem compromised despite adding another electrical component. Furthermore, the speed was acceptable even when using the single 12VDC/1A power supply.

The DPDT switch interfaced simply for human fingers, but may be too precise for dog paws. It also features an OFF configuration that would stop actuation midway, which is not ideal. Test results guided design decisions to pursue a single 12VDC/1A battery and an ON-ON *button switch* for final design.

Linear Actuator Motion Test

The linear actuator bodies were mounted at a downward angle from the back struts (see Figure __) although the screws were held in place by hand because the appropriate fasteners had not been ordered yet. The extendable rod tip was mounted fixed to the inner frame. The motion performed mostly as expected, and the speed was about __ seconds for lowering and lifting. Observed challenges were the actuator mounts bumped into the outer frame, and the actuation line of motion pushed the inner frame lower than ground level which lifted the entire wheelchair up slightly. Machining the inner frame will allow for more clearance to avoid obstruction of moving components. Mounting analysis was also decidedly necessary in order to derive the correct positioning of the hinge pivot point and the actuator mount that would allow the full stroke extension to more deliver the desired frame displacement.

Another challenge was securing the actuator to the strut. Large amounts of stress are applied on the extended screw as seen in Figure __. Flimsy actuator mounting would lead to an unsupported inner frame and compromise the integrity of the entire rear-support system. Uprights were machined in order to better support the weight of the actuator and reinforce the mounting point.

Linear Actuator Force Test

With the sit-stand motion working as expected, force testing would determine if the system fulfilled its functional requirement of supporting the load of Bodie's rear. The test bed was a box containing 25 lbs of weight, loaded centrally onto the saddle at the back of the inner frame. The mechanism lowered with ease but was unable to lift from lowered position. Possible causes were the motor stalled from supplying insufficient force, or the inner frame hinge bolt became loose which allowed the inner frame to slide. This escalated the machining of the inner frame which, like the outer frame, features perforation for secure bolting through. This would resolve the sliding issue in future force tests to help identify the cause of the actuation stall.

Another shortcoming to the test model is the center of mass of Bodie's rear (i.e. the point of applied load in this experiment) is unknown. A load further back in the frame would require greater force by the actuators, while a more forward load or optimally located actuators and hinge points might allow for better force distribution. In order to address this concern, more mounting and force analysis was issued. Springs were also discussed as a method for potentially assisting the actuators in lifting the system in the case of insufficient force.

Linear Actuator Mounting Analysis

To be added upon completion

Comparison of Results to Initial Performance Requirements

The 4-wheel design improved comfort by reduced the load applied onto Bodie's shoulders. Further adjustments to the positioning of the wheel struts, harness, and saddle were also made to ensure Bodie was resting naturally in the wheelchair and not too compressed or stretched out lengthwise. Later performance tests on the 4-wheel design evaluated how adding

2 front wheels and angling the 2 back struts outward affected mobility. It was concluded the range of mobility had not been compromised from these wheel design changes, confirming the 4-wheel design overall as a better option for greater stability and comfort.

The first sit-stand design implementing a flat frame motion failed to enable the critical requirement to transition from standing to sitting position. This design failed because the front and back ends were fixed horizontally in position, disabling sitting position. This finding led to the addition of another functional requirement: to enable independent front and back end lifting and lowering.

The sit-stand redesign featured an isolated sit-stand mechanism with a hinging inner frame, larger force and shorter linear actuators, and a more compact mounting design to address this issue. The linear actuator motion test evaluated the performance of the lifting and lowering motion of actuated system. The design was validated in that its movement performed as expected while also applying actuator force more efficiently than the flat frame design. Alongside this, the brake lock system was designed to allow the front harness to move independently of the rear to enable standing, sitting, and laying down positions.

Chapter 5: Design Recommendations and Conclusions

Design Recommendations for the Future

Consider self-charging batteries.

The current 12VDC/1A battery component is rechargeable but must be unmounted from the wheelchair and plugged into an outlet to do so. An improvement would be batteries that charge themselves, such as solar powered batteries or batteries that generate power from the rotation of the wheels. Improving the power component would decrease the amount of electrical maintenance needed by the pet owner and reduce the pet reliance on him. Further, alternative batteries sustainably increase the lifetime of the wheelchair. This notion of sustainable energy is reflected in the trend of modern cars that recharge themselves, such as Prius hybrids.

Design for owner's needs and comfort.

Although the primary user of the wheelchair is the paraplegic dog, a second critical user is the dog owner. This wheelchair design focuses primarily on solving the dog's needs such as being comfortable, being stably supportive, enabling sit-stand, and accounting for waste disposal space. Some considerations for the owner were still incorporated -- for example, the 4-wheel design allowed the cart to stand on its own which made it easier for Dr. Yu to load Bodie versus in the collapsible 2-wheel design -- but more design improvements can be implemented that primarily address owner needs.

The owner must interface with all the comfort components that must go onto Bodie: the front harness must slide over Bodie's shoulders and then clipped to the cart, the diaper pads must be folded and clipped to the cart. Currently these tasks are tedious and not optimized for the owner. Making the comfort components better integrated into the wheelchair design could improve the owner's user experience with the wheelchair as well. Ideas discussed but not explored due to scope limitations for this project include:

- **A harness fixed to the wheelchair with an over-the-top latch.** With this, the harness is no longer an independent comfort component the owner must keep track of and dress his pet in every time.
- **A diaper pad dispenser attached to the wheelchair.** Much like a tissue box or changeable table paper rolls used on medical exam tables, the idea is box that dispenses and automatically replaces single-use diaper pads. The owner can simply pull and attach the other end across the wheelchair, then dispose after use. More consideration would be needed to look into its mounting and attachment methods.

Scaling for Manufacturing

The previous team's (Winter 2018) prototype had unpremeditated holes drilled along the length of its frames because their frames were machined after trial and errors in efforts of locating optimal placements of components, making it non-adjustable by design. The current design proposed in this report addressed that issue by using perforated aluminum tubing. The tubing demanded that it still be manually drilled because different configurations regarding certain sizes and increments of holes are not sold on the market. Although the tubing itself was inexpensive and the machining was fairly straightforward, and much less time consuming with a programmable CNC machine- this component still required customization and effort beyond simply ordering a part. For mass manufacturing of the wheelchair, it is possible to switch aluminum perforated tubing with steel perforated tubing which is heavier but readily available on the market.

Safety Considerations

The project involves creating a wheelchair that is to replace Bodie's hind leg functionality, which means that to achieve the same level of functionality, there will be moving parts. The presence of moving mechanical parts introduces a need for safety precaution, as it will always be a possibility for the cart to collapse on Bodie, or for one of his body parts to get caught between moving parts. The design will be done to minimize occurrences like these.

This project is the first one of its kind to introduce electromechanical components to aid the dog in the transition from sitting to standing. The use of linear actuators to lift the dog's rear means they must exert a force equivalent to the weight of a dog. There are electrical components on the product with the exertion capacity to potentially pinch or crush body parts. The danger with electrical actuators is that they are much harder to stop than regular hinging components, so the design must guarantee that the dog will never be in the path of the actuators. Similar to the safety concern of moving parts, the design will be done such that the occurrence of having body parts in the path of actuated parts will be avoided.

wApplicable Standards

As user-focused assist devices, dog wheelchairs are primarily concerned with consumer safety standards and performance requirements. These are guided largely by ANSI standards for ensuring structural integrity and mobility, and ISO test methods and component specifications.

The International Organization for Standardization (ISO) also has a set of manufacturing and performance standards for wheelchairs, ranging from static/dynamic stability to test methods for fatigue strength[1], to power and control systems for electronically powered wheelchairs (ISO 7176-1 through ISO 7176-14)[2]. These standards ensure that specific test methods are performed to meet certain safety and performance requirements during normal use, and sets limits on forces applied for certain operations. While these standards are intended for human wheelchairs, dimensions for tolerance ranges may be adjusted for wheelchairs used by dogs.

Unlike existing dog wheelchairs in industry, the final design explored in this project features a motorized assist system for lifting and lowering the rear. This subjects the design to more ISO evidence-based practices to ensure standards for energy consumption and electromagnetic compatibility of electrical components are met. These include remaining within battery and charger specifications[3] and test methods for determining energy consumption and dynamic stability of the wheelchair[4,5].

The electromechanical components included in this project design introduce significantly greater risks and require close adherence to standard electrical safety protocols. Such standards define voltage and current ranges that components must operate within, and can be found with the Institute of Electrical and Electronics Engineers (IEEE), for example. Another set of standards that follow regulate the mechanical forces and electrically powered moving components, such as the torque and linear forces generated by linear actuators, and the dynamics of the moving frame. One code to meet for this criteria would be performance test codes (PTC) ___ and ___ that aid in planning, executing, and monitoring the force generation and physical performance of the moving frame.

The structural material of our design must also adhere to industry standards. Aluminum was selected for its lightweight and durable qualities in both last year's design as well as the 80/20 prototype extrusion frame. Aluminum parts used must comply with standards regarding chemical composition restrictions, and mechanical properties of the aluminum such as hardness and flex. Some material standards for aluminum may be found under the Aluminum Association (AA)[6].

One interesting niche standard that isn't necessarily applicable but would still be good to meet is the Restriction of Hazardous Substances Directive, or RoHS Compliance[7]. This standard restricts the existence of certain trace substances in electronic components, such as lead (Pb), Mercury (Hg) and Cadmium (Cd). The reason this standard may not be applicable is because it only applies to components shipped to/from Europe, which only comes into play if we source our electrical components from European vendors. At the moment, none of our components come from Europe, but at least one of our looked-at vendors met RoHS compliance because of its global shipping range (DigiKey). Still, the fact that our product isn't limited to the United States (can be used in any country with pet dogs) and that it is to be personally interacted with by our clients (dogs and people) means that limitations on toxic chemicals in our sourced components can only be a positive influence on the safety of our final product.

Impact on Society

Like humans, dogs can experience paraplegia. Their causes vary anywhere from tick bites to infection to malignant tumors, but most commonly result from spinal injury or disease.[8] Paraplegic dogs commonly lose control or mobility in their hind legs, and can experience a lifetime of pain, muscle atrophy, and general low quality of life if untreated. As domestic pets, the dog's disability can be a difficult change for both their and their owners' lives. For example, following paraplegic immobilization is often a lack of bladder and bowel control, invoking pet discomfort and a higher degree of caretaking responsibilities by pet owners.

Furthermore, paraplegia and its treatment is not as well researched or funded for dogs as it is for humans. In fact, before assist devices for paraplegic dogs were developed, it was not uncommon for pet owners to opt for euthanasia to relieve their dogs of their generally difficult experience. Once dog wheelchairs were created, they not only alleviated caretaking responsibilities of pet owners for tasks such as walking and carrying their dogs, but also returned to paraplegic dogs their sense of mobility, and increased their quality of life.

While existing solutions give paraplegic dogs a sense of normalcy and mobility, there are still no commercially available wheelchairs that allow a paraplegic dog to transition from standing position to sitting and/or laying down. Most industry manufacturers avoid this feature because of its operational danger and potential to atrophy the dog's muscles from over-reliance. However, the project strives to fully restore paraplegic dogs' independence with a wheelchair designed for everyday extended use; this means allowing the dog to walk and reposition himself in the wheelchair without external reliance. This wheelchair solution will be a more economical investment for pet owners since most own multiple assist devices, each one limited in functionality and serving niche purposes, to enable a wider range of capabilities for their dogs. Overall, this project's extended use assist solution uniquely incorporates the full range of key use features for paraplegic dogs, easing both their and their owners lives.

Our project goal of daily, extended use means designing from a holistic and user-centered approach. Priorities were the comfort, safety, and overall improvement to the quality of life for both end users, paraplegic dogs and their owners. By working primarily with recyclable, common non-ferrous metals in high-fatigue areas, and less recyclable material in low-fatigue areas, this project lessens its potential carbon footprint. As seen in the transition from the previous year's project, the replaceable parts (e.g. cart frame, wheel struts) are largely made of recyclable metal, while the non-recyclables (e.g. saddle, harness) are parts that can be easily reused in other dog assist devices. Safety-wise, all fabrication and assembly is completed in university machine shop with appropriate supervision and manufacturing practices. Mechanisms or electrical components are appropriately secured, with critical failure analysis performed before implementation.

Lessons learned

Under a tight timeline of 12 weeks, lessons were learned from both a technical, project management, and design standpoint. First, fast prototyping was critical to delivering the final wheelchair under a strict timeline of 12 weeks. Valuable assets to prototyping were 8020 rods that enabled sliding bolts for quick rough adjustments of cart parts and dimensions that could later be precisely calculated in analysis, then refined and implemented in final fabrication.

Because the previous 156B's final design and other wheelchairs on the market are purely mechanical, there already existed available databases of mechanisms for their research, design, and fabrication (turnbuckles, freewheels). The introduction of actuated motion in this electromechanical wheelchair was unprecedented. Not only did it involve consideration but there were also many more standards to adhere to after electrical components were implemented. It was acknowledged how much research, project planning, and user need finding must be considered for the development of a product, especially in order to release it to the public market where the engineers are liable for the users' safety and satisfaction.

A key lesson was that there should be no preconceptions or expectations when designing a user product. At first it seemed that a mechanical system for the wheelchair was going to be more feasible in terms of fabrication, cost, and timeline for this project scope. Motorized assist was therefore dismissed. After greater urgency from the sponsor to explore motor systems, the idea of linear actuators (over rotational motors) was discovered and developed. With more research and analysis, the possibility for an actuated system was revealed to be more practical, cost-effective, and valid than expected. It was unwise to prematurely dismiss electrical systems because further consideration and creative problem-solving allowed the discovery of actuators. Not only did working outside the team's comfort zone expand their technical knowledge and skills, but putting the sponsor and user needs before the team's preconceptions actually revealed the advantages of a electrical system over a purely mechanical system, which shaped the linear actuated concept implemented in the final design.

Conclusions

The Bodie Wheelchair is a motorized rear-assist device designed to improve the comfort and mobility of hind-leg paraplegic dogs. It was modeled after the English bulldog Bodie. The design used four wheel stabilization to alleviate poor weight distribution on his body, a linear actuated assist to lower and lift the pet's paralyzed rear, an integrated retractable harness for free motion in the front, and switch activation for easy operation. Altogether this promoted a full range of activity by making standing, sitting, and laying down positions all possible.

Bodie's Wheelchair redesigns current dog wheelchairs which are temporary and insufficiently thoughtful solutions. Industry dog wheelchairs addressed a single use case (walking/running), and neglected other key user needs (sitting/laying down to rest or relieve himself). Some makers wanted to avoid harmful collapsible sitting mechanisms, but dismissing the sitting need because of poor solution model was close-minded design thinking.

Furthermore, since pet paraplegia is not as well-funded or researched as human paraplegia, none of the existing pet solutions adequately address the larger and persistent challenge of restoring everyday independent mobility to pets. However with technological advancements (like electric human wheelchairs) and greater sociocultural trends towards pet adoption/domestication, there is a responsibility for every caring owner to respect their animal companion's rights and quality of life. The pet industry can help advocate these values by delivering more thoughtful product solutions such as Bodie's Wheelchair that directly design for the needs of dogs living with paraplegia.

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Appendix

Appendix A: User Manual

A.1: User Maintenance

Battery Charging. The 12VDC/1Ah battery is estimated to supply approximately 90 complete cycles of down and up motion. It is recommended to charge the battery at least ***X times a week.***

Before charging the battery, ***FIRST REMOVE YOUR PET FROM THE WHEELCHAIR COMPLETELY***. Although the 12VDC/1A supply is not enough to deliver a shock, it is best practice to keep your pet away from the charging battery. It is recommended to charge overnight when your pet does not need the wheelchair and can rest. Remove the red and black alligator clips from the two terminals. Attach the clips accordingly from the charger. Plug the charger into the outlet and charge for ***X hours*** or until fully recharged.

Circuitry. In the case of the electrical components not working, please feel free to consult with the team before attempting to resolve the issue.

Below is the intended circuitry of the electrical system implemented. The user can examine the circuit if familiar and comfortable with basic wiring. *Before examining the circuit,* ***FIRST REMOVE THE RED AND BLACK CLIPS FROM THE BATTERY TERMINALS.*** Once the power supply has been disconnected, the wires casing can be opened up to check for broken wires, disconnected terminals, or other issues.

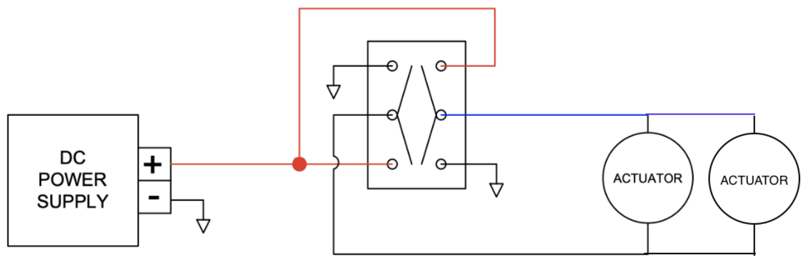


Figure __. Circuit diagram of electrical components in Bodie's wheelchair.

A.2: Pet Training for Switch Activation*

***Disclaimer:** Owners know their pets best and this manual is only one possible and suggested method for training your dog to use the wheelchair.*

Most dogs are treat-motivated and can learn a variety of actions with a reward-based method. However, owners know their pets best and this manual is only one possible and suggested method for training your dog to use the wheelchair.

Familiarizing the Motion. To teach your pet to use the switch-activated rear assist system, first familiarize him or her with the motion.

1. Load your dog into the wheelchair. Allow some time for him her to self adjust and get used to the new frame.
2. Toggle the switch down to introduce the rear lowering motion. Teach your pet he/she can both sit and lay down by with the rear lowered. Allow them to interact with the retractable harness in front by encouraging him/her to lay down and sit down. Always reward these actions!
3. Toggle the switch up to introduce to rear lifting motion. Reward your pet for waiting for the lift assist. Show your pet he/she can move around again by encouraging him/her to walk or run around.

Repeat this a few times throughout the day or until your dog seems comfortable with the motion. Your pet may act anxious or squirm once the lowering and lifting motions are first introduced. This is normal and one should keep snacks readily available to reward them for being patient. Once they seem comfortable with the motion, move on to the next step.

Teaching Switch Activation. Your dog is now ready to begin learning the toggle switch operation.

1. Load your dog into the wheelchair. Allow some time for him her to self adjust and get used to the new frame.

2. Encourage your dog to knock the switch down by using a treat to guide his/her snout to the toggle switch. Using your treat in hand to encourage a nodding motion to hit the switch. Once triggered, reward your pet! Allow the rear to lower. Reward optional for being patient for the motion.
3. In the same way, encourage your dog to toggle the switch up.

Appendix B: Drawings / Layouts / Parts

· Attach your technical drawings / product layout describing the parts, list of parts and quantity

Appendix C: List of Suppliers / Purchased Part Information

- *List of suppliers and which parts you bought from them.*
- *Also have contact info and thanks if necessary*

Appendix D: Preliminary Component Analyses

D.1: Frame Analysis

The component of the assist device under evaluation is the frame which is pivotal to supporting the dog and the parts that come in contact with him such as the harness, stirrups, etc. The frame must be able to have access points in order to install different methods of locomotion (e.g. strut and wheels) in order for the dog to actually move along with the frame. The prototype from the previous team had a U-shaped frame made of aluminum but was not adjustable as holes were drilled all over to make up for trial and errors in placing components.

Functional Requirements:

- Adjustability must be implemented in order to conform to the body of dog and allows for later changes.
- Efficient distribution of load over body of dog.
- Lightweight to not cause stress on dog through daily usage
- Access points for installing support fixtures and wheels.

In order to find suitable frames for assistive devices for paraplegic dogs, it can be a great start to begin researching into already established companies that provide products for such disabilities. One company that is fairly common or shows up whenever one searches “dog wheelchairs” is Walking Pets. A program manager who works there, named Jennifer Pratt, gave insight into how their product and design is better than most others out in the market. One key characteristic is the adjustability of the frame, where in other companies such as Eddie’s Wheels it is custom made to the dog and can't be used for any other dog or if the dog changes physically for any reason. The frame material is made of lightweight aluminum to not cause too much drag and stress on the dog when they move. Other components such as a saddle and harness can easily be attached to the frame.

Similar mechanisms can be found in other stores - mechanisms analogous to how a crutch would work. McMaster-Carr contains rails, particularly telescoping rail sets for our interest. These tend to come in larger sizes, 4 ft and up, but ideally they can be cut in order to have more parts for the frame. Unfortunately, the only material available is galvanized steel but it does include the locking pin for the nested rails with incremented holes.

Through Youtube videos, it can be shown that it is quite feasible to create your own perforated tubing. It would require one slightly smaller square bracket that can fit inside a bigger one and buying a stock of locking buttons and fitting it inside the smaller square bracket. This would require to use the machine shop, but will also require more time than acquiring purchased parts. Although the material can be any available at the machine shop or resources at hand. You would essentially end up with something similar to the one found on Mcmaster-Carr.

Another option would be continuing with the same frame material that the sponsor vouched for and improving upon it. That would be using the 80/20 or T-frame rods which also allow for adjustability but through connectors and sliders. Through risk reduction it was found that if the components were placed correctly such as the harness relative to the end of the frame it creates better weight distribution and helps the dog be more comfortable.

	Pros	**Cons**
Walkin' Pets	Already established. Frame is adjustable in fixed increments. Lightweight and durable. Positioning of additional equipment would relatively be easy.	Most expensive if trying to obtain the whole frame($6-$45 for individual extenders/connectors, $360 for entire frame kit). Can't really make additional adjustments such as holes.
McMaster-Carr	Can be obtained fairly quickly. Adjustable and can create a U-shaped frame with connectors. Positioning of additional equipment such as harness can be relatively easy.	May be a bit pricier than the 80/20 rods($65.36 for one 4' nested rails). May require more parts with connectors. Galvanized steel may prove to be a bit heavier.

DIY (Machine Shop)	Can have more direction over frame and make it more compatible with other individual components. Less expensive (no cost to abstract cost) and can be for the most part any material that is available at hand.	Can be very time consuming to fabricate. May delay project since frame is critical to making progress on the project and the other parts are contingent on it being done.
80/20 Aluminum Frames	Frame is adjustable in terms of where additional equipment is located, and relatively lightweight (aluminum). Not too expensive (~$70 for three 2' frames +connectors), and there are various similar frames available at the machine shop or at UCSD in general.	Can be time consuming adjusting parts. Requires additional parts such as connectors and sliders. Positioning of additional equipment is not in increments, so it is not always accurately placed right. Limited to only certain type of fasteners.

Informational Resources:
Keywords used (Web Search):
Dog wheelchair, telescoping rails/tubes, perforated tubing, locking buttons, push button rods

Walkin' Pets: https://www.handicappedpets.com/metal-parts/
Mcmaster-Carr: https://www.mcmaster.com/perforated-tubing
DIY: https://www.youtube.com/watch?v=y3V6o3eca0g
80/20 Frames: https://www.mcmaster.com/catalog/124/1978

Contacts:
Jennifer at Walkin' Pets, T: (888)253-0777 x 118, email: jenniferp@handicappedpets.com

D.2: Comfort Analysis

Overview
The comfort of paraplegic bulldog Bodie is a primary focus for his wheelchair redesign. Sponsor Dr. Dave Yu explains the current wheelchair model causes Bodie visible discomfort. He predicts comfort is directly correlated to the weight distribution of the wheelchair on Bodie's body.

Defining Comfort
A preliminary wheelchair prototype allowed the team to adjust the positions of wheelchair components (saddle, harness, wheels, etc) along the wheelchair frame. Hardware testing was

performed by adjusting component positions then observing Bodie's weight on his front legs as well as his performance behavior. One key finding was Bodie was ostensibly more or less inclined to move in wheelchairs of differently positioned parts--for some, he walked immediately; for others, resisted moving at all. The team observed his changed behaviors and defined key performance standards to evaluate Bodie's perceived comfort and enjoyment in the wheelchair. These include his speed, amount of waddle (indicative of the required amount of work), and eagerness to move.

Comfort System

The comfort system is used to describe the physical design decisions made in order to maximize Bodie's physical ease and minimize his effort and painful constraint in the wheelchair. Some functional requirements are: support the weight of Bodie's backside, elevate Bodie's hind legs off the ground, orient Bodie's backside in a painless and non-constraining way, minimize direct contact between wheelchair and body, and effectively distribute cart weight to reduce uncomfortable pressure points.

Research

Preliminary stages of research were conducted on transportation and support systems similar to a dog wheelchair. These included human wheelchairs, crutches, car seats, baby strollers, and cars. Immediate brainstorming of the comfort methods present in these systems elicited ideas of padding, elastic, shock absorbers and suspension systems, and principles of ergonomic design.

Initial research focused on the principles of ergonomic design. A few notable ergonomic principles were build for neutral posture, reduced excessive force, reduced static load, minimized pressure points, reduced excessive vibrations, enablement of movement and elasticity. These confirm Dr. Yu's prediction that improved weight distribution was key for comfort and better ergonomics. Both prototype testing results and following research suggested weight distribution as the most impactful factor for on wheelchair comfort for Bodie. Therefore, although additional research on comfort in human wheelchairs yielded several relevant ideas for a dog wheelchair like cushions, a footrest, lateral side supports, etc., further consideration of these alterations were suspended in favor of focusing on optimizing weight distribution.

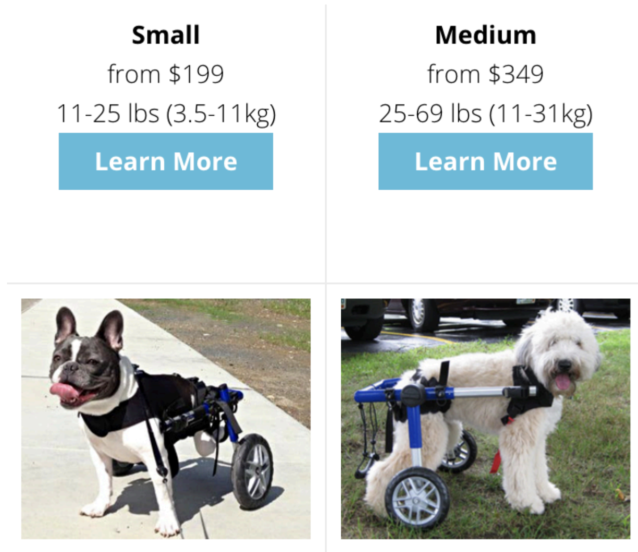
Next was to research how weight distribution and comfort is designed for in industry. Consultation with Ryan, a production technician at K9 Carts, revealed their philosophy on designing for comfort in similar rear-support wheelchairs is precision and custom fit to ensure natural hind-leg elevation. Elevation allows for the most natural, neutral posture of the pet, which falls in line with a central ergonomic principle. Another finding was that their wheelchairs for total hind-leg elevation (like Bodie's) use 4 wheels: 2 for locomotion (in the back), 2 for supporting the frame weight (in the front). This shifts the weight of the front frame off the dog onto to the front support wheels. The current model of Bodie's wheelchair uses 2 back wheels purely for mobility, so the front frame load rests on his shoulder harness.


(Left) *K9 Carts.* Industry rear-support wheelchair features 4-wheels.
(Right) Previous model of Bodie's wheelchair rests front frame on shoulder harness.

Another design consideration K9 Carts makes is the weight of the wheelchair frame. They opt for thinner stainless steel frames to avoid bulkiness and reduce static load. Their design has no contact between the metal frame the dog's body, enabling mobility and effectively removing risk of friction burns. These design decisions reflect the ergonomic principles researched. Meanwhile the current model of Bodie's wheelchair uses 8020 bars that are thicker and heavier, and the cart frame width does not provide enough clearance as his body touches the bars when walking.

Bodie's wheelchair uses 8020 bars as wheelchair frame.

Finally, consultation with Jennifer, a product manager at Walkin' Wheels, explained how the dog's weight is used to determine the size of the back wheel as well as the length of the strut (wheel leg). Both the wheel and strut elevate of the dog's hind and affect the equilibrium position of the frame weight distribution. The current model might have wheels that are too small relative to Bodie's dense weight, and possibly do not provide adequate lifting support of his rear.



Walkin' Wheels. Although Bodie the bulldog is likely the height of the French bulldog on the left (Small wheelchair), he weighs nearly 50 lbs which qualifies him for the Medium cart and wheels.

Redesign Method	Pros	Cons	Cost
4-wheel cart	Less weight on Bodie, stable.	More material, higher cost, potentially complicates the sit-stand mechanism.	$50-$70 per extra wheel (Figure A in Informational Resources). Also requires extra rods.
Thinner frame	Lighter wheelchair, less weight on Bodie. More clearance for rear. Lengthening wheel legs could potentially improve posture.	Less sturdy/rugged, incompatible with existing parts, more fabrication required.	$16-$62 per 3-ft rod (Figure B in Informational Resources). Also requires new fasteners and potentially new parts for compatibility.
Larger wheels	Elevate Bodie's rear, better weight distribution, stronger rear support.	Higher cost, potentially incompatible with existing parts.	$40-$60 per wheel (Figure C in Informational Resources).

Conclusion

Considering the researched ergonomic principles, hardware testing findings, and collected industry design practices for comfort design, the most effective solution seems to combine methods of 4-wheel cart and thinner frame rods in order to develop a more stable, robust, ergonomic wheelchair for Bodie. The impact of larger wheels on the weight distribution and wheelchair comfort are not as significant as the impact of thin-rod frames and 4-wheel support system combined. Not only does the thin frame and 4-wheel support system afford comfort through better weight distribution, but it also stabilizes and lightens the wheelchair cart. Even with the price of new parts, the total cost would be around +/-$200 which is around 25% of the team's spending budget, though the relative perceived cost benefit would be much greater given the high prioritization of comfort in Bodie's wheelchair re-design.

Informational Resources

Corrosion-Resistant Threaded-Stem Casters with Polypropylene Wheels

The lightweight polypropylene wheels on these casters provide impact resistance on smooth surfaces. Wheels ride directly on the axle rather than on bearings, making them an economical choice for equipment not frequently moved. Double-ball swivel bearings provide the smoothest swiveling and are shielded to resist dust and debris.

Swivel casters with total lock brake the wheel and lock the swivel in one operation.

CAD For technical drawings and 3-D models, click on a part number.

Wheel Dia.	Wheel Wd.	Mount Ht.	Cap. per Caster, lbs.	Frame Fabrication	Frame Material		Each
Swivel							
1/2"-13 Stem Thread Size—1 1/2" Stem Lg.							
Nonmarking Black Solid Wheels—Hard (Durometer 90D)							
3 1/2"	1 1/4"	4 13/16"	250	Stamped	304 Stainless Steel	2454T37	$56.98
4"	1 1/4"	5 7/16"	300	Stamped	304 Stainless Steel	2454T38	57.44
5/8"-11 Stem Thread Size—2" Stem Lg.							
Nonmarking Black Solid Wheels—Hard (Durometer 90D)							
3 1/2"	1 1/4"	4 13/16"	250	Stamped	304 Stainless Steel	2454T47	56.98
4"	1 1/4"	5 7/16"	300	Stamped	304 Stainless Steel	2454T48	57.44
3/4"-10 Stem Thread Size—2 1/2" Stem Lg.							
Nonmarking Black Solid Wheels—Hard (Durometer 90D)							
3 1/2"	1 1/4"	4 13/16"	250	Stamped	304 Stainless Steel	2454T57	56.98
4"	1 1/4"	5 7/16"	300	Stamped	304 Stainless Steel	2454T58	57.44

Figure A. Small wheels for supporting legs (McMaster Carr)

304 Stainless Steel Rods with Certification

- Yield Strength: 30,000 psi
- Hardness: Rockwell B75 (Medium)
- Temper Rating: Softened (Annealed)
- Heat Treatable: No
- Specifications Met: ASTM A276, ASTM A479

These rods come with a traceable lot number and test report. They are 304/304L stainless steel, which has less carbon than standard 304 for better weldability. From cookware to chemical-processing equipment, this material is a good all-around choice for a wide range of applications. It maintains its corrosion resistance in temperatures up to 1500° F.

Dia.	Dia. Tolerance	Fabrication	Straightness Tolerance		1/2 ft. Lg.	1 ft. Lg.	2 ft. Lg.	3 ft. Lg.	6 ft. Lg.
1/8"	-0.001" to 0.001"	Cold Worked	1/8" per 5 ft.	1301T586	$11.52	$12.72	$14.90	$16.42	$20.88
3/16"	-0.001" to 0.001"	Cold Worked	1/8" per 5 ft.	1301T587	11.67	12.98	15.36	17.03	21.92
1/4"	-0.001" to 0.001"	Cold Worked	1/8" per 5 ft.	1301T588	11.69	13.02	15.44	17.13	22.09
5/16"	-0.002" to 0.002"	Cold Worked	1/8" per 5 ft.	1301T589	12.04	13.64	16.55	18.59	24.56
3/8"	-0.002" to 0.002"	Cold Worked	1/8" per 5 ft.	1301T591	13.08	15.50	19.90	22.98	32.00
7/16"	-0.002" to 0.002"	Cold Worked	1/8" per 5 ft.	1301T592	14.24	17.57	23.62	27.86	40.27
1/2"	-0.002" to 0.002"	Cold Worked	1/8" per 5 ft.	1301T593	14.52	18.08	24.54	29.07	42.32
9/16"	-0.002" to 0.002"	Cold Worked	1/8" per 5 ft.	1301T594	15.39	19.62	27.32	32.70	48.48
5/8"	-0.002" to 0.002"	Cold Worked	1/8" per 5 ft.	1301T595	16.44	21.49	30.69	37.13	55.98
11/16"	-0.002" to 0.002"	Cold Worked	1/8" per 5 ft.	1301T596	16.50	21.61	30.89	37.39	56.43

Figure B. Thinner stainless steel rods for frame (McMaster Carr)

Solid-Tread Flat-Free Wheels

Get the cushioned ride of a pneumatic wheel without the possibility of a flat tire.

Polyurethane foam wheels are lightweight and water- and UV resistant.

Ball bearings are the easiest to roll.

Center-mount hubs are symmetrical for equal clearance on both sides of the wheel. **Side-mount** hubs are offset for extra clearance between the wheel and your equipment.

Two-piece rims consist of two pieces bolted together so the wheels can be quickly repaired or replaced.

Wheel										Temp. Range, °F				
Dia.	Wd.	Tire Size	Hub Lg.	Cap. per Wheel, lbs.	Tread Pattern	Wheel Color	Nonmarking Wheels	Hardness Rating	Hardness	Min.	Features	Choose a For Axle Dia.		Each
Center-Mount Hub with Ball Bearings														
Polyurethane Foam Tread on Steel Core														
8 1/2"	4"	9.00/3.50-4	4"	250	Solid	Black	Yes	Soft	Durometer 65A	-20°	—	5/8"	22245T31	$52.84
8 3/4"	2 11/16"	2.80/2.50-4	3"	270	Wavy Line	Black	Yes	Soft	Durometer 65A	-20°	Two-Piece Rim	5/8"	22245T11	40.23
9 3/4"	3 5/16"	4.10/3.50-4	3 1/4"	300	Wavy Line	Black	Yes	Soft	Durometer 65A	-20°	—	5/8", 3/4"	22245T21	60.45
10 1/2"	4"	11/4.00-5	5"	340	Solid	Black	Yes	Soft	Durometer 65A	-20°	—	3/4"	22245T32	72.61
13"	6"	13/6.50-6	3"	300	Solid	Black	Yes	Soft	Durometer 65A	-20°	—	3/4"	22245T33	121.02
15"	3 3/8"	4.80/4.00-8	3"	1,000	Straight Line	Black	Yes	Soft	Durometer 65A	-20°	—	3/4"	22245T16	101.14
15"	3 3/8"	4.80/4.00-8	6"	1,000	Straight Line	Black	Yes	Soft	Durometer 65A	-20°	—	5/8", 3/4"	22245T22	101.14
Side-Mount Hub with Ball Bearings														
Polyurethane Foam Tread on Steel Core														
8 3/4"	2 11/16"	2.80/2.50-4	2 1/4"	270	Wavy Line	Black	Yes	Soft	Durometer 65A	-20°	Two-Piece Rim	5/8"	22245T38	40.23
9 3/4"	3 5/16"	4.10/3.50-4	2 1/4"	300	Straight Line	Black	Yes	Soft	Durometer 65A	-20°	—	5/8"	22245T39	60.45
9 3/4"	3 5/16"	4.10/3.50-4	2 1/4"	300	Wavy Line	Black	Yes	Soft	Durometer 65A	-20°	—	5/8"	22245T17	60.45

Figure C. Wheels for back support (McMaster Carr)

“10 Easy Ways to Make Your Wheelchair More Comfortable.” Karman Healthcare, www.karmanhealthcare.com/10-easy-ways-to-make-your-wheelchair-more-comfortable/.

Elmansy, Rafiq. “Principles of Ergonomics: Designing with User Comfort in Mind.” Designorate, 17 June 2015, www.designorate.com/principles-of-ergonomics-design/.

The Role of Comfort in Product Design. Logitech, www.logitech.com/images/pdf/articles/eng/role_of_comfort_in_product_design-EN.pdf.

Databases: Google Scholar
Keywords: wheelchair, comfort, product design, ergonomic design, weight distribution
Contacts: Ryan Neal, (800) 578-6960, K9 Carts; Jennifer Pratt, (888) 253-0777, Walkin’ Wheels

D.3: Wheels and Locomotion Analysis

Background Information: Physiology

In order to best understand the Functional Requirements of the eventual method of locomotion in the final design, it is important to learn a little bit about how dogs move. As the link (https://www.chewy.com/petcentral/dog-physiology-how-dogs-move) explains, dogs most often move using these 4 gaits: the walk, the trot, the rotary canter, and the rotary gallop.

The walk works one foot at a time, starting with the back foot on one side, followed by the front foot on that same side. For example, a walking foot pattern may go something like this: back right—>front right—>back left—>front left.

The trot is the most efficient gait used by dogs, where they move the back leg on one side simultaneously with the front leg on the opposite side, then are suspended in the air briefly before moving the other two feet together. For example a trotting foot pattern may go something like this: back right & front left —> suspended in air —>back left & front right.

The rotary canter is the gait most commonly used by dogs for tight turns. Here, they move the back foot on one side, then both feet on the other side, before stepping with the front foot on the original side. An example rotary cantering foot pattern is: back right—>both left—>front right.

Lastly, the rotary gallop is the most often used gait for running dogs. Here, dogs will have a lead foot in the front on one side and a lead foot in the back on the other side. They first extend their spine, reaching out with both front paws, with the lead front foot hitting the ground first. Then they move both back feet together, with the lead back foot hitting the ground first.

When Bodie--who is paralyzed in his hind legs--moves, identifying which gait he uses most often is not as simple as watching the order in which his paws hit the ground. Because his back legs are suspended in the stirrups of his cart, determining which gait he uses requires close observation of his hind quarters. The direction and timing of Bodie's hip motions when he's walking in a cart tells us which hind leg he is moving. By slowing down the videos and watching closely, we can see that Bodie most often walks and trots when in his carts.

Due to Bodie's disability, he is unable to hinge at the shoulders of his hind legs. This results in a very prominent tail wiggle whenever he moves. Current cart solutions do not account for this side-to-side action in his rear. When Bodie moves in a cart, there is a lot of energy and motion wasted because the carts are limited to forwards and backwards motion. This can be addressed as a functional requirement in our wheels.

Functional requirements:

- Move naturally with Bodie's body
- Offer sufficient stability when standing
- Traverse different terrains
- Allow for easy turning

Components

While there are many factors at play when considering method of locomotion, the focus of this component analysis will be on the different kinds of wheels and wheel orientations. This is because Bodie is most comfortable moving with his front legs supplying the power and doing the steering, while the cart serves as support.

<u>2 Fixed Wheels</u>

The current wheel design features 2 wheels, fixed to only allow for forward and backwards motion. The variance here comes in the size of the wheels--with small wheels making turning easier, while large wheels offer more stability. Despite the stability and ability to traverse all kinds of terrains, the 2 wheel design is not ideal because of its limitations to forward and backward motion. When Bodie moves in the 2 fixed wheel design, he has to forcefully shift the entire cart in order to turn. Additionally, there is a lot of wasted side to side motion in the cart because it does not move naturally with Bodie's hind side, slowing him down further.

<u>Single Wheel/Ball</u>

The single wheel or single ball design is inspired by the Dyson vacuum design and the wheelbarrow. When looking at ways to simulate Bodie's motion in MAE 156A, someone brought up testing the Human Wheelbarrow. From that idea, it was possible to see how Bodie's motion in the cart is similar to a traditional wheelbarrow, but backwards. The larger single wheel allows for better turning, greater degree of freedom to move more naturally with Bodie's hind side, while still being able to traverse all types of terrains. The downside would come in the standing stability. Bodie is a strong dog, but it is unclear whether he will have the core strength or torso control to keep the wheel from sliding out from under him when standing still.

<u>Omni Wheel/Swivel Wheel</u>

Seen in many competition-level robots and some forklifts, omnidirectional wheels (pictured below) offer just that--motion in every direction. Omni wheels and swivel wheels have that in common, where turning and rotating is smooth, as well as diagonal motion. This will move more naturally with Bodie's hind side, but this solution struggles to traverse uneven surfaces, and motion can be bumpy. And additional disadvantage is that omni wheels are generally more expensive--though the team was fortunate enough to receive a donation of 4 omni wheels early last quarter.

	Pros	**Cons**	**Average Cost**
2 Fixed Wheels	Traverses all terrains, good standing stability, cheap	Not made for turning, does not move naturally with body	$10 (available everywhere)
Single Wheel/Ball	More side-to-side freedom, easier turning, traverses all terrains	Relatively poor standing stability,	$20 (home depot, wheelbarrow wheels)
Omni Wheels/Swivel Wheels	Moves well in all directions, best for turning	Does not work well on uneven surfaces, motion can be bumpy	$30+ (vexrobotics.com) *team has wheels donated from

			colleague

Informational Resources
Keywords
- dog physiology, motion, walk
- omnidirectional wheels, omni wheel, advantages/disadvantages,
- dyson ball, technology, single wheel, wheelbarrow wheel/motion

Dog Physiology: https://www.chewy.com/petcentral/dog-physiology-how-dogs-move
Dyson Ball: https://www.dyson.com/cylinders/dyson-ball-technology.html
Wheelbarrow: https://sciencing.com/simple-machines-make-wheelbarrow-7420727.html
Omni Wheels: https://robohub.org/pros-and-cons-for-different-types-of-drive-selection/

D.4: Sit-Stand Mechanism

Functional Requirements:
Since our client and their problem exist beforehand, our canvas is not blank, and we must work to replicate the ideal situation, which would be a fresh pair of legs for Bodie. Therefore, the functional requirements would be for our design to replicate all actions that a dog's hind legs have biologically evolved to enable. Our design must allow Bodie to move forward at various paces, be able to transition himself from sitting to standing and vice versa, be able to lie down comfortably while in the wheelchair, and to have little to no turning radius.

Under the assumption that our design relies on wheels to support Bodie, more narrow function requirements would be for our design to be robust enough to deal with situations that wheels are notorious for having difficulty with, such as slopes, uneven terrain (grass, rocks), stairs & curbs, and even potentially shallow water.

The 3 main mechanisms that I consider that can achieve hind leg rotation are usage of an electric motor, usage of a cylinder or usage of cue-triggered transition mechanisms.

Motor
A torque motor would be mounted to the frame and would be connected to some mechanism that could fold/unfold the hind legs. One possible connection is to directly have the torque of the motor be applied to the hind leg joint, although this would have a large torque requirement. Another connection option would be with a ball screw assembly that converts rotational motor motion into the linear translation of a ball screw, which can be connected via linkages to the leg for folding/unfolding. This mechanism is inspired by the mechanical dog projects at Boston Dynamics and openDog, as it is the method of folding the mechanical leg itself.

Cylinder

A cylinder would be attached to the frame and would be functionally similar to the 2nd mentioned motor application: since a cylinder already executes linear translation, a linkage can be directly connected to it and to the frame leg, which would enable folding/unfolding via extension and contraction of the cylinder. The main issue with this is the size of cylinder and stroke needed, as their lengths would have to be comparable to the two other linkages in this assembly (the back leg and the connector linkage would each be around 17.78 cm (7 inches), which is not feasible for a small handheld cylinder). A difference between a cylinder and a motor is the discrepancy of gradation for motion: a ball screw assembly would have a spectrum of positions defined by the motor, whereas a cylinder would either be fully open or fully closed. Though this is usually an advantage of motors over cylinders, our application doesn't care as much for intermediate positions.

Cue-Triggered Transitions

This potential solution is inspired by the previous year's mechanism to enable Bodie to sit: by having him back up slightly, the rubber feet would catch the floor and pull the legs under him so he could sit. This clever solution's main drawback is the need for space around Bodie such that he can back up to sit and move forward to stand up. A similar principle with different mechanisms may be possible to enable his transition, such that electrical equipment and actuators can be avoided. For example, in training one's dog to sit, the cue is to hold a treat over his head, then move it behind him over his back; in an attempt to keep looking at the treat, the dog tilts their head up and their back down, which inevitably makes them sit. In our case, we could train Bodie to tilt his head back to trigger some mechanism that causes the legs to swing under him. Similarly, standing up from a seated position involves Bodie leaning forward and lowering his head, which can possibly be connected to a mechanism that lifts the back of the cart and thus unfolds the legs.

	Pros	**Cons**	**Estimated Cost**
Motor	● Compact enough to be mountable onto the frame ● Straightforward usage (no clever solutions required) ● Enables both standing and sitting transitions.	● Electrical equipment and support required ● Control mechanism is needed to operate the motor, which would either be Dr. Yu's responsibility or Bodie's.	DC motors with positional rotation control: $4.48 - $37.24 (in this narrow selection at DigiKey) (prices vary greatly based on motor's purpose)
Cylinder	● Adheres to our desires for an open and closed state ● Single-action cylinder used for unfolding legs can	● Electrical equipment and support required ● Typical cylinders are too large and heavy for our usage	Prices vary too greatly based on the purpose that each cylinder is designed for

	enable gravity to re-fold them rather than forced contraction	• The stroke we need is hard to be met by small cylinders • Cylinder has 2 states, we have potentially 3 (standing, sitting, lying down) each with different required linear positions	
Cue-Trigger Mechanism	• Lack of need for electrical equipment • Can potentially be more form-fitting and function-fitting to Bodie's movements than separately controlled components.	• Must devise a clever solution similar to the previous year's braking mechanism • Unless fine-tuned properly, can be subject to operational failure (Ex: if it doesn't activate upon Bodie's actions)	No defined mechanism to search for, therefore price is abstract.

Informational Resources
Keywords: dog leg free body diagram, small electric motor, small cylinder actuator, dog robot (Boston Dynamics), bulldog leg length, ball screw

openDog Dog Robot project:
https://www.youtube.com/watch?v=4j-diMsv5s4&index=2&list=PLpwJoq86vov_PkA0bla0eiUTsCAPi_mZf
DigiKey DC motors with positional rotation control:
https://www.digikey.com/products/en/motors-solenoids-driver-boards-modules/motors-ac-dc/178?FV=2dc1ffd%2Cffe000b2%2C1e1c000c&quantity=0&ColumnSort=1000011&page=1&pageSize=500
SMC Linear Actuators (Cylinders):
https://www.smcusa.com/products/actuators/linear-actuators~53351

D.5: Linear Actuators

Overview
In evaluating the risk of developing an electrical sit-stand system, linear actuators were researched along with relevant electrical components (power supply and operating switch) for

preliminary component analysis of the sit-stand mechanism. Actuators provide external force to drive the lowering and lifting motion. They vary in stroke lengths, supplied load, and configuration.

Functional Requirements

- Provide two-directional motion that lifts and lowers Bodie's rear.
- Support the wieght of Bodie's rear.
- Be safe and reliable.
- Be easy to operate.

Products Considered

Below details a brief summary of the types of components researched and considered before moving forward with the final linear-actuated sit-stand mechanims.

Linear Actuators	
• 12V mini rod actuator: ○ extendable rod ○ larger range of supplied force (max 200 lbs) ○ price: $109 	• Mini track actuator: ○ sliding notch ○ more compact ○ smaller range of supplied force (max 50 lbs) ○ price: $116 

12VDC Power Supplies	
• 12V, 5A batterpower supply: ○ 4lbs, 5A ○ dimensions: 3.5" x 2.7" x 4.0" ○ price: $40 	• 12V, 1A power supply: ○ 0.5lbs, 1A ○ dimensions 5.3" x 0.8" x 1.2" ○ price: $21.50 

DPDT Switches		
Foot switch  ● larger, easier target: 5.91" x 2.56" x 3.54" ● heavier (1lb)	Non-momentary rocker switch 10A  ● clear directionality ● requires more precision ● ON-OFF-ON	Non-momentary rocker switch 20A  ● ON-OFF-ON

Contacts: Frank, 1(800) 676-6123, Progressive Automotives

Appendix E: Designs Considered

- *Table that you referenced in the above comparison section*
- *Information / calculations and anything else used in other designs*

Appendix F: Equations and Formulas Used

Appendix G: Calculations

Appendix H: Project Management

Task Distribution

Ming Ming	Elias	Sherman	Aryan
Documentation, budgeting, competitor analysis, risk reduction efforts,	SolidWorks, prototyping, communicator between sponsor and	Project management, checking and updating progress	Scribe, primary communicator between sponsor and

hardware testing performance and analysis.	team, industry research, fabrication of parts.	with Gantt chart, fabrication of parts.	team, force analyses, fabrication of parts.

Risk Reduction Effort

List high risk issues identified and how risk was reduced

Intermediate Deadlines

Appendix I: Budget

This project was budgeted $2600, of which $1800 was allotted for machine shop resources. This left $800 for spending budget on design components for prototyping and final development.

Due to initial concern of rotational motors being expensive, the sponsor stated willingness to go over budget in favor of an electrical system. Linear actuators were discovered as a less expensive alternative which yielded significant savings in budget.

As of 3/1/19, the financial expenditures has been documented as follows:

	Total Spending Budget	$800.00	Amount Spent	$796.17	Amount Remaining	$3.83	Amount Refunded	$22.40					
Item N	Item	Quantity	Date of purchase	Buyer	Vendor	Order No. (Online)	Part No.	Total Spent	Other details/notes	Use	Reimbursed?	Returned?	Amount Refunded
0	eg. 8" PVC pipes	3	eg. 11/26	eg. Ming Ming	eg. McMaster		e.g 5546T104	eg. $3.57	eg. $1.19/pipe; came in packs of 4	Preliminary prototype frame	Yes/No	N/A, Needed, Re	
1	2' Aluminum T-Slot Frames	4	12/03/18	Elias Solorzano	McMaster-Carr		5537T101	$41.39	$8.03/frame	80/20 adjustable frame for preliminary prototype	No	N/A	
2	1" Corner Brace	4	12/03	Elias Solorzano	McMaster-Carr		5537T81	$29.05	$5.39/brace	Fasten bars together for frame	No	N/A	
3	C-Loop Connector	1	12/06	Elias Solorzano	McMaster-Carr		8863T56	$12.00	Package of 5	Make buckle part compatible with 80/20 protoytpe frame	No	N/A	
4	M5 Socket Head Screw - 35mm	1	12/06/2018	Sherman Yip	Home Depot		887480447989	$1.23	2 screws/packet	Thicker screws to fasten wheels to 80/20 frame	No	N/A	
5	M4 Socket Head Screw - 35mm	1	12/06/2018	Sherman Yip	Home Depot		887480446487	$0.91	2 screws/packet	Standard screws to fasten wheels to 80/20 frame	No	N/A	
6	M4 Socket Head Screw - 10mm	2	12/06/2018	Sherman Yip	Home Depot		887480032185	$1.24	2 screws/packet	Standard screws to fasten saddle to 80/20 frame	No	N/A	
7	M4 Socket Head Screw - 8mm	2	12/06/2018	Sherman Yip	Home Depot		887480445886	$1.56	2 screws/packet	Standard screws to fasten side cushioning to 80/20 frame	No	N/A	
8	Perforated Square Tube (Zinc-Galvanized Steel) - 6ft	1	1/23/19	Ming Ming	McMaster-Carr		6535K312	$31.33	0.105" wall thickness, 1" x 1", 6 ft long	Adjustable frame - 2nd working prototype	No	Needed	
9	Wire Lock Pins	2	1/26/19	MM	Home Depot			$6.40	$3.20/packet, 2 screws/packet	To show sponsor alternative solution for easy adjustable part fasteners	No	N/A	
10	#10-32 Socket Head Screws (1-1/8")	2	1/26/19	MM	Home Depot			$3.30	$1.65/packet, 2 screws/packet	Compatible with new alumnim frame	No	N/A	
11	#10-32 Socket Head Screws (1-1/4")	3	1/26/19	MM	Home Depot			$5.31	$1.77/packet, 2 screws/packet		No	N/A	
12	#10-32 Lock Nuts	2	1/26/19	MM	Home Depot			$2.36	$1.18/packet, 2 nuts/packet		No	N/A	
13	#10-32 Screw Nuts (pack of 12)	1	1/26/19	MM	Home Depot			$1.18	12 nuts in packet		No	N/A	
14	Mini Linear Actuator (12", 35lbs)	2	1/30/19	MM	Progressive Automations	#56978		$217.98	$108.99/actuator		No	Needed	
15	Power Supply (12VDC / 1A)	2	1/30/19	MM	Progressive Automations			$43.00	$21.50/power supply		No	Needed	
16	Mounting Bracket	4	1/30/19	MM	Progressive Automations			$34.00	$8.50/mount		No	N/A	
17	Aluminum Square Tubing (48"x3/4"x1/16")	1	1/24/2019	Sherman Yip	Home Depot		887480013177	$15.98		For perforated tubing prototype	No	N/A	
18	3" Non-marking Rubber Swivel Wheel	2	1/24/2019	Sherman Yip	Home Depot		#074523503133	$18.54	$9.27/wheel, 2 wheels	For front wheel testing (larger wheel)	No	N/A	
19	2" Non-marking Rubber Swivel Wheel	2	1/24/2019	Sherman Yip	Home Depot		#074523203125	$9.36	$4.68/wheel, 2 wheels	For front wheel testing (smaller wheel)	No	N/A	
20	3/8" Zinc Nylon Lock Nut	1	1/24/2019	Sherman Yip	Home Depot		887480115116	$1.18	$1.18/packet, 2 nuts/packet	For mounting front swivel wheels	No	N/A	
21	M4 Socket Head Screw - 8mm	3	1/30/2019	Sherman Yip	Home Depot		887480445886	$2.34	$0.78/packet, 2 screws/packet	Mounting gussets/corner brackets/front wheel struts to 80/20s	No	N/A	
22	M4 Socket Head Screw - 6mm	4	1/30/2019	Sherman Yip	Home Depot		887480445787	$3.00	$0.75/packet, 2 screws/packet	Mounting gussets/corner brackets/front wheel struts to 80/20s	No	N/A	
23	M4 Pan Head Machine Screw - 8mm	4	1/30/2019	Sherman Yip	Home Depot		887480428285	$2.80	$0.70/packet, 2 screws/packet	Mounting gussets/corner brackets/front wheel struts to 80/20s	No	N/A	
24	Gate Latch - Zinc	1	2/2/2019	Sherman Yip	Home Depot		#030699154616	$4.49		Harness lock prototyping	No	N/A	
25	Steel Square Tubing (36"x1/2"x1/16")	2	2/9/2019	Sherman Yip	Home Depot		887480012675	$11.70	$5.85/tube	Inner frame assembly	No	N/A	
26	Aluminum Round Tubing (36"x1/2"x"1/16")	2	2/9/2019	Sherman Yip	Home Depot		887480012477	$22.40	$11.20/tube	Consideration for inner frame assembly	No	Returned	$22.40
27	Carriage Bolt (3/8-16"x1-1/2") - Zinc Plated	2	2/10/2019	Sherman Yip	Home Depot		ANB	$0.75		Mounting caster wheels to angled struts	No	N/A	
28	Round Head Machine Screw (10-32x2")	2	2/23/2019	Sherman Yip	Home Depot		887480144512	$2.36	$1.18/packet, 2 screws/packet	Mounting brake lock assembly to outer frame	No	N/A	
29	M4 Pan Head Machine Screw - 80mm	2	2/23/2019	Sherman Yip	Home Depot		887480602883	$4.92	$2.46/screw	Screw through hinge point of sit-stand mechanism	No	N/A	
30	Flexi Classic Retractable Dog Leash - XS	1	2/19/2019	Sherman Yip	Unleashed by Petco		#002685795	$18.31		Inside retractable leash mechanism used for brake lock system	No	N/A	
31	Mini Linear Actuator (4", 150lbs)	2	2/13/2019	Elias Solorzano	Progressive Automations	#158249		$264.58	$108.99/actuator + $19.55 shipping				
32	M4 Tension Lock Nut	4	2/28/2019	Sherman Yip	Home Depot		887480102086	$3.62	$0.84/nut	Mounting and fixing brake lock stoppers	No	N/A	

Once the appropriate returns are made, this leaves approximately $300 (plus the sponsor's flexible budgetary range) for final components and updates.