Fall 2023

MEMS 411: Vehicle Entry Aid

Sara Wargo
Washington University in St. Louis

Joshua Doro
Washington University in St. Louis

Benjamin Swonger
Washington University in St. Louis

Justin Stohlman
Washington University in St. Louis

Washington University in St. Louis
JAMES MCKELVEY SCHOOL OF ENGINEERING

Mechanical Engineering Design Project
MEMS 411, Fall 2023

VEHICLE ENTRY AID

The client for this project has a prosthetic right leg, requiring him to carpool for daily activities. This disability also makes entering trucks and other large vehicles very challenging. Currently, the client carries a rigid, one-step step stool with a rope tied to it and uses the rope to lift the stool into the vehicle after he has sat down. The main issues are that the step stool is hard to carry and manage, and that there is no good place to hold onto when getting into the vehicle.

As a solution, the group collaborated to develop a step stool that would not only collapse into a compact position but also automatically retract up to the user. The step stool design included backpack straps as well to allow the client to have a free hand while walking around with his cane. Necessary design goals were for the steps to support a 235 lb man, retract between 1 to 3 seconds, and weigh no more than 10 lbs.

A 2-part telescoping handle extends with a spring in tension, and pins lock the handle in place. After pulling a bike brake, the pins retract, and the spring is released from tension, collapsing the handle up to the user. The steps then collapse due to gravity and retract with the handle. The steps were largely made out of aluminum, with a few exceptions. With all of the parts that were used for this final project, the steps totaled to about $114.

In the final testing of this mechanism, two of the three design goals were met. The first, supports the weight of a 235 lb individual, and the second, weighing under 10 lbs at 8.2 lbs. Unfortunately, as the final model was assembled, the spring mechanism became jammed, and the retracting feature for the third design goal was not successful.

DORO, Joshua
STOHLMAN, Justin
SWONGER, Benjamin
WARGO, Sara

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1 Introduction

According to the World Health Organization, an estimated 1.3 billion people experience a significant disability, classifying them as handicapped [1]. For those who are able to drive, they often have to limit their vehicle choice to one that fits their physical capabilities, otherwise, they have to pay a premium for accommodations such as ramps and steps. For handicapped individuals who are not capable of driving, such as our client, they will require support from those around them to transport from place to place. Our client has a prosthetic leg and lives alone. With this, he must reach out to friends and family for transportation, and occasionally, members of that support system travel in larger vehicles such as trucks or vehicles with a suspension lift. Those vehicles can be very challenging to climb into, so our goal is to design a system that may accommodate him for various vehicles across his support system.

Our client's current solution for getting into large vehicles is a plastic, single-step stool which he drilled a hole into and secured a rope through. He carries this stool out to the vehicle, places it on the ground, climbs into the vehicle, and then uses the rope to lift the stool into the vehicle where he holds onto it for the duration of the ride. In order to support our client, we aim to design a lightweight, two-step ladder that can collapse into a compact position for easy storage while traveling, lift simply into the vehicle for efficiency of use, and function as a backpack to free his hands when walking with a cane in one hand and other items such as groceries in the other.

While this mechanism is being designed specifically for our client, we hope that it may be beneficial for individuals across various disabilities and living situations. This struggle is common among individuals with diabetes, individuals recovering from knee surgery, and elderly people to name a few. Similar solutions currently exist, but they all lack some key factor, whether it be too heavy, too expensive, too big, or not having the ability to lift it into the vehicle without assistance from a second person. After interviewing our client, we have taken note of each downfall in these current solutions and will design a mechanism that can support the needs of various people.

2 Problem Understanding

2.1 Existing Devices

2.1.1 Existing Device #1: Powered RV Steps

Figure 1: Electric 2 Steps Entry Steps (Source: Lippert Tread-lite)

Link: https://www.camperid.com/lippert/lippert-tread-lite-entry-step-1690340481.html

Description: 2-step motorized stairs that provide safe and easy entrance into any RV. It boasts it is faster and sturdier than competing brands. Folds in underneath/behind the motor for easy storage and quick access. A non-slip coating has been applied to the steel steps to help with weight reduction and overall safety, supporting 400 pounds. LED lights have been added to the design for ease of access when no light is available.

2.1.2 Existing Device #2: Bee Neat 2-Steps Stool

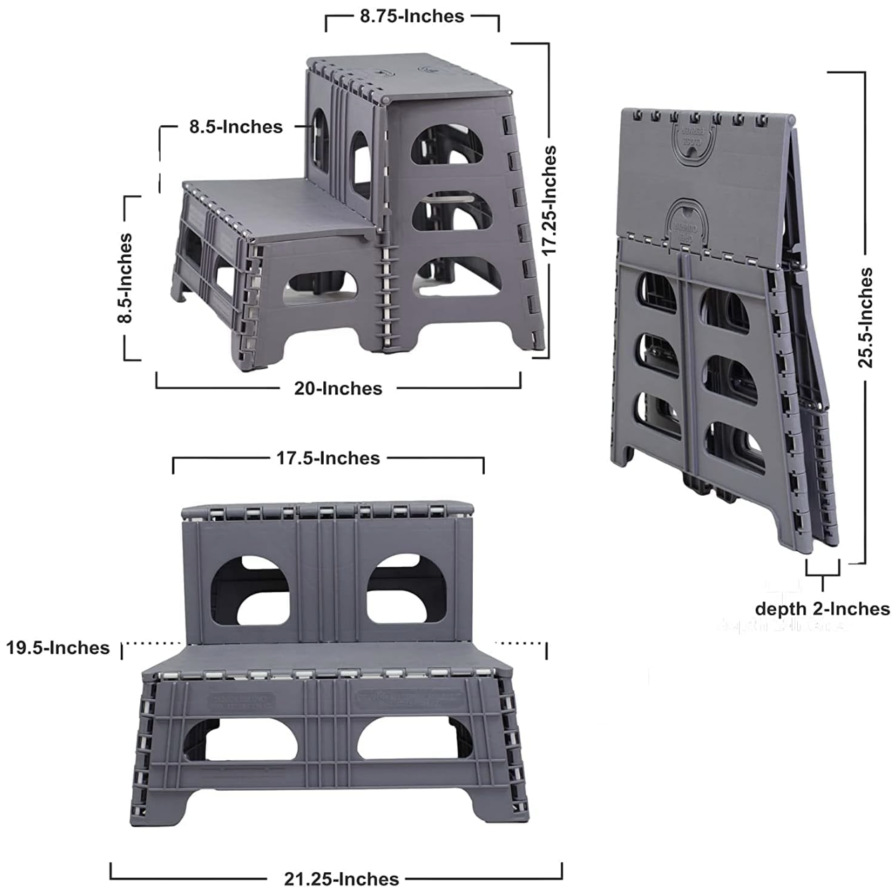

Figure 2: Bee Neat 2-Steps Stool (Source: Bee Neat)

Link: https://www.amazon.com/Folding-Portable-Steps-Medium-Doggies/dp/B08GNX74XF?ref_=ast_sto_dp
Description: Bee Neat 2-step stool is a lightweight, portable step stool supported at the joints with what seems to be steel/aluminum rods. While it is quite portable and easy to store/use with a single hand, it lacks weight capacity, maxing out at 200 pounds. It is quite practical to have two different steps that are at different heights, making its utility high. While this is aimed at dogs, its design can work for the average adult male.

2.1.3 Existing Device #3: Powered Running Rails

Figure 3: AMP Research Power Step (Source: AMP Research)

Link: https://realtruck.com/p/amp-research-power-step-xl/
Description: AMP Research running board runs 3 inches lower than the body to provide quick and easy entrance/exit from the high-up vehicle. It also offers a high ground clearance while retracted to protect itself. It is ergonomically designed to be non-slip, with LED lights for ease at night and a wide build of 6 inches for stability. It has an incredibly high load tolerance of 600 pounds. It has a relatively quick extension/retraction time of 3 seconds.

2.2 Patents

2.2.1 Compact Collapsible Step Ladder (US 2009/0294214 A1)

This patent uses possible combinations of components we may need to use in the step we create. This design protects a step ladder that uses pegs to hold legs together, with steps on one side and a platform on top. Combining horizontal and parallel connections, a very strong base foundation is made. Due to the pegs/pins holding things in place, it is easy to move them, fold, and store this ladder.

US006347687B1

(12) **United States Patent**
Alim

(10) **Patent No.: US 6,347,687 B1**
(45) **Date of Patent: Feb. 19, 2002**

(54) **COMPACT COLLAPSIBLE STEP LADDER**

(75) Inventor: **Prakasa Alim**, Surabaya (ID)

(73) Assignee: **PT Indal Aluminum Industry TBK.**, Gedangan (ID)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **09/398,124**

(22) Filed: **Sep. 16, 1999**

(51) **Int. Cl.**[7] **E06C 1/00**
(52) **U.S. Cl.** **182/161**; 182/159
(58) **Field of Search** 182/156, 159, 182/161, 163, 165, 228.1, 228.6; 403/102, 119; 16/335, 355; D25/64

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Primary Examiner—Daniel P. Stodola
Assistant Examiner—Hugh B. Thompson
(74) *Attorney, Agent, or Firm*—Banner & Witcoff, Ltd.

(57) **ABSTRACT**

A novel compact collapsible step ladder that can be efficiently, easily and practically stored in space limited locations or areas when not in use. The compact collapsible step ladder when folded, and not in use, is no thicker that the combined thickness of its adjacent and substantially parallel front and rear ladder legs. The collapsible step ladder comprises a pair of pivotally connected ladder legs, a pivoting step with rear opposing pegs engaging rear ladder channel guides, and at least one ladder pivoting rung connected to the step through connecting rods. The connecting rods synchronize the movement of the pivoting step and the at least one pivoting rung as the ladder assumes the open and closed positions. In the ladder open position, the step and at least one ladder rung assume substantially horizontal orientations. In the ladder closed position the step and the at least one ladder rung are substantially parallel to the ladder legs.

23 Claims, 9 Drawing Sheets

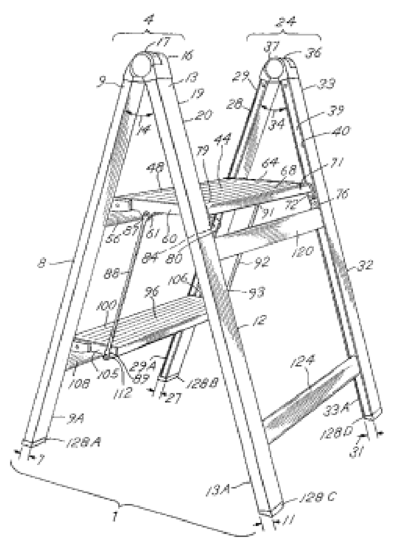

Figure 4: Patent for collapsible step ladders

2.2.2 Folding Step Stool (US 6,347,687 B1)

This patent protects step stools with a handle attached at a pivot point. Slots form through the step for the handle to go into. The handle is a U-shape with a comfortable yet reliable grip on top. The legs on the bottom of the platform fold into the base. Leading to a safe and compact step stool.

US 20090294214A1

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(12) **Patent Application Publication** (10) **Pub. No.: US 2009/0294214 A1**
Vosbikian et al. (43) **Pub. Date: Dec. 3, 2009**

(54) **FOLDING STEP STOOL**

(75) Inventors: **Peter S. Vosbikian**, Moorestown, NJ (US); **Jace Weaver**, Gilbertsville, PA (US); **Vince Cella**, Medford, NJ (US)

Correspondence Address:
WILDMAN HARROLD ALLEN & DIXON LLP
225 WEST WACKER DRIVE, SUITE 2800
CHICAGO, IL 60606 (US)

(73) Assignee: **QUICKIE MANUFACTURING CORPORATION**, Cinnaminson, NJ (US)

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Related U.S. Application Data

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Publication Classification

(51) **Int. Cl.**
A47C 12/00 (2006.01)

(52) **U.S. Cl.** **182/129**

(57) **ABSTRACT**

A step stool having a step and a handle pivotably connected to the step. The step has a top surface and a wall extending therefrom, the top surface and the wall defining a cavity. A pair of slots is formed through the step, each slot extending from a first end formed through the top surface to a second end formed through the wall. The handle is generally U-shaped and has a pair of arms, a middle section connected between the pair of arms, a first leg extending from an end of one of the pair of arms, and a second leg extending from an end of the other of the pair of arms. Each arm extends through one of the pair of slots formed in the step.

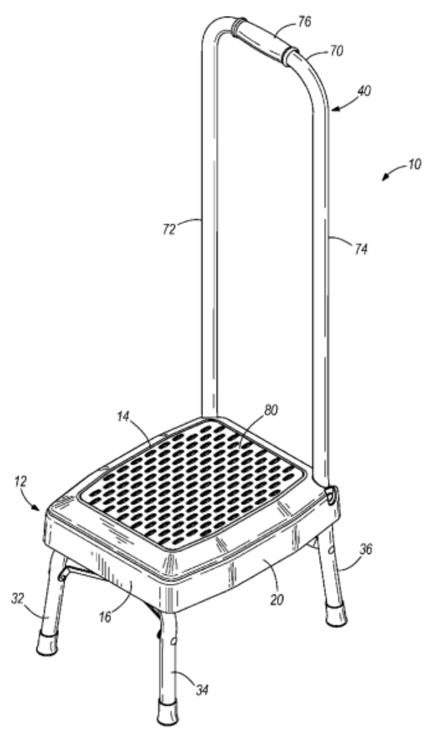


Figure 5: Patent for a folding step stool

2.3 Codes & Standards

2.3.1 Ladders - American National Standard for Ladders (ANSI-ASC® A14.2-2017)

This American standard covers a wide array of stools, ladders, steps, portable extensions, etc. This standard covers the duty rating of metal ladders, e.g., how many pounds the ladder can withstand before failing. While this standard does not cover special-purpose ladders, it is important as it ensures the standard step-ladder/step-stool we make is not overloaded and thus safe.

2.3.2 Building Code: - International(IBC) International Building Code (IBC))

This international code sets regulations. This includes things like steps, ramps, and handrails. All regulations are set to a specific set of dimensions/code construction must fall under. The design of our step-stool/step-ladder will most notably be used when we make the multi-tier base and handrail. This will be important for ergonomics and safety.

2.4 User Needs

The interviewee is Mark Wargo, Sara Wargo's Uncle. He has a prosthetic leg and is currently using a plastic step stool and rope to get into the truck. He puts the rope through the handle in the truck, uses the step stool to step up, and then uses the rope to pull it up and bring it into the truck. He has multiple people drive him around, and they all have differently-sized vehicles. Our goal is to design a step stool that makes it easier for him to get into trucks and other large vehicles while also being easier to carry around.

2.4.1 Customer Interview

Interviewee: Mark Wargo
Location: Zoom
Date: September 8^{th}, 2023
Setting: The four interviewees met in a conference room at the Danforth University Center and used Zoom to meet with the client. Both sides could see one another and hear one another. We discussed his needs, and he showed us his current system for getting into the truck. The meeting took around 30 minutes.

Interview Notes:
Would attaching the stool to your cane be okay for you?

- The interviewee did not like the idea of attaching anything to his cane for transport. He feels it would make the cane off-balanced.

What is a good weight for the stool?

- The interviewee said it just has to support his weight as he gets into the truck.

Can the stool be transported like a backpack (straps to back)?

- The interviewee liked the idea of a step stool that can fit into a backpack or be backpack-like (have straps to go on his back like a backpack) very much.

Can we see the current stool and rope you are using?

- The interviewee showed a basic, plastic one-step step stool with a rope tied to a handle in the middle of it.

What are some features you would like to see?

- The interviewee said he would like to see the stool have a surface with a grip to prevent slipping.
- The interviewee said he would like to have a handrail so that he does not have to stretch for the roof handle to get into the truck (shared a story about a relative of his ripping one out of the roof by using a roof handle in a truck too heavily).

How many steps would be best?

- The interviewee stated two steps would be best, but one is still okay.

What are your feelings on electrical options vs. mechanical?

- The interviewee prefers mechanical solutions over electrical solutions. Making it simple and mechanical seems to be his preference (don't over-engineer it).

Is a ramp or stool better?

- The interviewee described that since his prosthetic leg is rigid, it is hard to go up a ramp with it, and thus steps are better.

How high does the stool need to be?

- The interviewee noted that the stool should be tall enough to get into a tall truck (the current stool appears to be around a foot tall).

Would you feel comfortable pulling the step stool up and into the truck?

- The interviewee said he would be comfortable pulling it up and into the truck.

2.4.2 Interpreted User Needs

Table 1 lists what the client needs from the designed device. Each need is listed in the center column, and the weight of importance is listed to the right of each need. The importance rating is based on a scale from 1 to 5, with a rating of 1 having little importance and a rating of 5 being a requirement.

Table 1: Interpreted Customer Needs

Need Number	Need	Importance
1	The step stool is lightweight	5
2	The step stool has straps for carrying on back	3
3	The step stool collapses easily	5
4	The step stool is compact when folded	4
5	The step stool has grips for foot traction	3
6	The step stool can hold a lot of weight	5
7	The step stool has two steps	4
8	The step stool has a handrail	3
9	The step stool can be lifted into the vehicle without a second person	5
10	The step stool is durable/can be used outside and lasts under normal wear and tear	4

As indicated by the table, there are four needs that have a score of 5, making them an absolute for the project design. Each of those needs was discussed as a matter of ease of use for the client, allowing him to easily transport the device without requiring further help from the person giving him a ride. While those four needs are of the utmost importance, all other needs are still essential to consider when generating the final design.

2.5 Design Metrics

Looking at the list of user needs for the product in Table 1 above, a plan needs to be made for what specifications to measure to see if a design meets the customer's needs. Table 2 breaks down the needs into specific specifications, associating the specifications with the needs in Table 1 and listing what an acceptable and ideal value is.

Table 2: Target Specifications

Metric Number	Associated Needs	Metric	Units	Acceptable	Ideal
1	1,9	Total weight	lb	10	5
2	3,4	Total volume folded	in^3	< 1200	< 540
3	3,4	Largest area folded	in^2	< 240	< 180
4	5	Grip level of steps	μ(no units)	≥ 0.25	≥ 1.25
5	6	Supporting weight load	lb	> 300	> 500
6	7	Number of steps	integer	1	2
7	9	Max expanded height	ft	4	6
8	10	Waterproof	IPX Rating	IPX4	IPX6
9	10	Electrical rating (If motorized)	IP Rating	IP64	IPX68

2.6 Project Management

The Gantt chart in Figure 6 gives an overview of the project schedule.

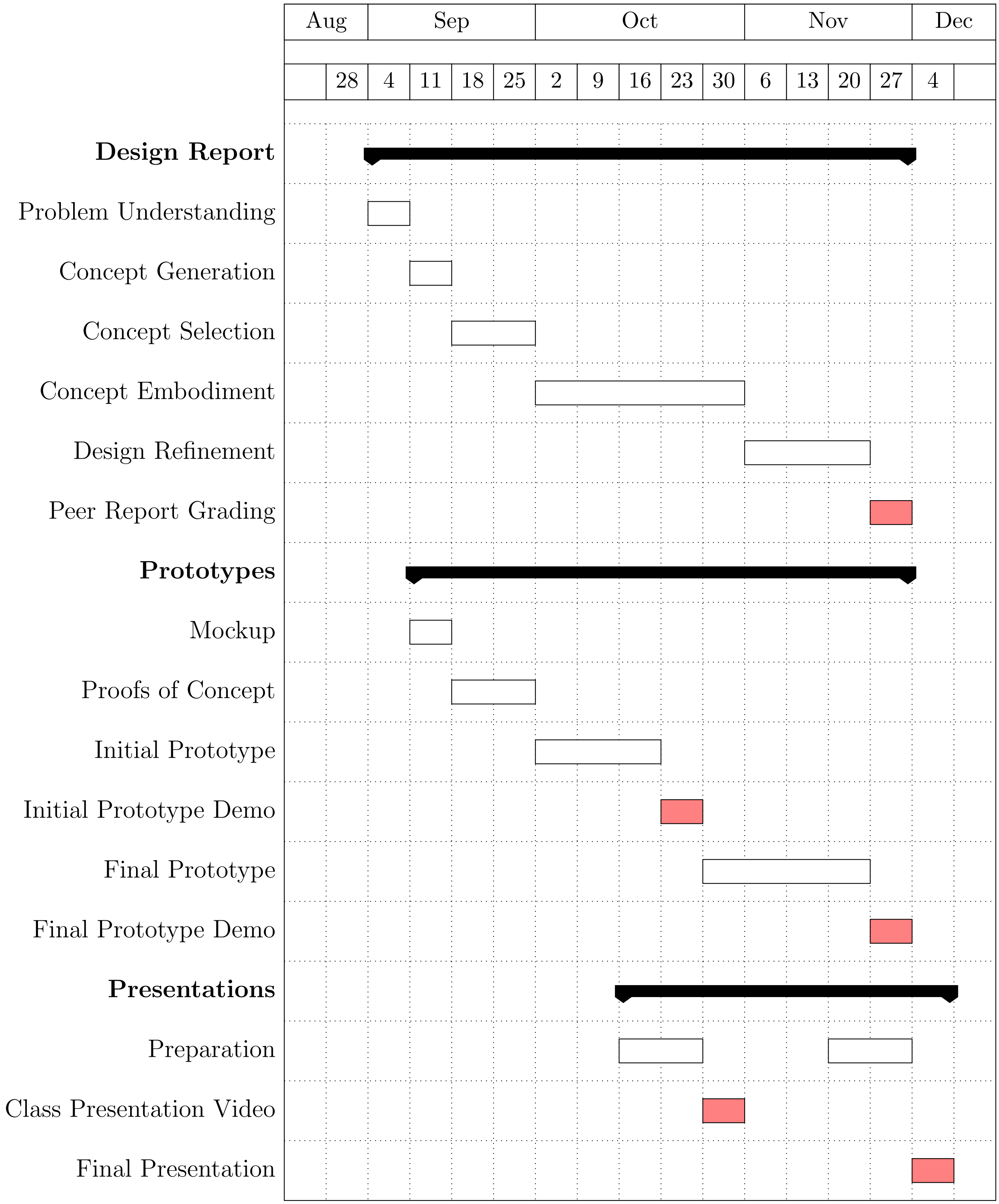


Figure 6: Gantt chart for design project

3 Concept Generation

3.1 Mockup Prototype

To begin creating a mock up prototype, we decided to keep it purely mechanical to maximize our time. We also were given a time limit of around 1-2 hours to create the prototype, meaning we had to keep it simple. We cut up a cardboard box and began taping three rectangular pieces (around 18 in. by 12 in.) together to create the steps. After creating some legs (folding cardboard into rectangular tubes), we realized it would not be tall enough and made the legs longer (around 12 ft.). We then adjusted the distance between steps from 12 in. to 6 in. to make it easier to step up. We used the material we cut out (from the 12 in. to 6 in. portion) to make the legs for the bottom of the step (6 in. long). To make it foldable, we used tape to make mock hinges for the legs. We realized the legs needed a standoff to clear the steps when folded, so we folded some cardboard and taped it to where the legs attached to give them some gap room. We also had to offset the legs on the front and back of the steps so they did not hit one another when they folded in. We also realized it was unstable with the hinges folding down and into the step, so we flipped it around so the legs folded up and on top of the step when folding it up. We also added an additional flap under the vertical portion where the two steps meet for extra stability. We made a basic handrail to see that it needs to be at least 3 ft. tall, preferably 4-6 ft. tall. Sitting on a high chair simulated sitting in the truck, and we tried pulling it up. We realized we needed some mechanism to fold it up better as it is lifted, and this became a main focus of discussion for future designs (motorized vs. mechanical solutions). The mockup prototype is shown in Fig. 7.

Figure 7: Photo of the mockup prototype created. Benjamin is shown holding the handle while on a high chair, simulating how it would be inside a truck.

3.2 Functional Decomposition

Function tree 8 shows the requirements for the step stool's design. The sub-functions fit the customer's needs and leaves room for expansion/improvement.

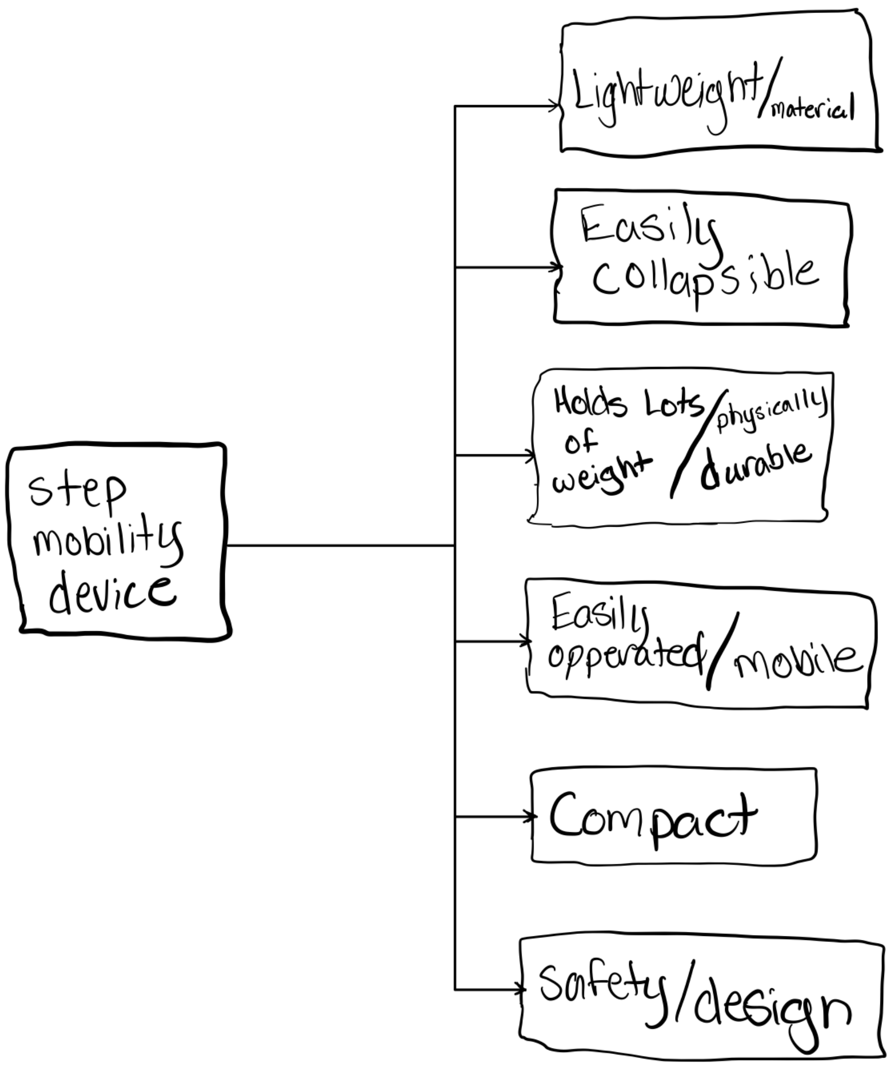


Figure 8: Function tree for a mobile step stool/step ladder, hand-drawn and scanned

3.3 Morphological Chart

This morphological chart focused on the clients main issues. The issues presented are as follows: a carrying feature, foot traction, a handrail for stability, a retracting mechanism, and a compact design for transportation in a large vehicle. This was created with the fact the client has a prosthetic leg. The morphological chart is shown in Fig. 9

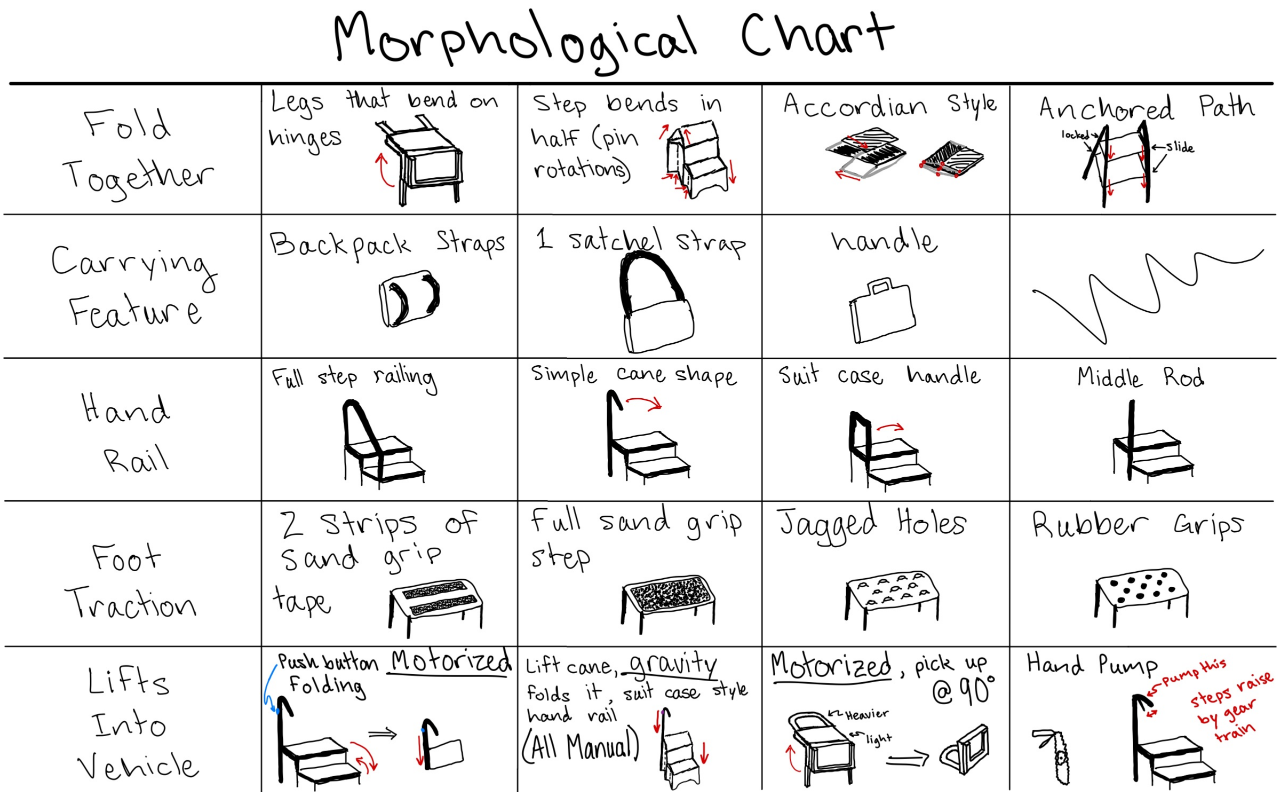


Figure 9: Morphological Chart for Mobile Step-stool

3.4 Alternative Design Concepts

3.4.1 Concept #1: Motorized Folding

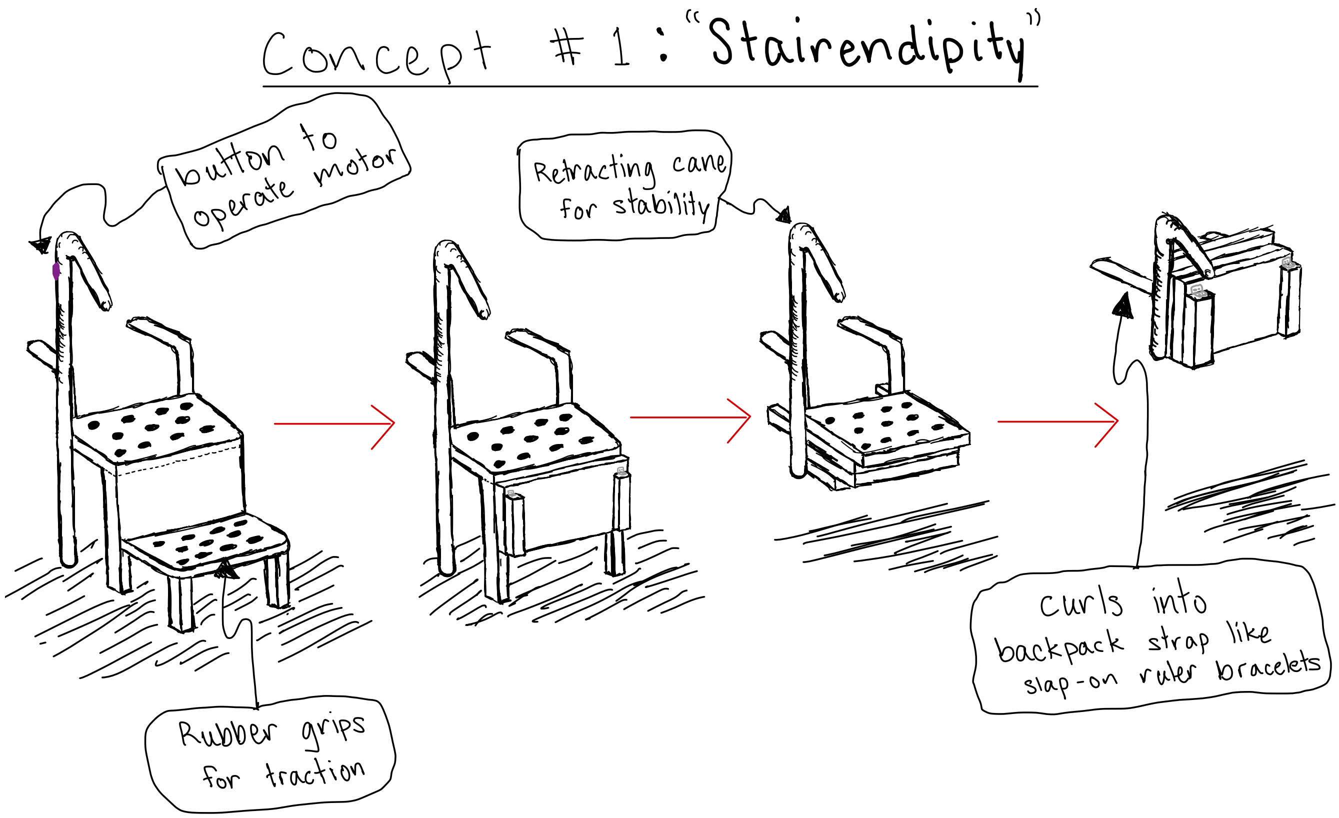


Figure 10: Sketches of Motorized Folding concept

<u>Description</u>: A microcontroller moves different motors and is triggered by a button on the back side of the support rail. While the user is sitting in the vehicle and holding the handrail, the button can be pushed to the "on" position. At this time, the steps begin folding while the handrail simultaneously retracts towards the user. Once the user is ready to exit the vehicle, they can hold the compact steps out and push the button again to return the steps to the climbing position. Layered, flexible stainless steel straps sealed within silicone are used to balance the steps on the vehicle. When the steps are compact, the straps may be bent around the shoulders to function as a backpack.

3.4.2 Concept #2: Lever Folding

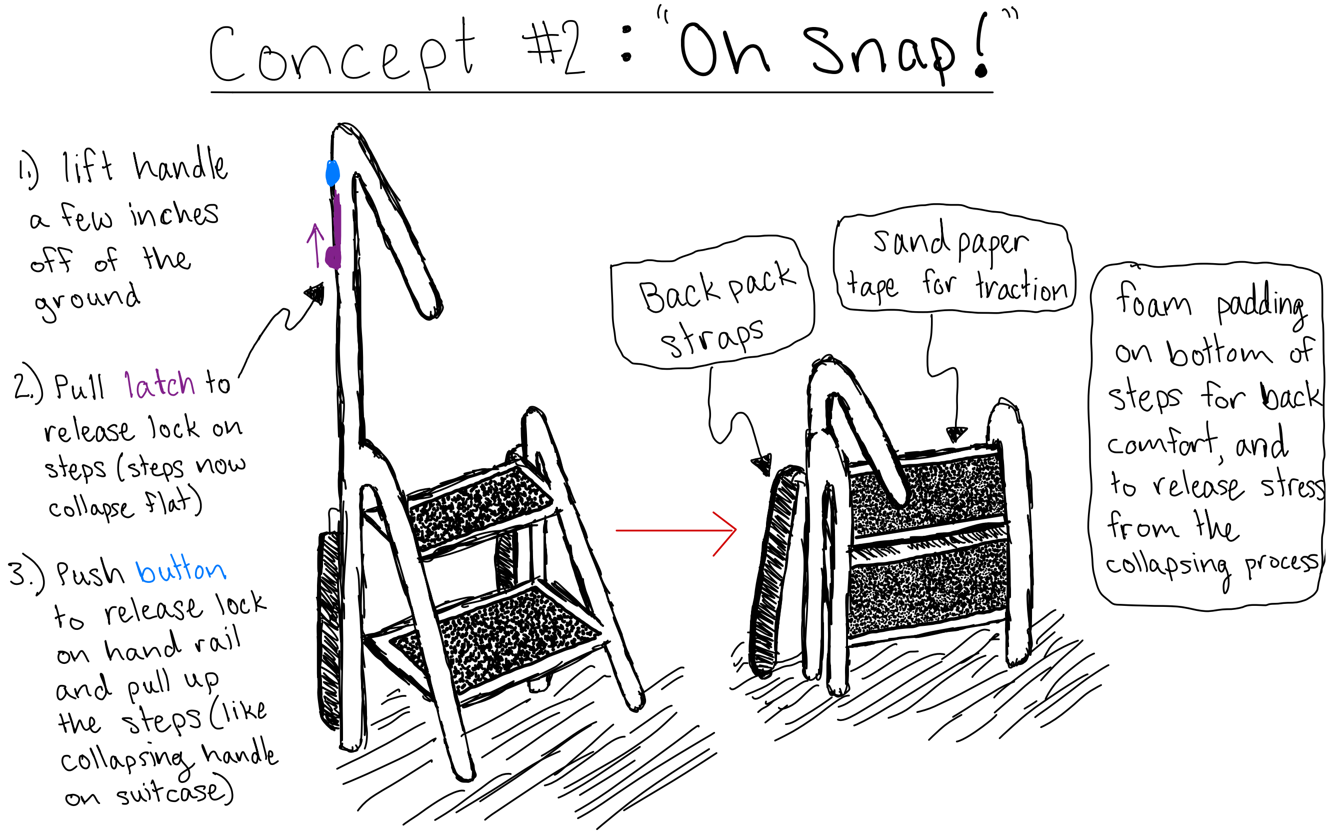


Figure 11: Sketches of Lever Folding concept

Description: A lever on the back of the handrail connects to the front end of the steps. When the lever is pulled up, the steps fold into a flat position. The handrail then functions like a suitcase handle by which a button can be pushed to unlock it. From here the user may pull the steps up the handrail into a compact, retracted position. Backpack straps are available on the back of the steps for traveling.

3.4.3 Concept #3: Vehicle Support

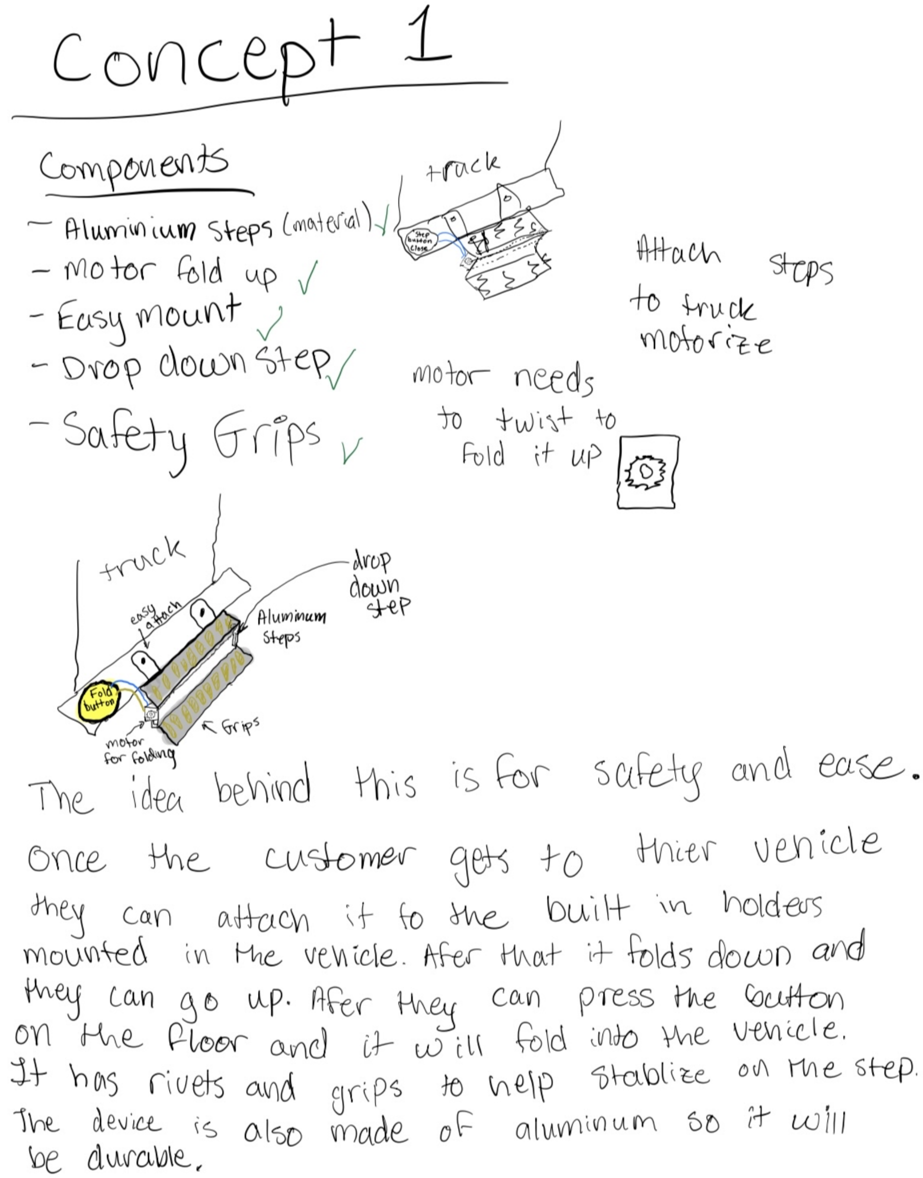


Figure 12: Sketches of Vehicle Support concept

Description: Supports on the vehicle are used to secure the steps. When locked in place, the user can walk up the steps, then activate a motor to retract the steps inside the vehicle. The user would not need to bend over to move the steps or lift them at anytime during the traveling process. Once the user has exited the vehicle, they may detach the steps and carry them back inside their home.

3.4.4 Concept #4: String Mechanism Folding

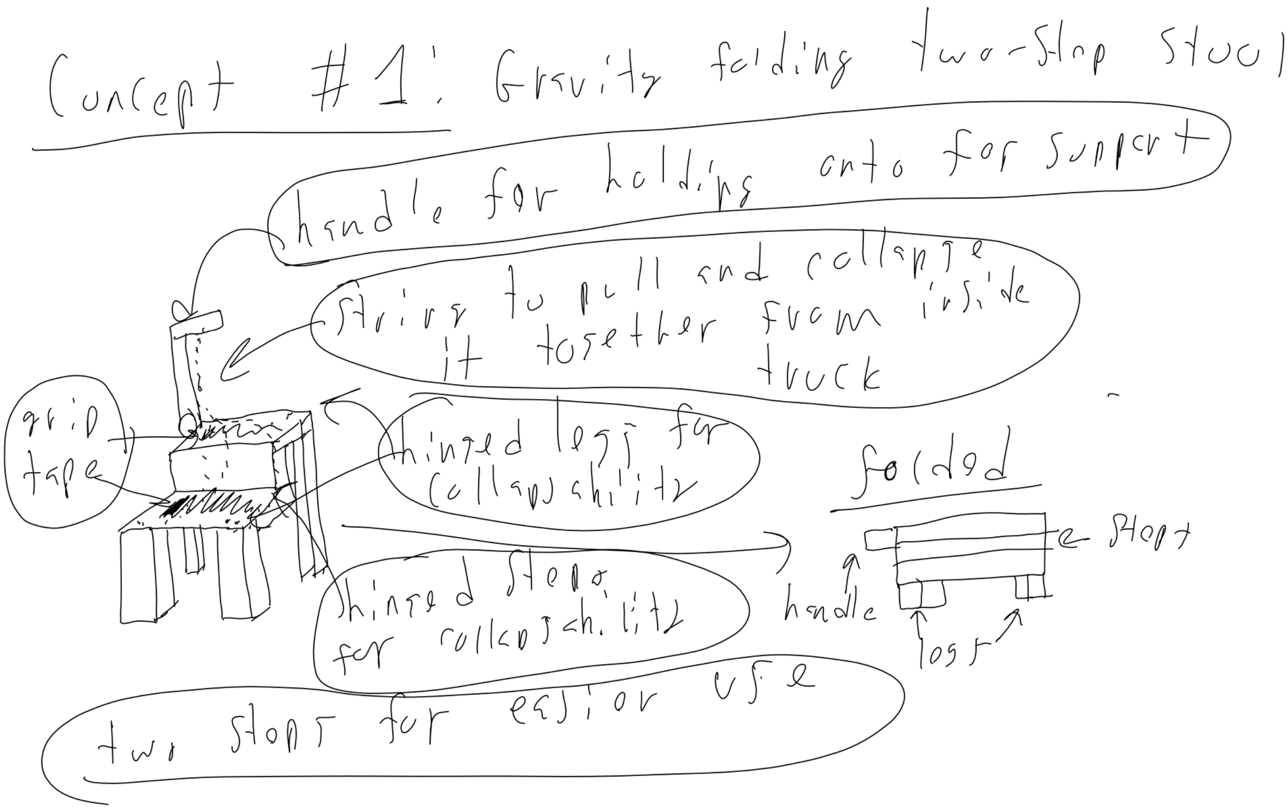


Figure 13: Sketches of String Mechanism Folding concept

Description: A rope travels from the top of the handle to each of the steps, and when pulled, the steps will collapse. The steps and legs are all connected by hinges for easy, durable folding. Once the user has pulled the rope, they may easily lift the steps inside the vehicle. Grip tape is applied to the steps to provide better traction for the user, and a handle is available for further support.

4 Concept Selection

4.1 Selection Criteria

The Analytic Hierarchy Process (AHP) is a simple scoring method to determine the weighted percentage of importance for design aspects of the step stool/step ladder. Figure 14 includes design constraints for user needs, such as the stool having foot traction, Weight support, and weight support. Most importantly, it also needs to be easy to operate. As shown, the "Foot Traction" category is a very low percentage and shouldn't be taken into account as heavily as something like "Weight Support(Handrail)" or Rows 3-4 of Figure 14 (Easily operated) when designing.

	Weight Support(Hand rail)	Portability	Easily set up	Easily Retractable	Foot Traction		Row Total	Weight Value	Weight (%)
Weight Support(Hand rail)	1.00	3.00	0.33	0.33	3.00		7.67	0.25	25.27
Portablity	0.33	1.00	1.00	1.00	1.00		4.33	0.14	14.29
Easily set up	3.00	1.00	1.00	1.00	1.00		7.00	0.23	23.08
Easily Retractable	3.00	1.00	1.00	1.00	1.00		7.00	0.23	23.08
Foot Traction	0.33	1.00	1.00	1.00	1.00		4.33	0.14	14.29
						Column Total:	**30.33**	**1.00**	**100.00**

Figure 14: Analytic Hierarchy Process (AHP) to determine scoring matrix weights

4.2 Concept Evaluation

The weighted scoring matrix shown in Fig. 15 displays four alternative concepts and compares them to each other based on five different criteria. The chosen criterion was weight support, portability, easy setup, easy retraction, and foot traction. Based on these five subjects, Concept #2 had the best overall score. With this, the general idea of Concept #2 will likely be used going forward. Modifications will be made based on future calculations and any issues the team encounters through experimentation.

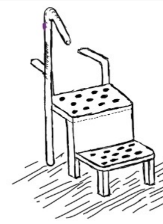
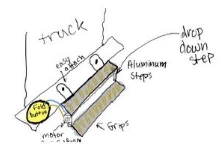
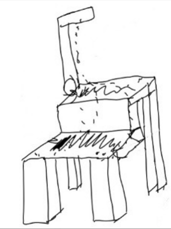
Alternative Design Concepts		**Concept #1**		**Concept #2**		**Concept #3**		**Concept #4**	
									
Selection Criterion	**Weight (%)**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**	**Rating**	**Weighted**
Weight Support (Hand rail)	20.00	4	0.80	5	1.00	0	0.00	4	0.80
Portability	15.00	3	0.45	5	0.75	1	0.15	1	0.15
Easily set up	25.00	5	1.25	4	1.00	2	0.50	4	1.00
Easily Retractable	25.00	5	1.25	3	0.75	5	1.25	3	0.75
Foot Traction	15.00	3	0.45	5	0.75	5	0.75	5	0.75
	Total score	**4.200**		**4.250**		**2.650**		**3.450**	
	Rank	**2**		**1**		**4**		**3**	

Figure 15: Weighted Scoring Matrix (WSM) for choosing between alternative concepts

4.3 Evaluation Results

The best result given by the weighted scoring matrix (concept 2) aligns with what we already believed to be the best design. This design offers the same foot traction as the others (since they all have 4 feet of the same area), yet it is able to fold up smaller than the others (more portable) since the steps fold into one another. It also has the highest handle (best handrail) out of all the designs. While not the easiest to set up, it is still very easy to set up, for it just folds up (like a suitcase handle) and then out (like most ladders). It retracts by pressing a button on the handle, which allows the extended springs in the frame to retract and pull the step stool back to its folded form. Overall, this one is the best for the criteria we are looking for and also adheres to the client's preference for a mechanical solution (instead of electric) while also being easy to fold up from within the truck.

4.4 Engineering Models/Relationships

Hooke's Law 1 shows the relationship between the force required to stretch an object and that object's extension for small distances.

$$F = -k * \Delta x \tag{1}$$

Where $F[N]$ is the force from the spring, $k[\frac{N}{m}]$ is the spring constant, and $\Delta x[m]$ is the change in displacement.

Equation 1 applies to the step stool/step ladder in reference to the spring that will be built in. The idea is to use a spring to help the steps fold up(compact form). This will only be possible if the correct spring constant(k) is selected. If the k value is too high, the steps will compress at a dangerous speed; if the k value is too low, the steps will fail to fold up with spring assistance, making ease of use (easy setup) very difficult.

Newton's second law of motion as shown in Eq. 2 gives the relationship between the customer's weight and the stool.

$$F = m * g \tag{2}$$

Where $F[N]$ is the force from the customer, $m[kg]$ is the mass of the customer, and $g[\frac{m}{s^2}]$ is the acceleration due to gravity.

we are neglecting the weight of the step stool itself in Eq. 2 as we are only concerned with the amount of force the customer applies to the stool. The stool should be able to fully support the much more than just the force of the customer as the customer's weight will be shifting over time. Otherwise, the stool will be open to failure as the customer steps up and down. Each step should fully support the entire weight of the customer.

Equation 3 shows how much the support handle will deflect under the customer's weight.

$$\delta_{max} = e[sec(\frac{KL}{2r}\sqrt{\frac{P}{AE}} - 1)] \tag{3}$$

$\delta_{max}[mm]$ is the deflection of the handle/beam, e is the eccentricity, K is the theoretical effective length factor, $L[m]$ is the unsupported length of the column, $r[m]$ is the radius of gyration, $P[N]$ is the force applied to the pillar/handle, $A[cm^2]$ is the cross sectional area, and $E[\frac{kg}{cm^2}]$ is the elastic modulus.

It is possible we can assume the support to be inline with the pillar's center, which would simplify this equation. However, not knowing how the customer will want to support himself, it is assumed that his force will be an eccentric load. The support is pinned/fixed at one end while free at the other. Finding the max deflection will help in finding a suitable material that is stiff enough to support the required load as well as if the design will work.

5 Concept Embodiment

5.1 Initial Embodiment

Below are three different drawings of a preliminary concept of our design in SolidWorks. The first drawing shows the dimensions of the fully expanded model, the second drawing provides an enlarged 3-D view, and the third drawing gives an exploded view with a bill of materials. It should be noted that, as this is a preliminary model, the spring system is not drawn in the assembly. This system will run through the tall handle which is designed to be triple telescoping for ultimate compactness. A button will be located on the back of the handle (item no. 12) which, when pushed, will release the springs from tension, causing the model to collapse upward towards the handle.

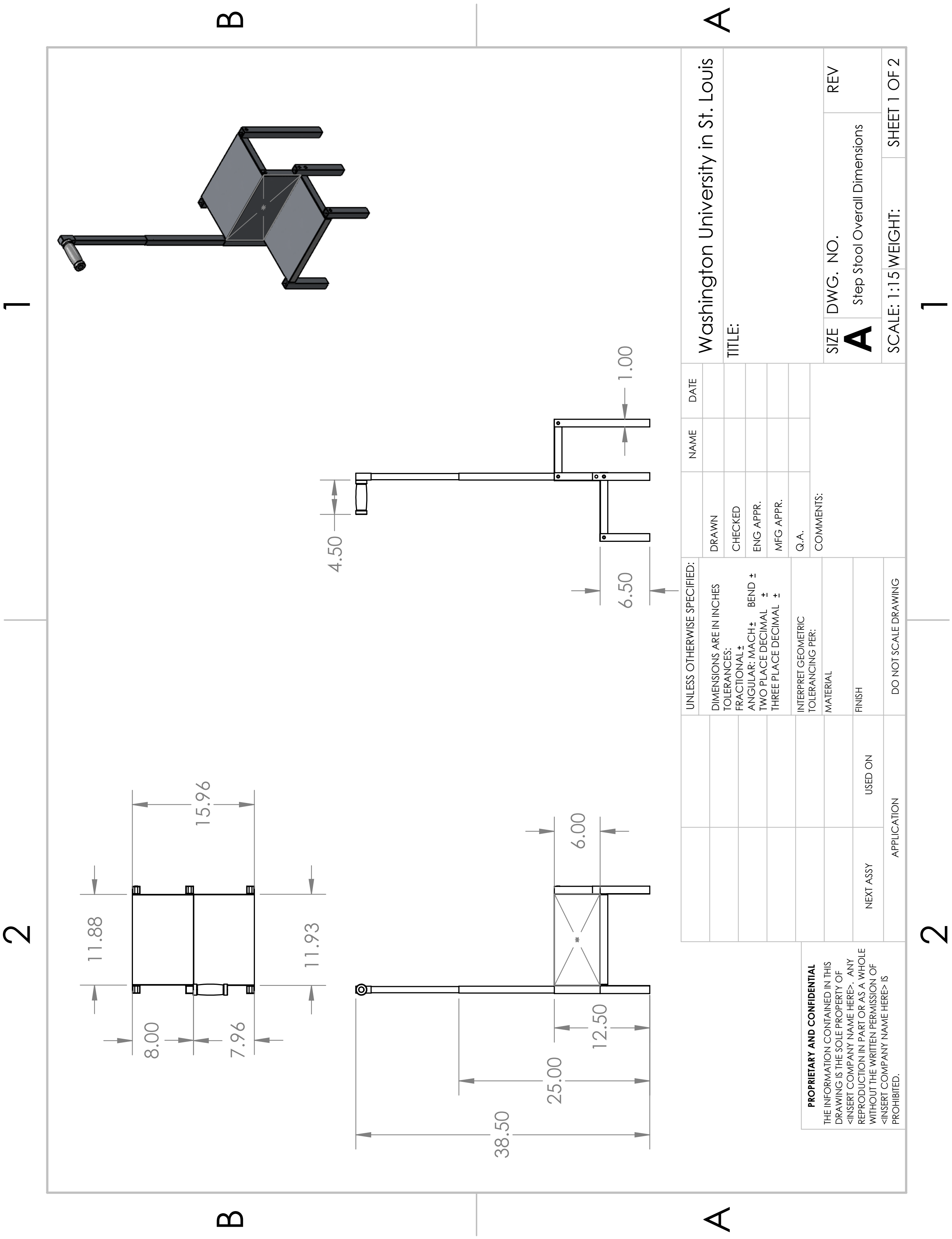


Figure 16: Assembled projected views with overall dimensions

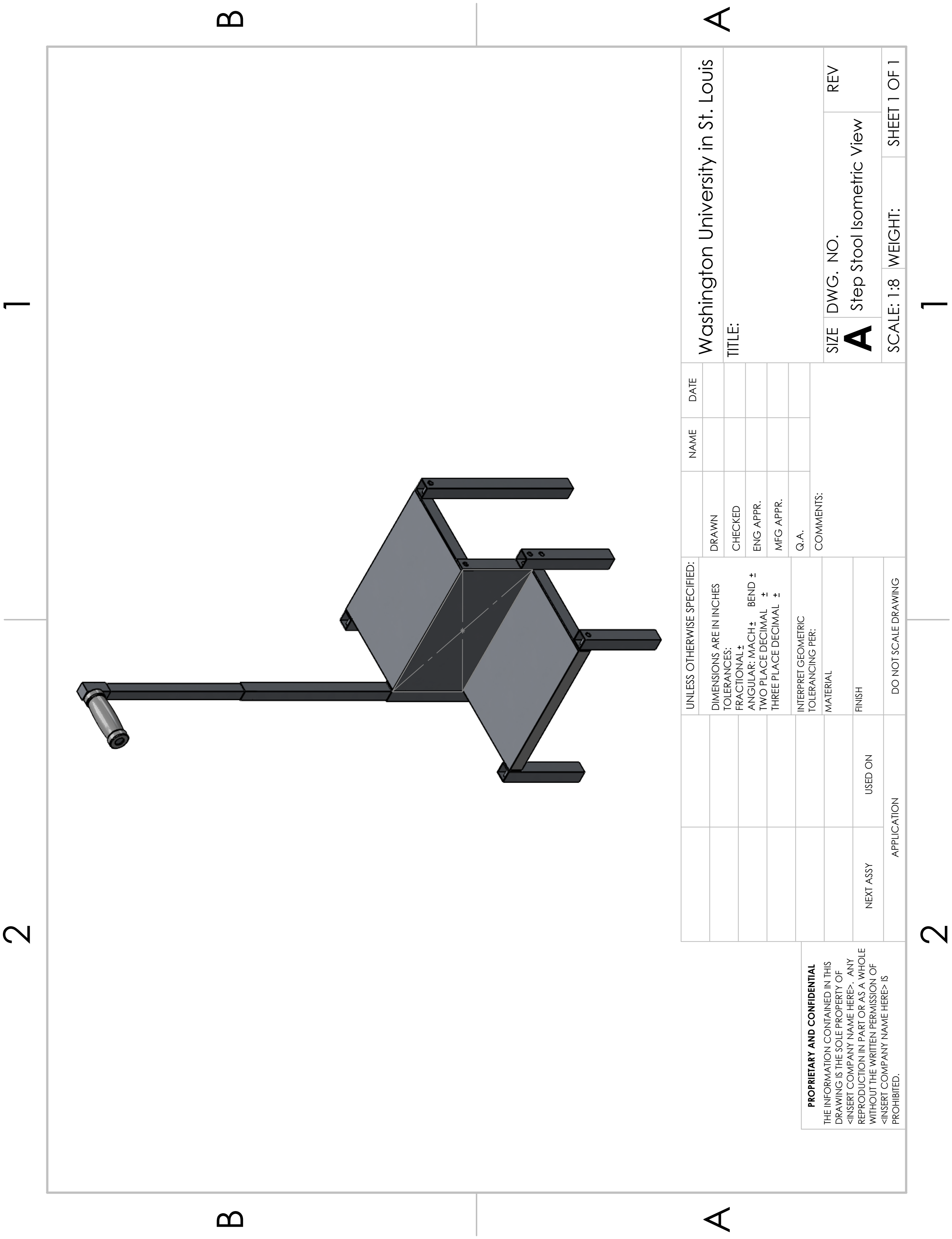
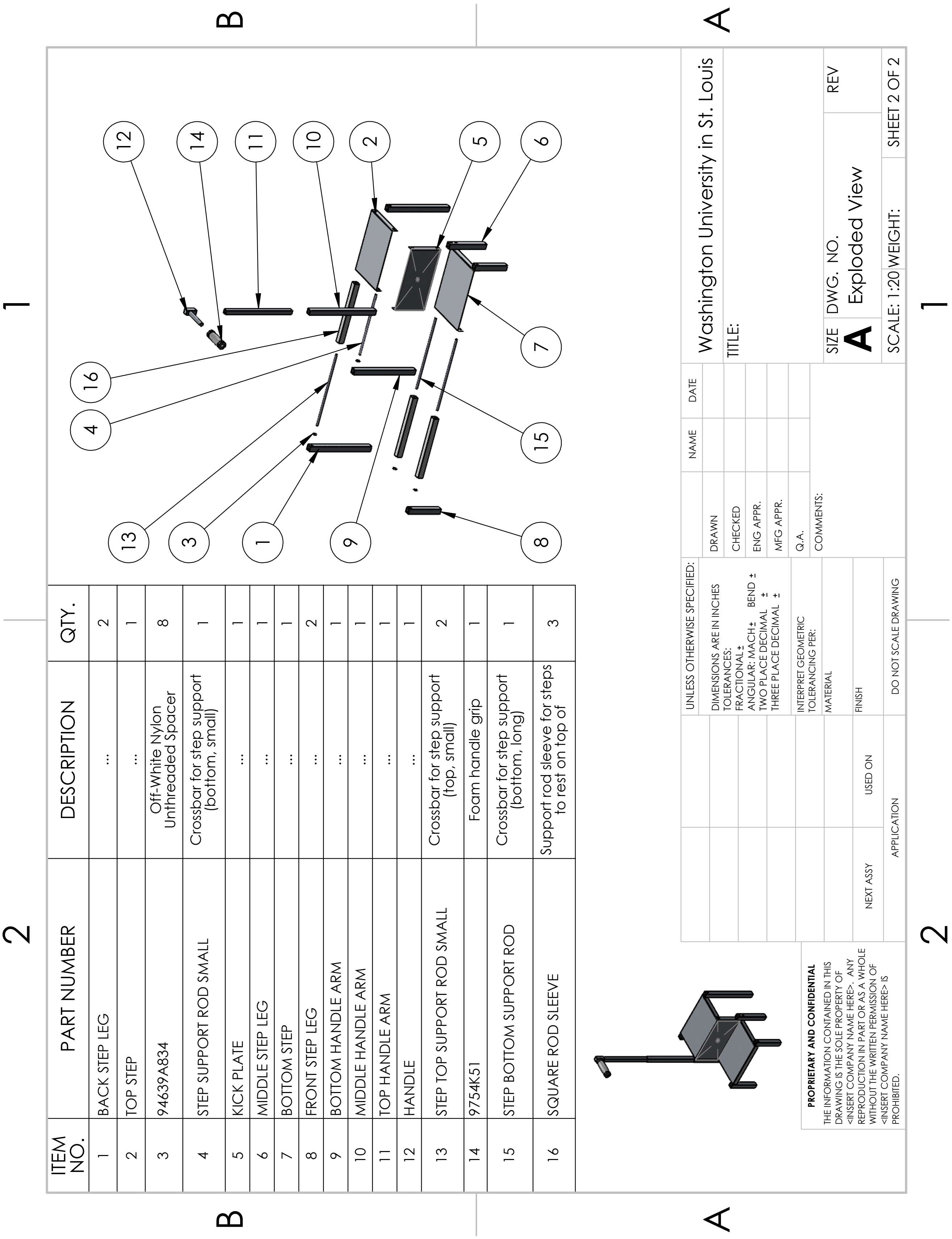


Figure 17: Assembled isometric view with bill of materials (BOM)



ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	BACK STEP LEG	...	2
2	TOP STEP	...	1
3	94639A834	Off-White Nylon Unthreaded Spacer	8
4	STEP SUPPORT ROD SMALL	Crossbar for step support (bottom, small)	1
5	KICK PLATE	...	1
6	MIDDLE STEP LEG	...	1
7	BOTTOM STEP	...	1
8	FRONT STEP LEG	...	2
9	BOTTOM HANDLE ARM	...	1
10	MIDDLE HANDLE ARM	...	1
11	TOP HANDLE ARM	...	1
12	HANDLE	...	1
13	STEP TOP SUPPORT ROD SMALL	Crossbar for step support (top, small)	2
14	9754K51	Foam handle grip	1
15	STEP BOTTOM SUPPORT ROD	Crossbar for step support (bottom, long)	1
16	SQUARE ROD SLEEVE	Support rod sleeve for steps to rest on top of	3

Figure 18: Exploded view with callout to BOM

Ensuring our prototype worked in a safe efficient manner, we devised 3 performance goals to test:

1. The prototype can withstand being walked up and down 100 times by a 235 lb. tester without signs of buckling during or after the test.

2. The spring mechanism retracts the stairs within a time of $1 \leq t \leq 3$ second.

3. The prototype is less than or equal to 5 lbs.

The prototype failed all performance goals. However, they can be fixed by the following:

1. The prototype could not withstand the weight of a 235 lb. tester. This can be fixed by extending our support rods and upgrading our materials. Wood alone is not sufficient.

2. The spring mechanism did not work due to not having a strong enough spring. Finding a reliable enough spring mechanism would also greatly improve the functionality of the system.

3. The prototype is made of wood and is currently around 12.8 lbs. This should greatly go down by using 6061-T6 aluminum.

While our prototype failed, issues 1 and 3 can be fixed by upgrading our materials. As with issue 2, a more reliable system needs to be built, as well as a stronger spring.

5.2 Proofs-of-Concept

The initial concept 19a only shows the building materials used as well as the initial base for the step system. There were a few problems with the size of the steps, so that was accounted for in the second proof of concept19b. The second version of the steps was built from the first version, yet it included the stairs and a backdrop so the customer's foot doesn't step too far past the bottom step. This was almost a finished product, although it was missing final touches, such as foot grips missing and the metal rods being held in place well, so they often slid out.

The final and best prototype 19c was improved upon with additional glue to support the metal support rods, as well as plastic mats representing adhesive for better foot grip. This design was also able to hold roughly 150 pounds and fold up to a reasonable size. The spring-loaded cane system had a very rough attempt made, resulting in a cane that was spring-loaded but lacked the proper spring constant to be used in the final design. This is what the final step stool design will be based on.

(a) Initial design phase: assembling building materials and the base created

(b) Proof-of-Concept 2: The concept is almost complete but needs a few refinements

(c) Final Concept Prototype: Includes plastic mats for increased grip when stepping. The beams running across are strong and held in place with hot glue.

Figure 19: Proof-of-Concept's 1 & 2 & 3

5.3 Design Changes

Our initial design has changed drastically throughout the process. The initial prototype looks like Fig. 17, the final CAD prototype, except it is made out of cardboard and uses hinges instead of rods to connect the legs (see Fig. 7). The idea was to use the hinges in the legs to get the legs to fold inward upon themselves. However, we realized during the design cycle that spring mechanisms in the legs are very complicated and are a major source of failure if not properly done; the springs would have to be strong enough to unwind the legs against gravity. Thus, we attempted to make it only use 4 legs instead of 6 and have the two legs just rotate upright (see Fig 19). However, this system has very long legs (around 30 in long), is very bulky, and requires custom-made hinges. Trying to make the legs telescope into itself also did not work because the beams holding up the steps got in the way. Learning all of this, we returned to the original cardboard design but made some modifications. Taking the idea from the Bees Neat 2-Step Stool (see Fig. 2), we made the original cardboard design able to fold up purely due to gravity when lifted up. Folding compact when raised up by the middle, the handle will be located in the middle of the step stool. With this, the spring mechanism is now only needed in the handle. The handle will telescope into itself with springs, allowing it to retract up easily and into the truck with the press of a button and still be compact; we only need to design a basic spring system for one part of the design instead of multiple for the other designs. This final model can be seen in section 5.1. One of the big issues with designing our step stool compared to more traditional step stools is that we needed a plate connecting the first and second steps so that a foot cannot slip under the step stool. This final design perfectly accounts for that and uses this plate as a main support connector for the system. Thus, the final design is the simplest, cheapest, most compact, and less points of failure design to make.

6 Design Refinement

6.1 Model-Based Design Decisions

6.1.1 Model-based design rational #1:

The image below depicts a model of the torsion spring that will be used to hold the two telescoping rods together, as well as the 3-D printed box that will be pulled up with a cable to release the two rods from each other.

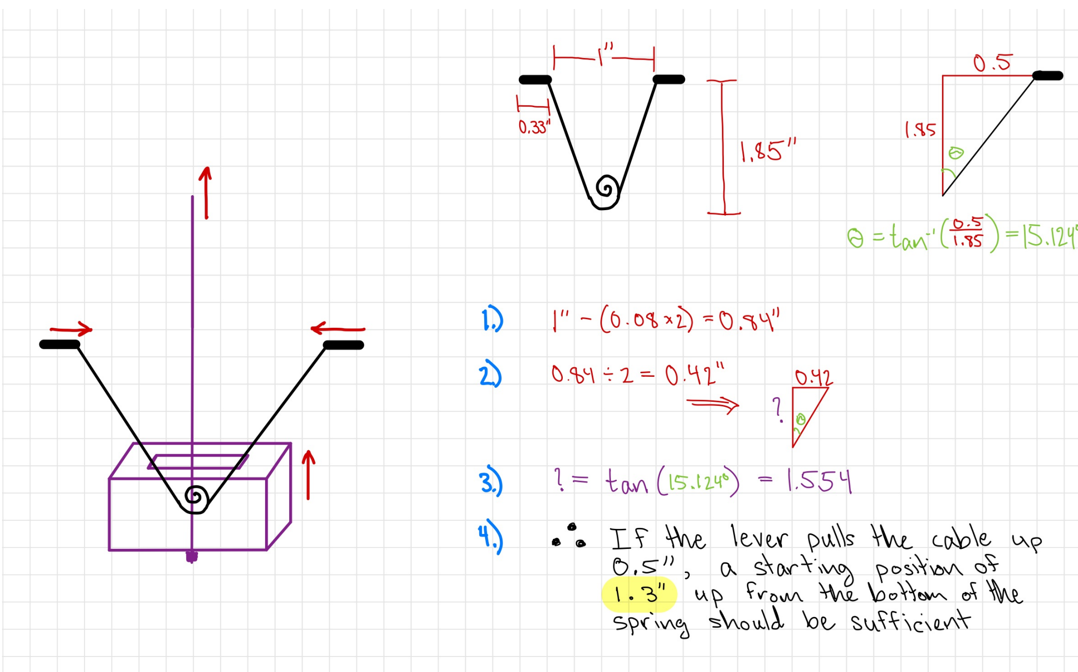


Figure 20: Model of torsion spring pincher.

The calculations shown in this model represent the position that the 3-D printed box needs to sit at on the torsion spring in order for it to close the proper distance. In step one, the 0.08 inches represents the distance that the spring needs to close in order to be released from the outer rod. This number was then multiplied by 2 to account for both sides of the spring. This showed that the final x-distance needs to be 0.84 inches. From here, step two was used to find the distance of the spring from the center, and step three was used to calculate the position where the spring was 0.84 inches. With the cable being pulled up 0.5 inches, step four explains that the 3-D printed box needs to sit around 1.3 inches down the torsion spring.

6.1.2 Model-based design rational #2:

The image below depicts a model of the telescoping handle from different views and calculates the length of cable that needs to be used in our system.

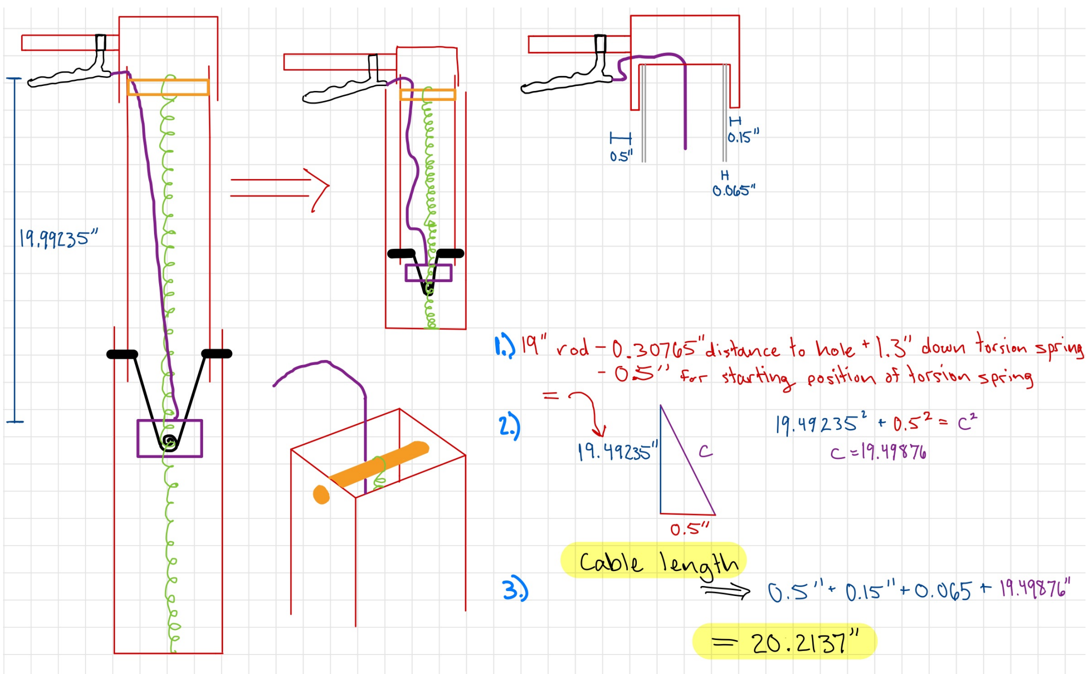


Figure 21: Model of telescoping handle and cable length.

In these calculations, step one shows how the y-axis length of the cable was calculated. The top rod is 19 inches, but the hole that the cable is threaded through sits 0.30765 inches down from the top of the rod. Based on the calculations in the Model-based design rational #1, we know that the box will also sit 1.3 inches down the torsion spring, which begins 0.5 inches from the bottom of the rod. This gave a vertical distance of 19.49235 inches for the cable; however, realistically, the cable will stretch to the center at an angle from the hole. Thus, step two calculates this distance in the hypotenuse position. This value of 19.49876 inches could then be added to the x-direction distances that are present due to the distance from the lever to the plastic handle, the thickness of the plastic handle, and the thickness of the aluminum rod. This gave a taught cable length of 20.2137 inches.

6.2 Design for Safety

6.2.1 Risk #1: Leg Collapse

Description: The steps experience a horizontal load and collapse/fold down, causing the stool to collapse.
Severity: Catastrophic
Probability: Frequent

Mitigating Steps: Currently, the step-stool is being redesigned with brackets to prevent this collapse from occurring.

6.2.2 Risk #2: Handle Pins Failure

Description: The pins in the handle have to support the full load of someone holding onto the handle; with them being so small, there is a chance they yield.
Severity: Critical
Probability: Seldom
Mitigating Steps: Testing it 100 times with the full load of a person; if there are signs of yielding, replace it with stronger pins.

6.2.3 Risk #3: Spring Failure

Description: The spring inside the handle has already permanently deformed; there is a chance it can no longer be strong enough to collapse the handle over time.
Severity: Marginal
Probability: Occasional
Mitigating Steps: Testing the handle mechanism 100 times and then determining if a different spring is needed.

6.2.4 Risk #4: Slippage

Description: The step stool is made out of sheet metal. There is a chance that the person slips off of the metal.
Severity: Catastrophic
Probability: Unlikely
Mitigating Steps: Putting friction tape on the steps increases the friction between the person's foot and the steps, reducing the chance of slippage.

6.2.5 Risk #5: Steps Buckling

Description: The steps are made out of sheet metal. With enough weight on the step, the sheet metal will buckle.
Severity: Critical
Probability: Unlikely
Mitigating Steps: Plastic supports are put under the rods of the step to distribute the load more evenly. This has been successful in making sure the step does not buckle.

6.2.6 Heat Map

Severity of risk	Category	Probability that something will go wrong: Frequent Likely to occur immediately or in a short period of time; expected to occur	Likely Quite likely to occur in time	Occasional May occur in time	Seldom Not likely to occur but possible	Unlikely Unlikely to occur
	Catastrophic	Leg Collapse				Slippage
	Critical				Handle Pins Failure	Steps Buckling
	Marginal			Spring Failure		
	Negligible hazard presents a minimal threat to safety, health, and well-being of participants; trivial					

Figure 22: Heat map of the risks of the design

Figure 22 is a heat map of the five risks discussed before. According to the heat map, the first priority is to make sure the legs do not buckle. This is the current number one issue that we are looking into and intend to solve with brackets bracing the legs to prevent them from buckling. The next issue to address is adding the friction tape and testing the pins and spring for failure. Since the telescoping rod has not been fully made yet, these tests still need to be completed, and then the risk of failure can be reassessed. Lastly, there is the minor issue of the steps buckling. The steps do flex when they are stood on, but they to not buckle or bend past an acceptable amount. The steps only bend because the sheet metal is slightly warped and thus not in full contact with the 3D-printed braces.

6.3 Design for Manufacturing

Current # of Components(excluding threaded fasteners): 30
Current # of Threaded Fasteners: 45
Theoretical Necessary Components:

1. Aluminum Sheet Metal Step Platform: The sheet metal steps need to be separate from the rest

as they fold in a downward direction (-90 degrees) from the initial step platform (0 degrees). This process also needs to be reversible, thus freely moving apart from other components.

2. Aluminum 3/8-16 inch all-thread: The all-thread is an important component for holding the overall structure of the steps together. Attached are nuts that help to tighten the entire step system. Without this component, the legs wouldn't be able to be connected to the sheet metal step platforms.

3. Aluminum Step Legs: The legs are required to preserve the classic stepped structure of the system. Without these legs, the essential vertical variation would be gone, and thus not steps.

It is difficult to minimize the number of components in our step design as each one plays a crucial role in structural integrity and safety. Any removal of these components would result in an immediate failure of our design.

If we were to explore potential minimization, it would be found in the telescoping handle system. Theoretically, it could be condensed into a single external shell. However, the challenge arises during the design phase, as using a material robust enough to support the customer would compromise the structural integrity of the system. This approach also over-complicates our existing design despite reducing the overall number of components.

6.4 Design for Usability

Vision Impairment Considerations: Our device has been designed with color vision impairments, such as red-green color blindness, in mind. Critical features, such as ledges, could be marked with yellow reflective tape to enhance visibility. However, due to the reflective nature of the metal, we elected to forgo the yellow reflective tape. Additionally, the mechanism to lock/unlock the device involves a button. We've ensured that the button's color (red) stands out without conflicting nearby colors. This design choice minimizes usability issues for individuals with red-green color blindness.

Hearing Impairment Considerations: The nature of our device is not reliant on auditory signals, therefore making it accessible to users with hearing impairments. We acknowledge the potential risk where a user might not hear auditory cues indicating mechanical issues, such as a creaking step indicating buckling, failure, or failing spring mechanisms. For the most part, by visual inspection of the steps and a simple test of the handle, we have concluded wear can be indicated without an auditory cue.

Physical Impairment Considerations: Our design prioritizes accessibility for users with physical impairments, in particular those with prosthetics. Key features include an ergonomic handle that ensures stability during use and prevents the device from tipping. We have also incorporated a foot stop at the end of each step to prevent the user's foot from slipping or getting caught under the subsequent step. Prostheses reduce the range of motion for the client. The step height has been reduced to a 6-inch height to ensure ease of accessibility. These design choices aim to make the device more user-friendly for individuals with mobility challenges.

Control Impairment Considerations: The device is designed with smaller steps and includes a support handle, making it easier to climb and less physically demanding. This design consideration is particularly beneficial for users with control impairments due to factors like distraction or fatigue.

The simplicity of the device's operation – a single button press to extend, retract, and lock the ladder – reduces the cognitive load and minimizes the risk of accidents due to control impairment. However, the risk of distraction remains a concern, and we continue to explore ways to make the device even safer for users in such situations. A distracted person could become mobile and shake the device more than intended. We are currently looking at a more secure locking mechanism, such as a locking lever to ensure the stool becomes more stable.

6.5 Design Considerations

Table 3: Factors considered for design solution

Design Factor	Applicable	Not Applicable
Public Health		X
Safety	X	
Welfare	X	
Global		X
Cultural		X
Societal	X	
Environmental		X
Economic	X	

Table 4: Contexts considered for ethical judgments

Situation	Applicable	Not Applicable
Global context		X
Economic context	X	
Environmental context		X
Societal context	X	

7 Final Prototype

7.1 Overview

The performance goals for analyzing the final prototype's success were:

1. Hold 235 lbs.

2. Weigh less than 10 lbs.

3. Fully collapse between 1 to 3 seconds.

The first two goals in the final model were achieved; the stool weighs 8.2 lbs and supports a load of 235 lbs. However, the spring system inside the support handle is jammed and does not expand properly. In future iterations, a channel would be used to separate the spring from any other mechanisms inside the handle. Also, the stool still exhibits some instability when experiencing forces in the horizontal direction. This issue would be solved by making adjustments to the brackets that are currently being used to hold the stool steady. Improvements would be made in tolerances of the brackets, and potentially even in doubling the brackets so that the legs are restricted on the top and bottom. Overall though, the step stool can be used to successfully step up into a vehicle. The step stool also achieves many other user needs such as ease of transport with the backpack straps and compact shape, as as well as non-abrasive foot traction with the rubber grips on the treads. These features can be seen in Fig. 23.

Figure 23: The final step stool prototype expanded.

7.2 Documentation

The final prototype was modeled very similarly to the cardboard mock-up shown in Fig. 16. The original mock-up design had many flaws though. These flaws were all addressed in the final design, and the necessary adjustments are discussed below.

Figure 24: The step stools folded up and carried on back.

7.2.1 Handle Improvement

The final design for the handle is a 2-part telescoping handle. A 2-part system was used rather than a 3-part system because it collapses to the same overall length while also dramatically simplifying the internal mechanisms. An expanded view of the final telescoping handle is shown in Fig. 25 which was captured before the handle was fully assembled.

Figure 25: The final handle assembly disassembled.

For the spring to be secured, holes were drilled into the square rods, and pins were inserted into them. The spring ends wrap around these pins to secure the spring in place. One pin is at the top of the upper telescoping rod, and the other is at the bottom of the lower telescoping rod. One of the pins can be seen in Fig. 26 from before the spring was wrapped around it.

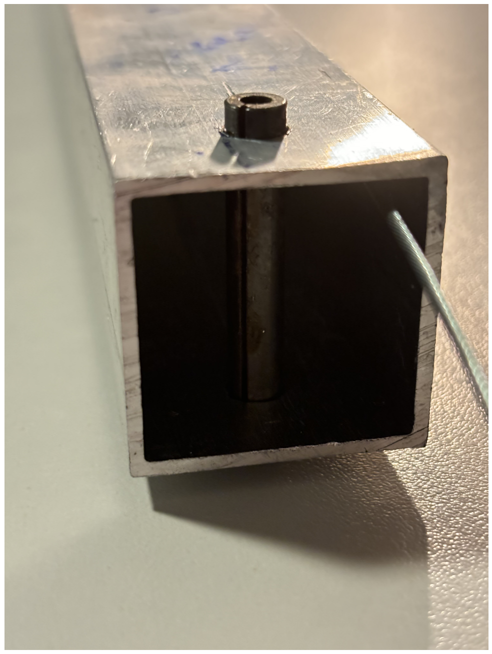


Figure 26: The final handle assembly disassembled.

Brackets are used around the lower section of the telescoping rod to allow the handle to attach to the stool without interfering with any internal mechanisms. Drilling through the handle to fix it to the stool would have also required the upper telescoping rod to have slits for sliding up and down, which would, in turn, compromise the integrity of the metal. These brackets can be seen in Fig 27.

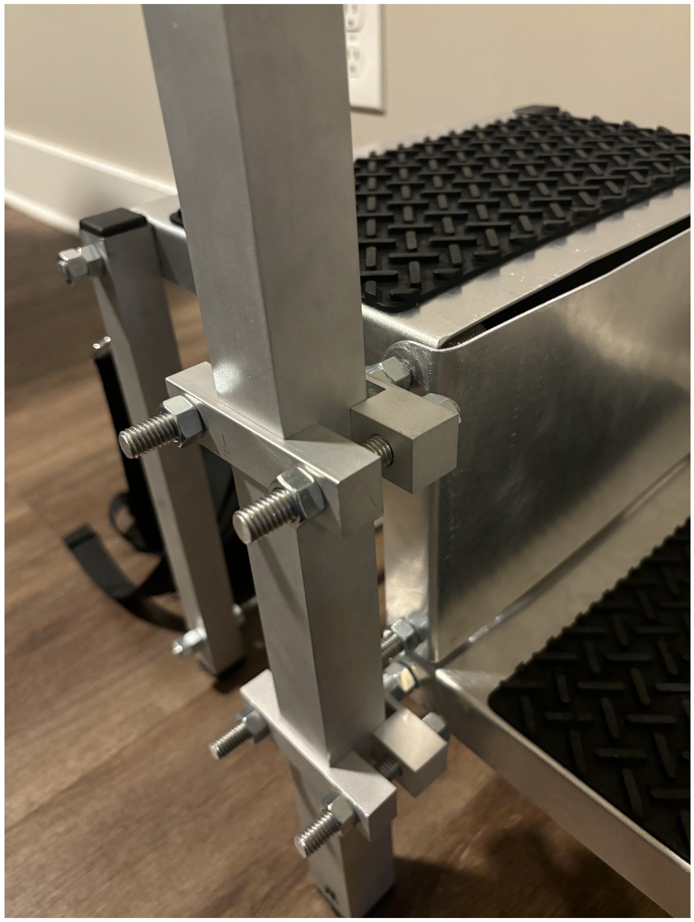


Figure 27: The final handle assembly disassembled.

The handle uses the pin and spring mechanism described in Fig. 21. While the mechanism works in theory, the spring has become jammed inside the rod and does not physically work properly. For future iterations, this issue would be analysed, and adjustments would be made to compartmentalize the spring away from the rest of the mechanism. It is predicted that the spring is getting caught on the pin-box mechanism and thus is not expanding correctly. The pin and box assembly that the cable manages can be seen in Fig. 28. The box slides up when the cable is pulled and pinches the pins inwards, releasing the connection between the upper and lower telescoping sections.

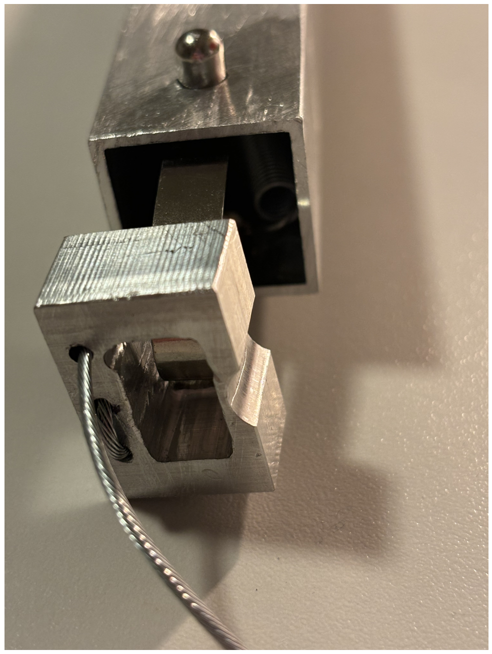


Figure 28: The pin-box mechanism that holds the handle in the expanded position.

Both the spring and pin are aligned in the center of the rod, requiring the spring to be forced to the side by the pin box. In future iterations, these pieces would be aligned opposite of each other, allowing them to move without interference. The width of the telescoping rods may also be increased to give more room for the mechanisms to operate. This would be one of the main focuses if the project were to be continued.

7.2.2 Horizontal Load Stability

The design from Fig. 16 was not sturdy enough to support a horizontal load on the treads of the step stool. When a person's momentum moved forward on the steps, the legs would fold and collapse. To prevent this, the legs were all connected to each other with either brackets or all-thread rods, creating a box-like shape. While the brackets hold the bottom of the legs at the proper distance, the top of the legs still have too much freedom to rotate, allowing the step stool to sway when being used. With this, the design for the brackets would be modified in future iterations of the project. The current brackets can be seen in Fig. 29.

Figure 29: The pin-box mechanism that holds the handle in the expanded position.

7.2.3 Additional Considerations

In addition to the previously stated issues (spring mechanism jamming and horizontal instability), there are a few additional improvements that could be made in the future. For instance, the aluminum treads showed signs of fatigue. This fatigue is most likely due to the tolerance gap between the 3-D printed spacers (PETG material) and the treads. The PETG spacers are used to help support the treads, and the gap between them allows the treads to flex until they hit these spacers. The all-thread rods are also sticking out in certain places, and should be trimmed down to prevent snagging. It would be beneficial to create caps that cover any exposed nuts or all-thread as well for safety purposes in transportation. While the final model is not as refined as it could be, and the retracting feature does not work, the step stool does meet two of the three design goals that our group set out to achieve and is overall a well thought out project for the fall 2023 semester of senior design.

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[1] World Health Organization. *Disability*. URL: https://www.who.int/news-room/fact-sheets/detail/disability-and-health#:~:text=An%20estimated%201.3%20billion%20people%20%E2%80%93%20or%2016%25%20of%20the%20global,diseases%20and%20people%20living%20longer.. accessed: 09.10.2023.