

**Assistive Mobility Device for an Elementary School Student with
Arthrogryposis**

A Major Qualifying Project Proposal
Submitted to the Faculty
Of the
Worcester Polytechnic Institute
In partial fulfillment of the requirements for the
Degree of Bachelor of Science
In Mechanical Engineering
By:

Nicholas Algieri

Alan Humphrey

Grant Raymond

Date Submitted: April 30th, 2014

Professor Allen H. Hoffman
Mechanical Engineering

Professor Holly K. Ault
Mechanical Engineering

Abstract

An eight year old male in a Worcester public school has Arthrogryposis, a condition which prevents him from using his arms and walking. He has access to several mobility devices; however, they are all unfit for use in a classroom setting. The student writes and types using his feet and works at a specialized desk. The goal of this project was to design a custom mobility device suited for the student's specific needs. A device was created that could easily navigate in a classroom, while still providing a comfortable, ergonomic seat and a safe, stable platform that would allow him to work at his desk. The main features of the device include: a zero turning radius, lateral support, lockable wheels and adjustability for his growth in the next several years. The device was successfully tested and met with enthusiastic acceptance from both the client and school personnel.

Authorship

This report represents the cumulative work of Nicholas Algieri, Alan Humphrey, and Grant Raymond. All members of the team contributed equally to the completion of the project and this report.

Acknowledgements

This project would not have been successful without the support of a number of people. We would like to take a moment and thank everyone who has helped us during the course of our MQP

- Professor Allen Hoffman and Professor Holly Ault - *Advisors*
- Sally Goodhile and the Norrback Avenue School - *Project Sponsors*
- Jonathon Labrie and Connor Morette - *WPI Machine Shop*
- Barbara Fuhrman and Statia Canning – *Mechanical Engineering Department*

Table of Contents

Abstract	i
Authorship	ii
Acknowledgements	iii
Table of Contents	iv
List of Figures	ix
List of Tables	xiv
Chapter 1: Introduction to the Client	1
Chapter 2: Background	3
2.1 Arthrogyrosis	3
2.1.1 History and prevalence	3
2.1.2 Symptoms	3
2.1.3 Causes	4
2.1.4 Existing treatments	4
2.2 Existing Devices/Market Assessment	5
2.2.1 Manual Wheelchair	5
Compatibility with the Client	6
2.2.2 Powered Wheelchairs	7
Compatibility with the Client	8
2.2.3 Gait Trainers	8
Compatibility with the Client	9
2.3 Environment	9
2.3.1 Educational Facilities	9
Accessible Routes	9
Walkways	10

Ramps	10
Entrances	11
Doors and Doorways	12
Restrooms	13
2.4 Needs Assessment	14
2.4.1 The Client's School Environment	15
2.4.2 The Client's Devices	15
Stroller	16
Gait Trainer	16
Permobile Power Chair	17
2.4.3 Skills Assessment	18
2.4.4 Unmet Needs	18
Chapter 3: Project Goals	19
Chapter 4: Design Specifications	20
4.1 Safety and Stability	20
4.2 Maneuverability	20
4.3 Adaptability	21
4.4 Comfort	21
4.6 Miscellaneous	22
Chapter 5: Functional Decomposition	23
5.1 Balance	23
5.2 Interaction with peers	23
5.3 Mobility	24
Chapter 6: Preliminary Design Process	25
6.1 Morphological Chart	25

6.1.1 Frame	25
6.1.2 Contact Points	25
6.1.3 Movement	25
6.1.4 Propulsion	25
6.1.5 Steering	26
6.1.6 Active Braking and Parking Brake	26
6.1.7 Restraint	26
6.1.8 Seat	26
6.1.9 Seat Features	26
6.1.10 Adjustable Height	26
6.1.11 Transfer	27
6.2 Creation of Design Alternatives	29
6.2.1 Preliminary Designs	29
Design 1	30
Design 2	31
Design 3	33
Design 4	34
Discarded Designs	35
6.3 Design Selection	36
6.5 Zero Order Prototyping	38
6.6 Prototype Assessment	39
Chapter 7: Final Design	40
7.1 Changes Made to the Final Design	40
7.2 Detailed Analysis	43
7.2.1 Static Analysis	44

7.2.2 Dynamic Loading	48
7.2.3 Collisions	48
7.3 Component Selection	51
7.3.1 Steel Tube 0.12 inch wall thickness	51
7.3.2 Steel Stock for Frame Clamps	52
7.3.3 Bucket Seat	53
7.3.4 Caster Wheels	54
7.3.5 Axle Wheels	54
Chapter 8: Manufacturing	55
8.1 Side Members	55
8.2 Cross Members	56
8.3 Seat Framing	59
8.4 Axle Wheels	61
8.5 Armrests and Seatbelt	62
8.6 Safety Precautions	63
8.7 Full Device	63
Chapter 9: Verification and Testing	64
9.1 Safety and Stability	64
9.2 Maneuverability	64
9.3 Adaptability	65
9.4 Comfort	65
9.5 Miscellaneous	66
9.6 Testing	66
Chapter 10: Conclusions and Future Work	67
Bibliography	69

Appendices	a
Appendix A: Photos of the Client’s Classroom and Devices	a
Appendix B: Functional Decomposition of the Student’s School Activities	e
Appendix C: Decision Matrices	f
Appendix D: Morphological Chart	h
Appendix E: Contact Point Analysis	k
Appendix F: Preliminary Design Sketches	l
Appendix G: Testing protocols	n
Appendix H: Center of Gravity Calculations	o
Appendix I: Static and Dynamic Calculations	w
Static	w
Dynamic Loading	y
Collisions	y
Side Collision	z
Front Collision	bb
Appendix J: Part Drawings	ee

List of Figures

Figure 1: The Client's Specialized Desk and Chair	1
Figure 2: Adolph's original drawing of an infant with arthrogryposis (Nichols 2011)	3
Figure 3: Most Effective Force Direction of Propulsion for a Wheelchair (L.H.V. van der Woude et al 2001, pg 719).....	6
Figure 4: A Foot Powered Manual Wheelchair. Components 31 and 34 demonstrate the track ball design (US Patent #6257610 B1).....	7
Figure 5: Traditional (left) and power-base (right) electric powered wheelchairs (Cooper et al. 2007)	7
Figure 6: Stock Photo of Common Gait Trainer (Rifton).....	8
Figure 7 - Minimum Clearances for Turning (AAB 521 CMR 20.00:20.4)	10
Figure 8: Changes in Level (AAB 521 CMR 22.00:22.4).....	10
Figure 9: Ramp Width and Railing Height (AAB 521 CMR 24.00:24.3)	11
Figure 10: Space Allowance for Entrances and Vestibules (AAB 521 CMR 25.00:25.3)	11
Figure 11: Openings and Accessible Routes (AAB 521 CMR 26.00:26.1.1).....	12
Figure 12: Clear Openings (AAB 521 CMR 26.00:26.5)	12
Figure 13: Thresholds for doors of different types (AAB 521 CMR 26.00:26.10)	13
Figure 14: Accessible Toilet Stall, Left Approach (AAB 521 CMR 30.00:30.6.1)	13
Figure 15: Accessible Toilet Stall, Right Approach (AAB 521 CMR 30.00:30.6.1)	14
Figure 16: The Client's Classroom.....	15
Figure 17: The Client's Stroller	16
Figure 18: Stock Photo of Rifton Pacer with Chest Support Attachment (Rifton)	17
Figure 19: Functional Decomposition of the Problem.....	23
Figure 20: Component Pairing and Elimination.....	29
Figure 21: Preliminary Design Morphological Chart	30
Figure 22: Design 1.....	31

Figure 23: Design 1 Refined	31
Figure 24: Design 2 Wheel Layout	32
Figure 25: Design 2.....	32
Figure 26: Design 2 Refined	33
Figure 27 : Design 3.....	33
Figure 28: Design 3 Refined	34
Figure 29: Design 4.....	34
Figure 30: Design 4 Workstation.....	35
Figure 31: Trackball Design	35
Figure 32 – Go-Cart Design	36
Figure 33 - Sample of Decision Matrix	37
Figure 34 – Caster Dolly	38
Figure 35 – Dolly Modified with Axle Wheels.....	38
Figure 36: Testing Protocol for Long Distance and Confined Mobility Test	39
Figure 37: Solidworks Models of Various Design Iterations, from Earliest (left) to Final Design (right)	40
Figure 38: Original Design with Bent Frame (Top) versus Final Design (Bottom).....	41
Figure 39: New Clamp.....	42
Figure 40: Upright Supports.....	42
Figure 41: Device Terminology	43
Figure 42: Device Coordinate System	43
Figure 43 - Free Body Diagram for Ground Reaction Forces	44
Figure 44 - Free Body Diagram for Reaction Forces at Seat Posts.....	44
Figure 45 - Free Body Diagram for Cross Member Reaction Forces.....	45
Figure 46 - Reaction Moments of Cross Member.....	45

Figure 47 - First Free Body Diagram for Cross Member	45
Figure 48 - Second Free Body Diagram for Cross Member.....	46
Figure 49 - Shear and Moment Diagram for Cross Members.....	46
Figure 50 - 3 Points Investigated on Side Members	47
Figure 51 - FBD at Side Member Point A	47
Figure 52 - FBD at Side Member Point B.....	47
Figure 53 - FBD at Side Member Point C.....	48
Figure 54: Location of Collision Forces	49
Figure 55: FBD at Side Member Point A in Side Collision	49
Figure 56: FBD at Side Member Point B in Side Collision	50
Figure 57: FBD at Side Member Point C in Side Collision.....	50
Figure 58: FBD at Side Member Point A in Front Collision	50
Figure 59: FBD at Side Member Point B in Front Collision.....	51
Figure 60: FBD at Side Member Point C in Front Collision.....	51
Figure 61: Location of tubing sizes.....	52
Figure 62: Framing clamp.....	52
Figure 63: Ergonomic Bucket Seat	53
Figure 64: Seat base foundation	54
Figure 65: Exploded view of Caster Sub-Assembly	55
Figure 66: Completed Side Frame Sub-Assemblies	56
Figure 67: Clamp and Cross Member Sub-Assembly (Exploded).....	56
Figure 68: Clamp Sub-Assembly (Completed)	57
Figure 69: Crossbeam Attachment to Side Frame	57
Figure 70: Height Adjustment Sub-Assembly	58
Figure 71: Completed Frame with Cross Members	59

Figure 72: Seat Frame Ready for Welding	59
Figure 73: Seat Frame Welding Assembly	60
Figure 74: Plastic Molded Seat.....	61
Figure 75: Axle Wheel Attachment.....	62
Figure 76: Device with Armrests.....	62
Figure 77: Completed, painted device.....	63
Figure 78: The client in his chair	68
Figure 79: The Student’s Stroller	a
Figure 80: Back view of the Stroller	a
Figure 81: The Specialized Desk Setup.....	b
Figure 82: A second view of the Desk.....	b
Figure 83: The Student’s Specialized Keyboard	c
Figure 84: A Shot of the Current Classroom Setup.....	c
Figure 85: Another view of the student’s classroom.....	d
Figure 86: This image shows the limited space behind the student’s desk.....	d
Figure 87: Functional Decomposition of School Activities.....	e
Figure 88: First 6 Categories of the Decision Matrix.....	f
Figure 89: Last 5 Categories of the Decision Matrix	g
Figure 90: Morphological Chart for Design 1.....	h
Figure 91: Morphological Chart for Design 2.....	h
Figure 92: Morphological Chart for Design 3.....	i
Figure 93: Morphological Chart for Design 4.....	i
Figure 94: Morphological Chart for Track Ball Design (Discarded).....	j
Figure 95: Morphological Chart for Go-Cart Design (Discarded).....	j
Figure 96: Weight Distribution Proportional to Contact Points	k

Figure 97: Hand Sketch of Preliminary Design 1.....	l
Figure 98: Hand Sketch of Preliminary Design 2.....	l
Figure 99: Hand Sketch of Track Ball Design.....	m
Figure 100: Hand sketch of Go-Kart Design.....	m
Figure 101 – Testing Protocol for Long Distance and Confined Mobility Test.....	n
Figure 102: Testing Protocol for Targeting a Doorway Test	n
Figure 103: Testing Protocol for Tight Maneuverability Testing	n
Figure 104: Calculation of Maximum Center of Gravity Height with a Defined Base Dimension ...	o
Figure 105: Simple Collision Model.....	p
Figure 106: Still Shot from Slow Motion Video.....	p
Figure 107: Collision Forces	q
Figure 108: Collision Moments	q
Figure 109: Center of Gravity Heights versus Base Width for Varying Velocities.....	r
Figure 110: Standing Position for CG Approximation	s
Figure 111: Forward Lean with Feet on Ground for CG Approximation.....	s
Figure 112: Forward Lean with Legs Extended for CG Approximation.....	t
Figure 113: Sideways Lean with Feet on Ground for CG Approximation	t
Figure 114: Sideways Lean with Legs Extended for CG Approximation	u
Figure 115: Center of Gravity Calculations	v

List of Tables

Table 1: Example Morphological Chart.....	28
Table 2: Movement Pairwise Comparison Chart	36
Table 3: Prices of Devices.....	67

Chapter 1: Introduction to the Client

The client is an eight year old boy who has a condition known as Arthrogryposis, which prevents him from using his arms. His hips are also splayed, which is a common side effect of Arthrogryposis. Without the use of his arms, the client cannot walk or stand unassisted because he is at a much higher risk of injury in the event of a fall. Despite his condition, the client is a bright, friendly boy who enjoys being the center of attention. All of the employees at the school cannot say enough about his positivity and resourcefulness. He participates in all school activities, including gym and recess, and works to adapt to any activities with which he experiences difficulty. For example, despite not being able to stand or jump by himself, he developed a way to jump rope while sitting on the ground.

The client has learned how to write with a pencil and type on a keyboard using his toes, and uses these skills every day in school. He is not able to sit a normal desk because of his unique writing style. To accommodate him, the school has created an angled desk which sits closer to the floor to provide better access with his feet (Figure 1).



Figure 1: The Client's Specialized Desk and Chair

To use this desk he sits in a low chair that has lateral supports which he leans against when writing and typing. Though he does have a full time aide, she encourages him to be as independent as possible and only assists him when he cannot do something on his own. During class time, the client is either seated on the floor or at his desk. If he needs to go to the bathroom, he will slide on his buttocks all the way to the bathroom and back. In addition to taking a long time, sliding on the floor is not sanitary. This is especially problematic during the winter, because of the snow, dirt, and salt that gets tracked in by the boots of other children.

The client navigates through the school by himself using a few assistive devices. The client's current mobility devices are specialized, so he has to switch between them throughout the course of his day. As a result, the client spends quite a bit of time transitioning from one device to another, which always requires the help of his aide.

The client does not have a mobility device that is able to navigate the classroom. In order to get around, the student “scoots” around on his buttocks. This is a very unsanitary form of transportation, and puts unnecessary stresses on his body. Currently, there is no device on the market that meets the client’s specific needs, so a new device needed to be developed.

Chapter 2: Background

This chapter presents the preliminary research conducted to better understand Arthrogyrosis, existing assistive technologies, the accessibility requirements for public buildings, and the client's specific condition. This literature was used to develop an understanding of the requirements of a custom developed device, and to help uncover some of the difficulties that may arise during the design process.

2.1 Arthrogyrosis

2.1.1 History and prevalence

Arthrogyrosis was first officially documented in 1841 by Adolph Otto (Bevan et al., 2007; Mennen, et al., 2005; O'Flaherty, 2001). The first case of the condition was an infant who was described to have scoliosis, joints that were permanently bent, and extremities that curved inwards (Figure 2).



Figure 2: Adolph's original drawing of an infant with arthrogyrosis (Nichols 2011)

Otto called the condition “Arthrogyrosis Multiplex Congenita” and used it to describe other children who suffered from limited mobility in multiple joints. Originally a Greek term, the word *Arthrogyrosis* roughly translates to “curved joint” or “bent joint,” *congenita* translates to “from or before birth” and *multiplex* means “multiple.” Today, the diagnosis of Arthrogyrosis Multiplex Congenita (commonly known as Arthrogyrosis or AMC) is used to diagnose any joint contractures, encompassing almost 300 distinct disorders. . Common subsets of Arthrogyrosis include dislocated hips at birth, or the presence of a club foot. It is difficult to put an exact number on the prevalence of AMC; but nearly 1 in every 100 births has some symptoms of the condition, whether it is minor scoliosis or a more serious limb contracture. The most common major contracture is the condition known as a club foot, and occurs in 1 out of every 500 live births. 1 in 3000 children is born with contracture of multiple joints, which is a much more serious condition. (Chen 2013, Staheli 1998, Nichols 2011)

2.1.2 Symptoms

The symptoms of Arthrogyrosis are extremely diverse given the wide range of disorders that it encompasses. The most visible symptom of Arthrogyrosis is the contracture of joints. These are usually

symmetric, and are often seen along with the dislocation of the hip and shoulder joints. As a result of these contractures, muscle atrophy is usually present in the afflicted appendages. Depending on the specific condition, there is also the possibility of webs forming across joints, and permanent hip abduction. In the most extreme cases, AMC can also present with severe central nervous system damage, and near-complete immobilization of the body. In general, AMC is not a progressive disease; meaning that once the contractures have formed, they won't get worse. (Chen 2013, Staheli 1998, Nichols 2011)

Depending on the severity of the disorder, some individuals may be required to spend most of their lives in braces or using assistive technologies. In extreme cases of scoliosis, respiratory function can be restricted due to compression of the ribcage. People with less severe cases of AMC are expected to have a normal lifespan. There is a 50% mortality rate among infants in cases with irreparable central nervous system damage (Chen 2013, Staheli 1998, Nichols 2011).

2.1.3 Causes

The underlying causes of AMC are still not fully understood. While it has been proven that restriction of intrauterine movement of a fetus or a fetus's joints will lead to the formation of a contracture at birth, the specific causes of that restriction is not always clear. When the joints are restricted from moving, the developing connective tissue wraps around the joint, completely immobilizing it causing permanent contractures. (Chen 2013, Staheli 1998, Nichols 2011). There is no single cause of the limited intrauterine space. In many cases, the restriction is the result of uncontrollable factors, such as an abnormally shaped womb or a larger fetus, which may cause the fetus to have too little space. Arthrogyriposis can also be caused by a number of environmental factors during pregnancy. As with many disorders, if the mother consumes drugs and or alcohol during pregnancy the risk of Arthrogyriposis in the fetus is significantly increased. Other factors like trauma or maternal illness during pregnancy can also influence contracture development in the womb. The incidence of contractures in twins is higher than single births, because there are two fetuses trying to occupy the same space. In many cases, only one of the twins will develop contractures because the other twin pushes them to the side, further restricting their motion. (Chen 2013, Staheli 1998, Nichols 2011)

2.1.4 Existing treatments

For most cases of AMC, there are treatments that have been proven to be extremely effective. For minor joint misalignments and dislocations, a few years of physical therapy and the application of proper orthotic bracing can force the joint to track more normally. Even in more severe cases of Arthrogyriposis, physical therapy can help lengthen the tendons and improve underdeveloped muscles. This sort of therapy can return some degree of flexibility to the afflicted areas and allow for partial use of the appendages. In extreme cases, surgery may be necessary to return mobility to the joints. When the joints are restricted by connective tissue to the point where no motion is Surgery can free up the joints and allow the patient to develop better use of the afflicted area. (Chen 2013, Staheli 1998, Nichols 2011)

In general, people with AMC use a wide variety of braces and orthotics to improve mobility and prevent further injury. From correction to support, these kinds of devices can be used to help improve

the condition over time. Children born with dislocated hips can sometimes resolve the issue after a few years of wearing braces while they sleep. (Chen 2013, Staheli 1998, Nichols 2011)

Unfortunately, not every case of AMC can be solved through surgery or therapy. Sometimes the symptoms are so severe that there is no way to return normal function to the afflicted areas. These individuals can learn to overcome some aspects of their disability, such as using their feet as hands when their arms are afflicted, and can still live independent lives (Chen 2013, Staheli 1998, Nichols 2011).

2.2 Existing Devices/Market Assessment

Assistive mobility devices come in many forms depending on the abilities of the user. Many devices exist for persons who have limited mobility of the lower half of their body. These include manual wheelchairs, motorized wheelchairs, gait trainers, crutches, exoskeleton orthotics, and various types of walkers. These devices are specialized towards a specific type of user; many require the user to have some use of their upper extremities to operate the device, so these mobility devices are not suitable for this client. In order to effectively create a product suited for the client, it was important to consider the individual characteristics of these devices.

2.2.1 Manual Wheelchair

The manual wheelchair can be used to give mobility to individuals who have many different types of disabilities, including spinal cord injuries, multiple sclerosis, lower limb amputations, arthritis, stroke, and a large range of balance disabilities (Cooper et al. 2007). Different structural components can be used to create custom seating arrangements or support to address the specific needs of the patient. For example, additions can be made to the backrest and seat to provide extra support and improve the comfort of the user. The wheelchair is also an extremely stable device that when used correctly will very rarely tip over. Stability is a great asset as it allows users who are not well balanced to become more mobile without the risk of falling. Manual wheelchairs are most often propelled by the user's arms or by a second person pushing the wheelchair from behind. The most efficient way to propel the wheelchair is to grasp behind each wheel and push the wheels forward (Figure 3).

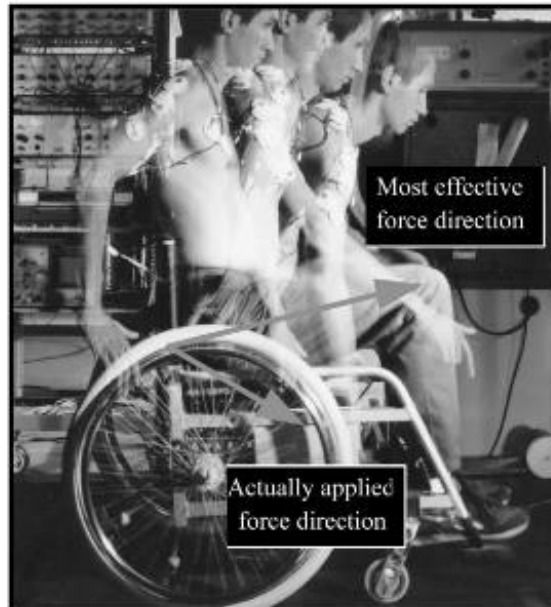


Figure 3: Most Effective Force Direction of Propulsion for a Wheelchair (L.H.V. van der Woude et al 2001, pg 719)

Compatibility with the Client

The manual wheelchair is not suited for the client as it requires the use of the arms to provide motion. The wheelchair does not promote physical activity in the legs and encourages sitting for prolonged periods of time which can cause issues such as pressure sores. Another major disadvantage of this inactivity is that osteoporosis and other diseases can be caused by a lack of muscle activity. Wolff's Law states that form fits function for all parts of the body, and if the legs are not being utilized to support and move the body, the ability to use them will begin to deteriorate over time (Frost, 1994). Figure 4 shows a patent for a wheelchair designed to improve lower leg utilization. This patent uses a track ball to give the user increased maneuverability using solely their feet. In this design, the feet are used to assist in turning the device while the majority of the forward movement is still generated by the arms of the user. The track balls are not an efficient way to propel the device long distances, due to their poor mechanical advantage.

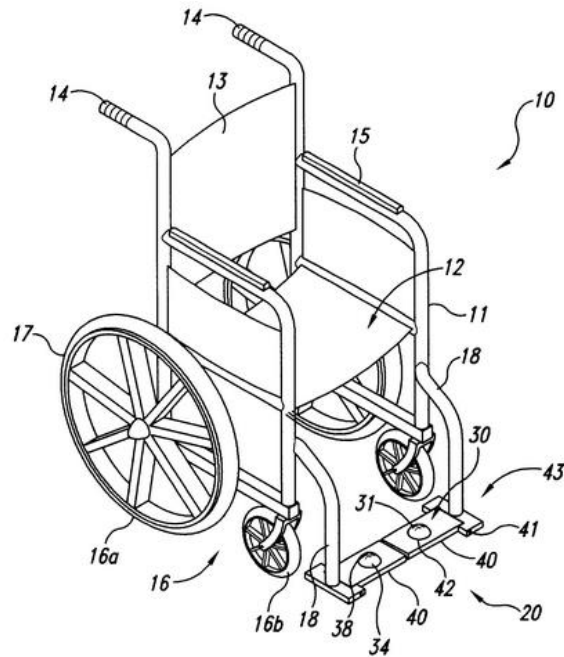


Figure 4: A Foot Powered Manual Wheelchair. Components 31 and 34 demonstrate the track ball design (US Patent #6257610 B1)

2.2.2 Powered Wheelchairs

Electric powered wheelchairs are often used for those who have very limited motor skills such as users with cerebral palsy, sensory motor impairments, or severe Arthrogyryposis. These devices are popular because they can be customized to the user's specific abilities, and they allow individuals with severe disabilities some independence. Electric powered wheelchairs (Figure 5) are grouped into two main categories: traditional (based on manual wheelchair design) and power-base (Cooper et al. 2007)

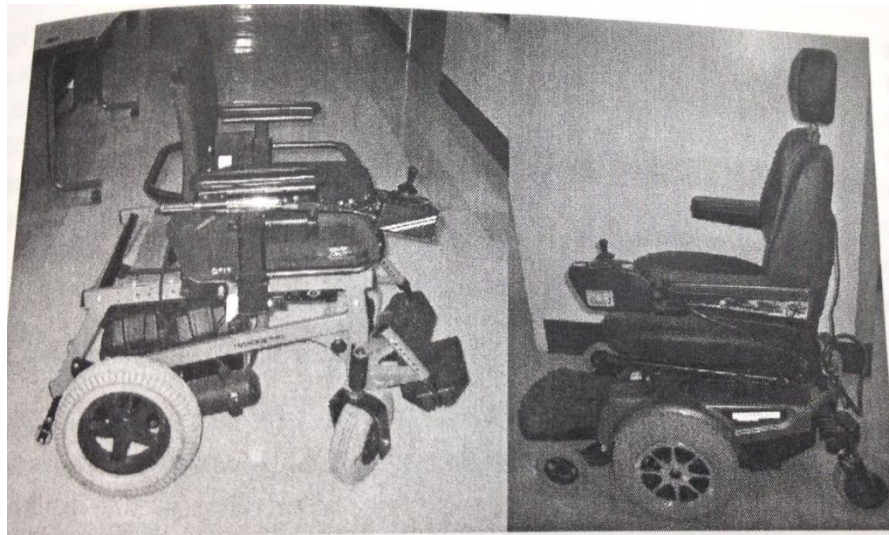


Figure 5: Traditional (left) and power-base (right) electric powered wheelchairs (Cooper et al. 2007)

The power base design is much more versatile than the traditional design. Power-base wheelchairs are capable of a range of different mechanical adjustments, such as: tilting, reclining, seat elevation, and, in some cases, these chairs can hold the user in a standing position. These adjustments help put the user in an anatomically correct position which promotes healthy circulation and prevents pressure sores. In particular, the ability to stand for short periods of time improves the health of an individual by reducing the complications caused by prolonged sitting. An individual that can stand for a short time throughout a day is less prone to sores, back pain, joint contractures, swelling, and poor posture (Cooper et al. 2007).

Compatibility with the Client

The power chair is not suited for the client because it prevents the use of his legs as a means of mobility. The electric powered wheelchair allows the user to move about by pressing a joystick or other user interface, discouraging physical activity. Similar to a manual wheelchair, this could cause complications, such as increased weight, muscle atrophy, and bone degradation. The design is also very bulky, discouraging its use in small areas. Given the device's size, it also makes the student self-conscious because some of the other students are intimidated by it (Keneally, Personal Conversation, 2013).

2.2.3 Gait Trainers

Gait trainers are used to give individuals with a variety of disabilities the independence to walk on their own (Figure 6). The gait trainer provides balance and stability allowing the user to focus on the act of walking. Gait trainers are very versatile and can incorporate many different attachments to accommodate arm placement, back support, weight support, hip position, pelvic position, and balance. The wheels of the gait trainer are typically caster wheels which allow for 360 degree rotation and excellent mobility. These wheels also have the ability to turn in all directions. The wheels generally have locks that can be used to keep the gait trainer from moving when the user wants to stand still.



Figure 6: Stock Photo of Common Gait Trainer (Rifton)

Compatibility with the Client

The gait trainer is a very good device for the student for many reasons. It requires him to stand and walk, which activates his leg and core muscles, promoting healthy muscle development. He uses a gait trainer for most activities outside of the classroom, including recess and gym class. However, these devices are not suited for the classroom because they have a large footprint, making it difficult to maneuver in tight spaces. In addition, the user is unable to lock the caster wheels by himself, and cannot get into this device without assistance, forcing him to rely on his aide. The gait trainer also keeps him in a standing position, which makes it impossible for him to write at his desk because he can't take his weight off of his feet.

2.3 Environment

In the past, public facilities were designed to accommodate the typical human form and abilities, resulting in standards for ceiling, doorway, desk and counter heights, stair inclinations, hallway widths, door sizes, etc. While these standards were appropriate for a person of typical size and ability, they proved to be an obstacle for a person with a physical disability. The concept of universal design focuses on the development of facilities that are accessible to people of all types of abilities. The use of universal design in America dates back to 1961 with the American National Standards Institute (ANSI) standard for accessible and usable buildings ("History of Accessible Facility Design." 2013). In 1968, the Architecture Barriers Act (ABA) was enacted requiring that all facilities built, modified, rented, or leased using federal funds must be fully accessible to persons with disabilities ("AAB Rules and Regulations" 2013). These two documents guide the design and planning of new facilities by the principles of universal design, and are updated every few years. An understanding of the standards and regulations in place for facility design was critical to consider during the design process.

2.3.1 Educational Facilities

Many design specifications for this project could be taken directly from the standards for facility design. For example, in a federally-funded building, hallways must be at least 36" wide. This means that this design must be able to fit through a 36" space; therefore it had to be less than 36" wide. Since the device aimed to increase the client's mobility in the classroom and around his school, the standards for educational facilities were the most important to consider.

Educational facilities must have access aisles 36" wide between tables, with no seating overlapping the access aisle. Each seating area should have clear floor space that does not overlap knee space by more than 19". For a person with disabilities, knee space should be at least 27" high, 30" wide, and 19" deep to accommodate a standard manual wheelchair. The standard for the height of the tops of fixed tables and counters should be between 28" and 34" high. However, inside a classroom it can be very difficult to maintain these requirements because chairs and desks can be moved very easily.

Accessible Routes

Accessible routes encompass many features inside and outside of a facility, including halls, corridors, aisles, skyways and tunnels. Stairs, steps, escalators, and elevators are not included as accessible routes in this standard, and have their own set of standards which will be discussed later in this section. All accessible routes should be at least 36" wide (Figure 7), with the exception of doorways that are less than 24" deep, which are controlled by the *DOORS AND DOORWAYS* standards.

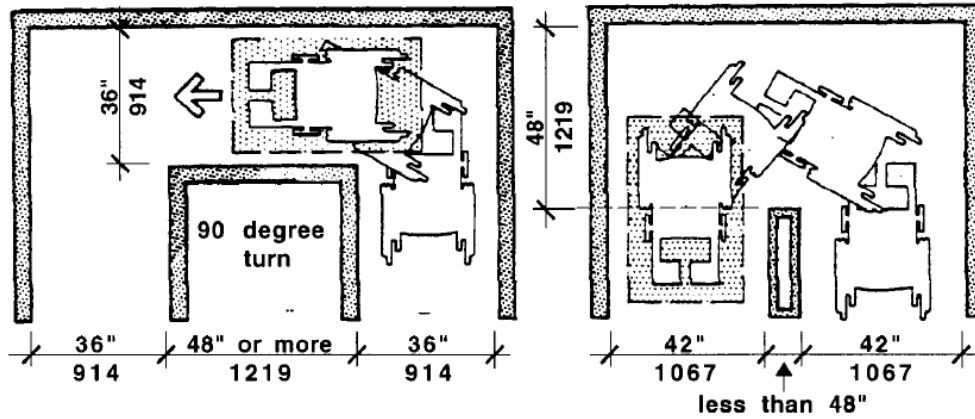


Figure 7 - Minimum Clearances for Turning (AAB 521 CMR 20.00:20.4)

If an accessible route is less than 60" wide (or has less than 60" of clear width), there must be clear 60"x60" spaces not more than 200' apart. If an accessible route has a slope steeper than 1:20 (5%), then it is considered a ramp and is controlled by the *RAMPS* standards discussed later in this section. The cross-slope (the slope of the route perpendicular to the direction of travel) of an accessible route should never exceed 1:50 (2%) (Architectural Access Board 521 CMR 20).

Walkways

Walkways differ from accessible routes in that they exclude hallways and corridors. A walkway is any walk, sidewalk, overpass, bridge, tunnel, underpass, plaza, court, or other pedestrian pathway. Walkways must be at least 48" wide and have a slope less than 1:20 (5%) and a cross slope less than 1:50 (2%). Walkways should not have any changes in level greater than 1/4", unless the change is beveled with a slope of less than 1:2 (50%) (Figure 8). This regulation ensures that walkways will have a smooth surface to allow mobility devices to travel safely and comfortably (Architectural Access Board 521 CMR 22).

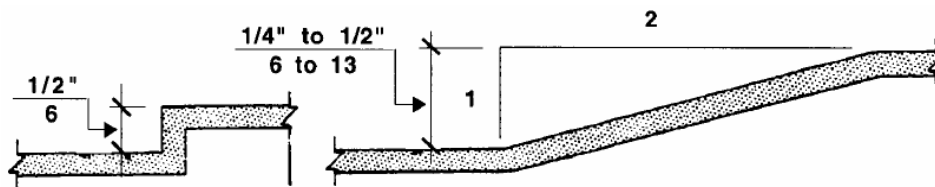


Figure 8: Changes in Level (AAB 521 CMR 22.00:22.4)

Ramps

Ramps include any slope that is greater than 1:20 (5%), and should always be constructed with the minimum possible slope based on the space available. The maximum slope of any ramp is 1:12 (8.3%), with the exception of a single rise of 3", where the slope can be a maximum of 1:10 (10%). The maximum rise for any single ramp is 30". Ramps should be at least 48" wide as measured from the railing, which should be between 34" and 38" high (Figure 9) (Architectural Access Board 521 CMR 24).

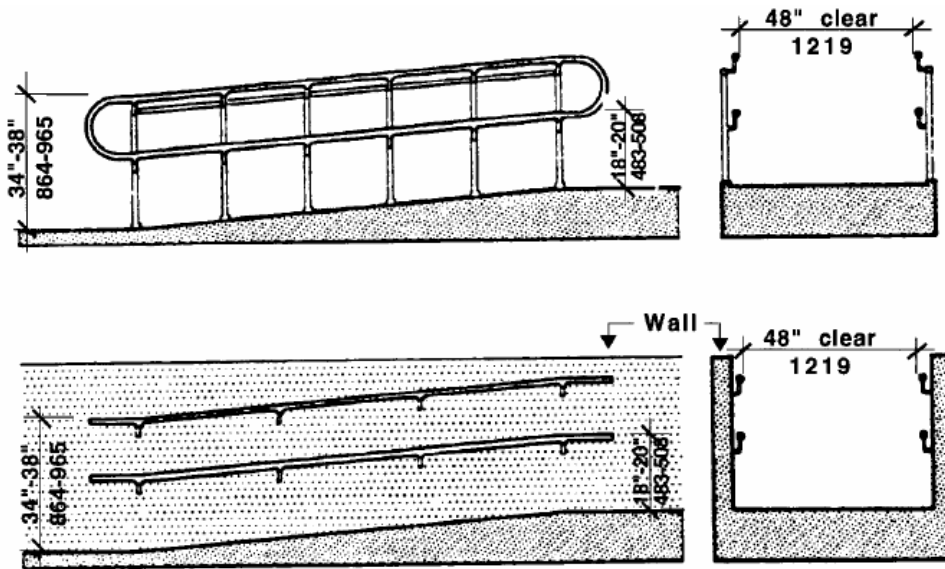


Figure 9: Ramp Width and Railing Height (AAB 521 CMR 24.00:24.3)

Entrances

Entrances are defined as any access point to a facility that is not solely for service, loading, or employee use. The area leading up to an entrance should be a paved walkway or ramp with a slip resistance surface and no steps. On either side of the entrance door, the ground should be level and clear for 48" (Figure 10) (Architectural Access Board 521 CMR 25).

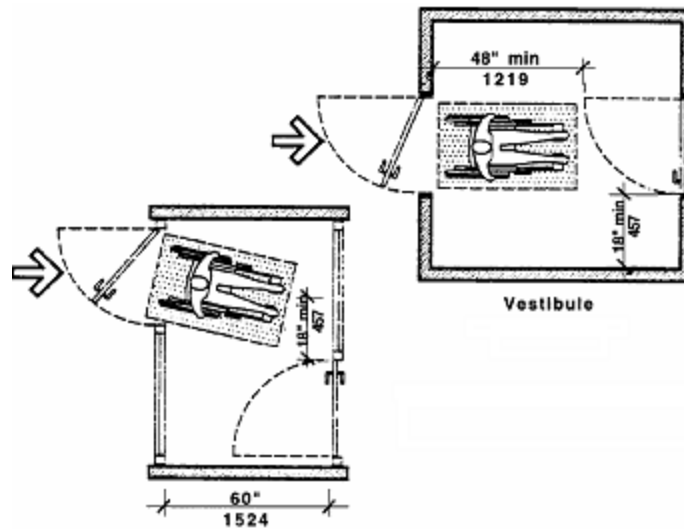


Figure 10: Space Allowance for Entrances and Vestibules (AAB 521 CMR 25.00:25.3)

The 48 inches of clear space must include any area that a door may swing into, and any obstructions in the entryway. These diagrams clearly show the range of dimensions that are acceptable when designing an entryway. These standards are based on the size of a typical wheelchair.

Doors and Doorways

Doors and doorways are categorized as any opening along an accessible route (Figure 11). If the opening is greater than 24" in depth then it is considered an accessible route and should be at least 36" wide. Openings less than 24" deep should be at least 32" wide. If the opening is not designed to allow someone to pass through it, such as a closet, the width can be reduced to 20."

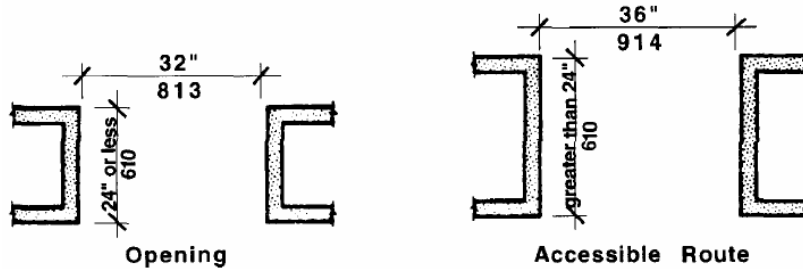


Figure 11: Openings and Accessible Routes (AAB 521 CMR 26.00:26.1.1)

Openings with doors installed should have at least 32" of clearance not including the width of the door (Figure 12).

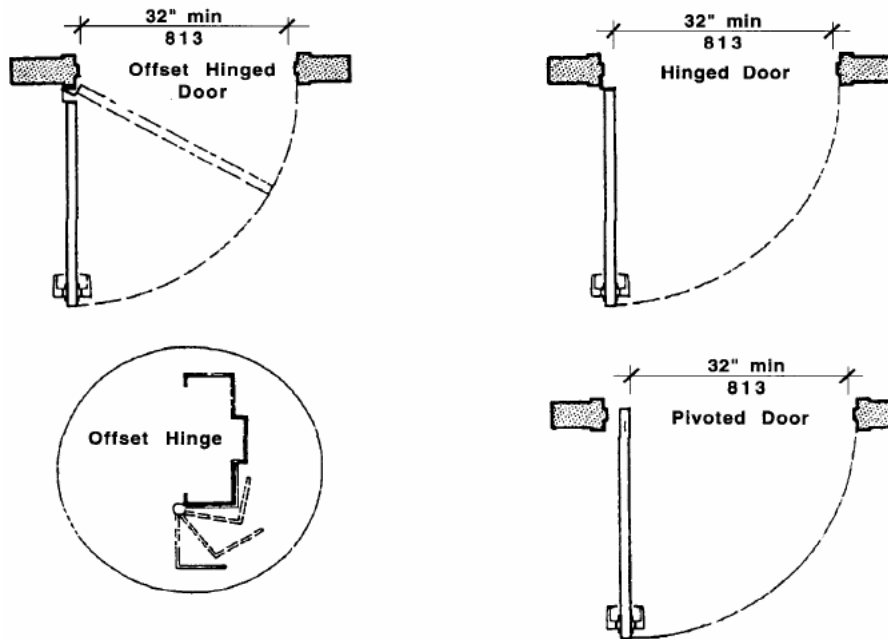


Figure 12: Clear Openings (AAB 521 CMR 26.00:26.5)

Revolving doors and turnstiles should not be the only entrances on an accessible route, unless they are designed to be accessible. The maximum force required to open an exterior hinged door should be less than 15 lbs, and less than 5 lbs for interior hinged and sliding or folding doors. Doors with automatic closing mechanisms should take at least 6 seconds to close from the 90 degree open position. Thresholds for doors should not be more than 1/2" in height and should be beveled on either side with a maximum slope of 1:2 or 50% grade (Figure 13) (Architectural Access Board 521 CMR 26).

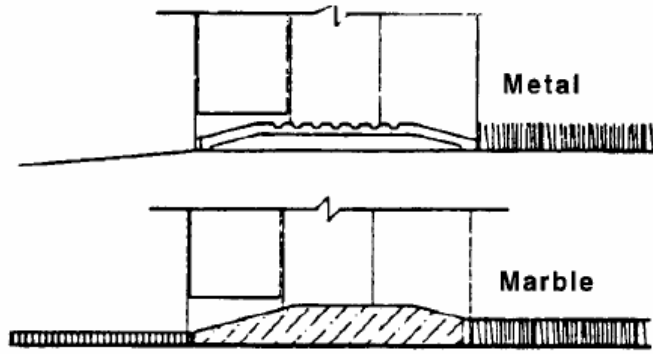


Figure 13: Thresholds for doors of different types (AAB 521 CMR 26.00:26.10)

Restrooms

Any accessible restrooms should be located on an accessible route, and should meet all of the requirements defined for vestibules, doorways, etc. as necessary. Accessible toilet stalls should be at least 60" by 72," with the toilet installed against the 60" wall. The door should swing outwards or slide, and the opening should be at least 32" wide. The door should close itself and have some kind of pull device on either side of the door to assist in opening and closing. The lock should be easy to use and located approximately 36" above the ground (Figure 14, Figure 15).

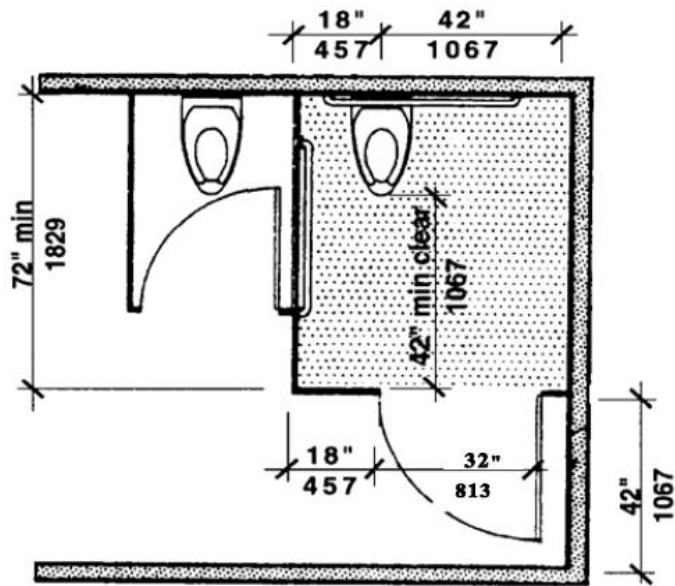


Figure 14: Accessible Toilet Stall, Left Approach (AAB 521 CMR 30.00:30.6.1)

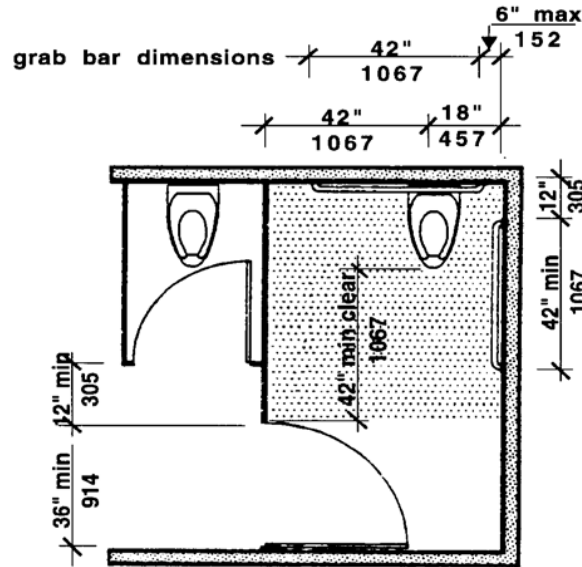


Figure 15: Accessible Toilet Stall, Right Approach (AAB 521 CMR 30.00:30.6.1)

The seat for an accessible toilet should be 17" to 19" off the ground, and the flush controls should be mounted no higher than 44". For bathrooms designed primarily for children, the seat of the toilet should be 11.5" to 12.5", 12" to 15", and 15" to 17" off the ground for pre-kindergarten, kindergarten to third grade, and fourth grade to sixth grade respectively. The flush controls should be 20" to 30" off the floor (Architectural Access Board 521 CMR 30.00)

2.4 Needs Assessment

The purpose of this project was to help a fourth grade boy with arthrogryposis be more independent at school. The client's arthrogryposis renders him with no use of his arms, wrists, or hands, and has caused his hips to splay outwards. Not having use of his arms and his splayed hips cause balance issues which makes walking very difficult, and poses a safety hazard if he were to fall. Although the general accessibility standards and available devices were known, it was important to consider the client's needs based on his specific school environment and devices.

2.4.1 The Client's School Environment

While many features of the school will follow standards, such as door widths, other potential obstacles, such as desks, will not be standard from building to building. Several aspects of his school were identified as obstacles that he must be able to navigate in the device, driving the design to be useful for the whole school day (Figure 16).



Figure 16: The Client's Classroom

While the standard for door widths is a minimum of 32," all of the doors in the client's school measured 34.5." There is no guarantee that the client will be placed in an equally accessible middle or high school, however the schools should have at least the 32" door width. The smallest width between obstacles in the client's current classroom was 29," which was the entrance to the coat rack area. It was determined that he would not likely have to navigate into this area, as his aide must already help him remove his jacket. Accessibility to bathrooms was the final important dimensional constraint. Stall doors are at least 32" wide and in an accessible stall, there is 42" of clearance for a wheelchair to turn around in, putting a maximum length constraint on the device. Overall the school's accessibility exceeds the standards for a public building. However, the classroom environment had some variability and unique size constraints. While he will be leaving this school at the end of the year, his middle and high schools are required to follow the minimum accessibility standards. Therefore, the device needs to fit within these standards.

2.4.2 The Client's Devices

The client currently uses several different assistive devices in his daily routine. He is pushed in a stroller to and from home, the bus, and the classroom. With this stroller, he is unable to propel himself,

and requires someone to push him. Outside of the classroom but still during school hours, he uses a gait trainer. The gait trainer provides him with the freedom to go where he wants, the exercise he needs, as well as a healthier posture. However, the footprint of the gait trainer is too large to be practical in the classroom, and does not put him in the proper position to write or type at his desk. The sling-style seat of his gait trainer is also not very comfortable, and not designed for sitting for long periods of time.

In the classroom, the client “scoots” around on his buttocks, using his right wrist as a support. He is able to get in and out of his chair unassisted, and writes at a modified desk using his feet. He scoots to the restroom, where he requires assistance to toilet. This scooting is a major hygiene concern, as well as a social disadvantage. While other students are at the same eye level in their desks, the client is either at a much lower desk, or on the floor when the class is doing group work and he is required to leave his modified desk.

Stroller

A stroller is used throughout the day to bring the client from room to room while not in the gait trainer (Figure 17). To move to and from an area, the aide needs to place the client in the stroller, secure him, and then proceed to push him from point A to point B. This method of mobility is not ideal for the client, as it eliminates independence and physical movement. The stroller is also not ideal for the aide as it requires the most amount of work on her part, having to push the client throughout the school.



Figure 17: The Client's Stroller

The stroller sits at a very high level and has very restrictive lateral supports, hindering the client from transferring in and out of the seat. The stroller also does not have a means to permanently lock the wheels which could result in a hazard if the stroller is sitting on some type of uneven flooring or ramp. The stroller meets a very specific need, which is simply to transport the client, and it does not benefit him in the classroom.

Gait Trainer

The client uses a Rifton Pacer gait trainer (Figure 18) as his primary means of travel when walking through the halls, and when he participates in gym class and recess. In his gait trainer, he sits in a small sling and is supported by a chest support attachment.



Figure 18: Stock Photo of Rifton Pacer with Chest Support Attachment (Rifton)

The gait trainer fills the client's needs for independence during recess and other physical activity. The client's occupational therapist was satisfied with the gait trainer for outdoor activities, and so outdoor use was not within the design space for the project. The gait trainer allows him to walk under his own power, and travel more quickly than scooting. Use of the gait trainer is encouraged by the client's aide and physical therapist because it promotes muscle growth in his legs and abdomen. The gait trainer is well designed for physical activities, and has large wheels designed to be able to navigate both indoors and outdoors. Additionally, the gait trainer allows the client to interact with his peers at eye level. The client can run and play with other students, allowing him to develop better relationships with his peers. The client can also move freely to spend time with different students at lunch and while on the playground. The aide also benefits from the gait trainer as it gives the client a high level of independence. This enables the aide to allow the client to go about his daily activities without having to fully engage the client as she knows that he will be kept upright and stable. Braking capabilities on the device also allow for the aide to lock the device in place when the client needs to remain still.

Though the gait trainer provides the client with a greater degree of independence, it is not suitable for all of the client's needs. A disadvantage that the gait trainer presents is that the device is too large to be used in the classroom. The gait trainer also keeps the client standing, whereas in the class he needs to be seated to take notes and do work at his desk. It is impossible for him to get in and out of the device on his own because he needs to be secured into the device; therefore, he relies heavily on his aide. Posture is also an issue when utilizing the gait trainer as it gives the client an opportunity to slouch and not fully support his bodyweight.

Permobil Power Chair

The elementary school has provided the client a Permobil © power chair, but he does not use it for several reasons. The chair has a lot of functionality; however, the primary problem with the Permobil © power chair is that it is too large and bulky to be able to navigate in a classroom. The client's aide

believes that other children are intimidated by the size of the chair, making it difficult for him to interact with other students. The power chair restricted the client from participating in recess or gym and does not allow for any physical activity. Especially for a person with disabilities, physical activity is important for general health and well-being. The power chair eliminated such activity and promoted a sedentary lifestyle.

2.4.3 Skills Assessment

In order to gain a better understanding of the client abilities, and to see how he interacts with the classroom, the team visited the school to work with the client. He was observed working and studying in a classroom environment, eating lunch in the cafeteria, and walking with his gait trainer between classes. The client was able to stand up by himself, as long as he had a wall or chair to lean on, though he was only able to stand up for about 30 seconds before he fell. It was also observed that the client was very competent when using his feet to write with a pen or pencil and type on a keyboard, allowing him to actively participate in class. He worked at a special angled desk which allowed him to see his papers and write while sitting back in a chair. His chair was a normal school chair, with armrests added to give him additional lateral stability. When not in his chair, the client scooted around on his buttocks. During this motion, he rested his weight on his wrist, and used his arm as a support; this position put a lot of stress on his wrist, and his physical therapist was concerned that this may injure his wrist after many years.

2.4.4 Unmet Needs

Although the client's current devices meet some specific needs, none address all needs simultaneously, and some needs are not addressed at all. There is clearly a need for a specialized device for the school day. This device should make the client more independent; it should be small and maneuverable enough to navigate a classroom; easy enough to propel that the client can move at a walking speed; and it should put him in a position to do work at his desk. In addition, it should also be comfortable enough for extended (7 hour school day) use.

Chapter 3: Project Goals

The goal of this project was to design and create a device that allowed the client to be more independent by giving him greater mobility in school. The device should minimize the number of assisted transitions that take place during the client's day. This means that the device should be able to fill several of the roles that the more specialized devices also meet. Ideally, the client will begin using the device when he gets off the bus in the morning, and continue using it throughout the rest of the day. It must be small and maneuverable enough to be used in his classroom, and allow him to move at a speed comparable to walking speed so that it is useful for traveling longer distances. For in-class activities, it should allow him to write and use his laptop, at his own modified desk or otherwise. As previously mentioned, his gait trainer is well-suited for active and outdoor environments, so the device will not accommodate those activities. The device will stay at the school, so it was not necessary to incorporate features needed for bus or van travel, such tie-down points.

One of the issues with the client's Permobil® wheelchair and gait trainer is that they are very obtrusive and "different" than the chairs his peers sit in. For this reason, the device should look as similar to a normal school chair as possible. This would allow the client to use the device without feeling self-conscious about the appearance, although this was secondary to the actual functionality of the device. Currently he spends a lot of class time on the floor, while his peers sit at their desks; the device should allow him to sit at a similar eye level to his peers while seated.

Chapter 4: Design Specifications

In order to facilitate the development of a device that can successfully achieve the project goals, the team created the following design specifications for evaluating proposed designs. These specifications address the form and function of a potential device. They were each placed into 1 of 5 categories: safety and stability, maneuverability, adaptability, comfort, and miscellaneous.

4.1 Safety and Stability

Assistive devices are strictly regulated for safety requirements. Therefore, it is imperative that the client stay safe while using the device. In order to ensure it is safe, the device should meet the applicable regulations and standards for assistive device.

1. A braking and locking mechanism must be included to keep the device in place when needed. The device will be designed to move so it is important to have a means to prevent unwanted motion. For example, the device should not be able to roll uncontrollably down an accessibility ramp.
2. The device must be able to support the weight of a 200 lb human. This specification is based on the weight capacity of the client's gait trainer making it as safe as his current devices (Rifton).
3. Device should not tip over at a 14 degree incline per wheelchair safety standards (. The client's physical capabilities would not allow him to slow a fall in the event the device was to tip with him in it. This is a major safety concern, and so any design must be stable with him in or on it.
4. Device should not tip in the event that the device collides with another object while travelling at 1.5 times the normal walking speed (7.5 feet per second).
5. The center of gravity (CG) should be less than 75% the total height of the device.
6. The device's CG should sit within its contact points with the floor when viewed from above. This is the accepted standard for stability.

4.2 Maneuverability

In order to be used in a school setting, the device must be very maneuverable so that it is compatible with all facility accessibility requirements. The device must be compact enough to fit in the restricted spaces of the school, while still being a stable platform.

1. The device should be no wider than 28". The standard width for a doorway is 32"; however the minimum gap between desks in the client's classroom was 30". This results in a 2 inch clearance on both sides of the device.
2. Must be less than 38" long. This will ensure that the device is shorter than the clients gait trainer.

3. The device must be able to have zero-turning capabilities. This will allow for the user to easily navigate small spaces.
4. The device should weigh less than 50 lbs. Heavy lifting standards indicate that anything over 50 lbs should be lifted by more than one person to prevent injury.
5. The device must allow the client to self-propel. This will encourage physical activity of the client, and allow him to use his legs on a more consistent basis.

4.3 Adaptability

The device will ideally travel with the client through middle school, and so it must accommodate the growth that he will likely undergo. He will grow heavier as he ages, and his height will increase.

1. The seat height should adjust to be the same as the average seat height for a school chair. This ranges from 14 inches to 17 inches off the floor.
2. While sitting, a person's calves should be perpendicular to the ground. The knee should be flexed at about 90 degrees in order to maintain a comfortable position.
3. The seat must be large enough to accommodate the client as he grows from 8 years old up into high school, age 18.
4. The device is designed to last for several years so the materials it is constructed from must be able to survive 6-7 years of use.

4.4 Comfort

One of the issues with the gait trainer that client uses is that it is not designed for sitting or extended use. The sling style seat is designed for safety feature more than comfort. However, the device is going to be used for several hours a day, so it is important that it is comfortable and it supports him in an anatomically correct position to maintain proper posture.

1. The client must be supported in an anatomically correct position.
2. The client must be laterally supported to prevent him falling out of the seat during normal activity.
3. The client must be supported in multiple positions or postures to allow him to shift his weight which will prevent pressure sores.
4. The device should be comfortable enough to sit in for 4 hours without discomfort.

4.6 Miscellaneous

1. The budget for our project is close to \$160 per project member, which totals \$480 for our team. With little financial input from the team members, the device should be under the allotted budget.
2. The device should facilitate physical activity on behalf of the client in order to help promote healthy development.
3. The device should be lightweight and able to be lifted by 1 person. Heavy lifting standards indicate that anything over 50 lbs should be lifted by more than one person to prevent injury.
4. The client has been helped enormously in the classroom by his modified desk and accessible laptop keyboard. The device should not diminish the functionality of, or otherwise detract, from the usefulness of these devices.
5. The client's favorite color is blue, and he requested that the device be blue in color. Preliminary design steps are not affected by this decision, but the final design should incorporate blue wherever possible.

Chapter 5: Functional Decomposition

A functional decomposition was completed, breaking the problem down into multiple tiers to determine the most important aspects of the device. The problem was broken down into six major parts(Figure 19).

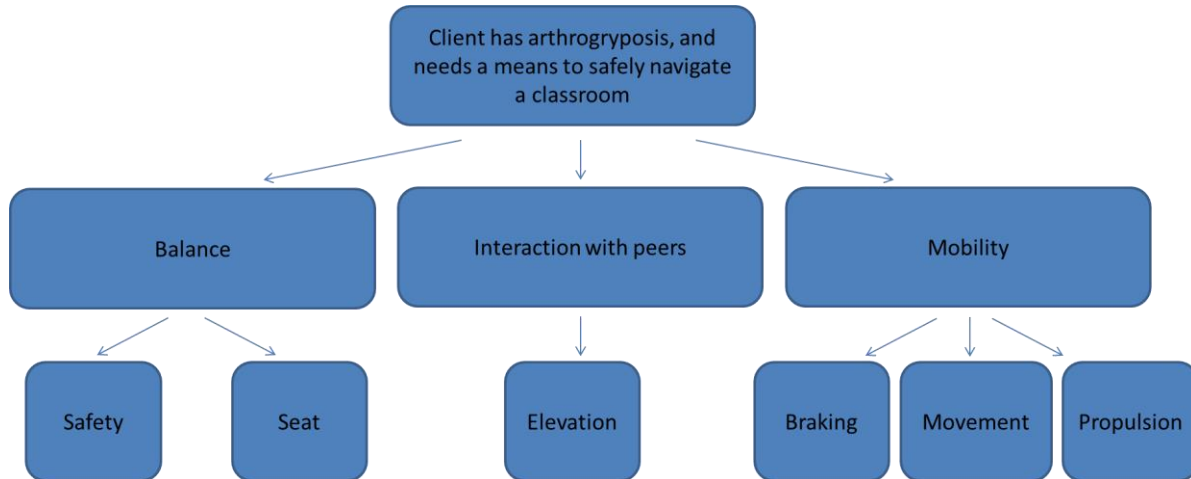


Figure 19: Functional Decomposition of the Problem

The problem was first divided into three major sub categories that were deemed to be the most important and vital to a successful design. These categories consist of balance, interaction with peers, and mobility. After determining the importance of these categories, they were further reduced to safety, seating, elevation, braking, movement, and propulsion. These six categories were then evaluated to create a large set of different methods that could fulfill each category. The categories were expanded to include mechanisms that could potentially satisfy that specific category. This was done to ensure that the design space remained large and any important aspects, method, or materials that could lead to successful creation of a device were not overlooked.

5.1 Balance

The device's ability to balance ensures the safety of the client, and as a result it is a vital part of the design process. As arthrogyriposis has hindered the client's use of his hands and arms, he struggles to balance when standing upright. Therefore, balance is essential because if the client falls he has no ability to break his fall, resulting in injury. Balance is also important for the client's everyday tasks such as writing, eating, and other activities within the classroom. The focus on balance ensures that client's safety is heavily considered within the design process. The two subgroups of safety and seating were placed within this section because they each have distinct aspects that are used to maintain the user's balance. For example, there are many safety mechanisms such as seat belts and supports, separate to the function of the seat, which can increase the balance of the client while using the device.

5.2 Interaction with peers

With his inability to stand, the client does not get to experience eye level day-to-day interactions with his peers. This can makes interactions difficult because he is always looking up at his fellow students, which can be detrimental to his mental health during preteen years, as peer

interactions are a large part of teenage development. The solution for this difference in heights is for his mobility device to place him at a higher level than the ground level at which he currently sits.

5.3 Mobility

Mobility is the single most important aspect of the device. As the client currently scoots to navigate the classroom, the primary goal of this device is to provide a more effective method of mobility around the classroom. Scooting causes many problems for the client including risk of injury, unsanitary hygiene, poor posture, and many other physical issues.

Chapter 6: Preliminary Design Process

6.1 Morphological Chart

A morphological chart was created to determine what specific features of the device could be used to meet the functions determined in the functional decomposition. A morphological chart allows for the creation of a wide variety of preliminary designs, thus increasing the design space. The chart contains different design options for the frame, number of contact points, movement, propulsion, steering, active braking, parking brake, restraint, seat, seat features, adjustability, and transfer method. In the morphological chart (Table 1) each row represents one of the functions identified in the functional decomposition. To the right of each function, all viable design options are listed. Design options were later selected from each category to create composite preliminary designs.

6.1.1 Frame

The style of the frame largely dictated many design decisions, including wheel arrangements and seating choices. Some of the frame options were more stable than others or restricted possible propulsion options. Additionally, some frame options were inherently stronger than others.

6.1.2 Contact Points

The number of contact points with the floor was a large factor in the stability of the device. The device required at least 3 contact points for static stability, but more were considered. Depending on the movement option, more contact points could reduce the device's maneuverability.

6.1.3 Movement

As discussed in the background chapter, the device's ability to navigate a classroom was a critical function. The device needed to make sharp turns and navigate narrow spaces. Additionally, the user will be using the device outside of the classroom, through the halls, into the bathroom, and into the cafeteria. Therefore the method for movement was ranked in a design matrix based primarily on durability, turning accuracy, independence or ease of use, stability, and cost.

6.1.4 Propulsion

The propulsion category coincides closely with movement. However, the propulsion of the device is specifically the mechanism that powers the device's motion. This can be divided into two sub-categories: powered propulsion and manual propulsion. Powered propulsion includes any system that requires energy to be stored on the device, e.g. electric motors and their batteries. Manual propulsion includes any system that requires input from the user, e.g. pedals. Both of these options have advantages and disadvantages within a device.

The main advantage of a powered device is that it allows the client to move very easily. Additionally, the speed of the device can easily be adjusted or limited. Though a powered device can be advantageous in that it is very easy to use, it would not likely provide much physical activity. The main advantage of a manual is its simplicity. Additionally, it would provide physical activity for the user, and

promote user independence. Methods for propulsion were ranked in the categories: health, ease of use, independence, speed, and cost.

6.1.5 Steering

Steering was not always independent from propulsion, for example, the user's legs could be used as the propulsion and steering method. Steering was especially important for the powered propulsion mechanisms.

6.1.6 Active Braking and Parking Brake

A braking mechanism is necessary for safety reasons. Brakes are important for many activities in the client's daily routine, such as transfers, sitting at the lunch table or his desk, and avoiding collisions in the hallways or otherwise. It was determined that having separate braking systems for active braking and parking could be advantageous, so they were considered separately. The different braking systems were evaluated in the following categories: independence, reliability, ease of use, engagement time, and cost.

6.1.7 Restraint

Safety is also a key aspect to the device design. As the client has no use of his arms and would be unable to catch himself in the event of a fall, a mechanism ensuring he does not fall out of the device was necessary. The restraint mechanism of preliminary designs was evaluated in the categories of independence, comfort, reliability, balance, and cost.

6.1.8 Seat

As the client will be in the device for the majority of the day, comfort played a major factor in selecting the seating. Furthermore, sores can occur due to incorrect seating and posture or extended periods without movement, so qualities such as correct seat depth, seat width, and padding were considered. To prevent sores, it is also recommended that the user have enough room within the device to change his position as needed. The seating design is also important for transfers, and can have great effect on the client's independence. Seating options were ranked in a decision matrix for balance, independence, comfort, pressure distribution, and cost.

6.1.9 Seat Features

An additional, but not mandatory, category was added for additional seat features, such as reclining or pivoting the seat. Seat features were seen to have the ability to either greatly enhance a design, or be unnecessary.

6.1.10 Adjustable Height

The purpose of adjustable height was to allow the user to be on a more equal level with his peers. Additionally, this could be used to make transfers easier for the user; the lower the seat is, the more easily the user would be able to get into the device. Finally, some kind of elevation mechanism

would increase the effective life of the device by allowing it to grow with the client. The adjustability mechanisms were ranked in a decision matrix with independence, ease of use, height differentiation, weight, and cost categories.

6.1.11 Transfer

As the client transfers in and out of devices during his day, it was important to consider different ways that these transfers could be simplified. Some transfer methods used mechanical devices such as an intermediate step, while others were simpler, by having the aide help transition the client.

Table 1: Example Morphological Chart

Functions of Device	Means to achieve each goal -->					
Frame	A-Frame	Circular Frame	Single Post (office Chair)	Polygonal	square	Semi circular (arch)
Contact Points	3	4	5	6		
Movement	caster wheels	single axle wheels	independent fixed axle wheel	caster/axle		
Propulsion	electric motor	track ball	eliptical	pedals	walking	
Steering	leaning	foot movement	rudder	handlebar/steering wheel	zero-turn bars	independent propulsion
Active Braking	disk brakes	bike brakes	pressure on wheels	clutch system	friction brake	footbrake
Parking Brake	wheel locks	friction pegs	lifting wheels off ground			
Restraint	lap bar	lab belt	torso belt	chest wrap	arm rest	underarm suport
Seat	bucket seat	platform	desk chair	sling		
Seat Features	reclining	standing	pivoting	rotating		
Adjustability	pushpins and tubes	fiction/pressure lock	threaded/screw	gears	ratcheting	
Transfer	ramp/slide	pulley	lower to floor	physical ability	tiliting chair	Aide

6.2 Creation of Design Alternatives

To remove impossible or incompatible designs, an evaluation was done that eliminated combinations from the morphological chart that would not create a functional device. This evaluation was done by pairing each aspect of the device against one another. This one-to-one comparison made it possible to determine which design features would and would not work together (Figure 20).

	caster /shaft	electric motor	track ball	elliptical	pedals	walking
caster wheels		X			X	
shaft wheels			X			
caster /shaft						
disk brakes						
bike brakes						
pressure on wheel						
clutch system						
dragging/friction on ground						
wheel locks						
lifting wheels off ground						

Figure 20: Component Pairing and Elimination

The Figure demonstrates that the combination of caster wheels and an electric motor was eliminated. This is shown by the gray “X” cell at the intersection of those two parts. The caster wheels were chosen out of the “movement” category of the morphological chart, and the electric motor was chosen from the “propulsion” category. Through discussion, it was determined that these aspects of the design would not be feasible together, and so it was eliminated. This was done for every combination of parts. Categories were not compared to themselves, illustrated by the blacked out cells between the *drive system* rows and *drive system* columns. This method was also useful in evaluating feasibility of different part combinations. Pairing two components together prompted discussion on how the components would interact, the pros and cons of each component pairing, how well the pairing could function, and ways they could be implemented into the device.

6.2.1 Preliminary Designs

Preliminary designs were created by selecting a component from each functional category; components were chosen depending on compatibility and feasibility of the design based on the results of the component pairing and elimination exercise (Figure 21).

Functions of Device	Means to achieve each goal -->			
Frame	A-Frame	Circular Frame	Single Post (office Chair)	Polygonal
Contact Points	3	4	5	6
Movement	caster wheels	single axel wheels	independent fixed axle wheel	caster/axle
Propulsion	electric motor	track ball	eliptical	pedals
Steering	leaning	foot movement	rudder	handlebar/steering whee
Active Braking	disk brakes	bike brakes	pressure on wheels	clutch system
Parking Brake	wheel locks	friction pegs	lifting wheels off ground	
Restraint	lap bar	lab belt	torso belt	chest wrap
Seat	bucket seat	platform	desk chair	sling
Seat Features	reclining	standing	pivoting	rotating
Adjustability	pushpins and tubes	fiction/pressure lock	threaded/screw	gears
Transfer	ramp/slide	pulley	lower to floor	physical ability

Figure 21: Preliminary Design Morphological Chart

For this step of the design process, it was a priority to create drastically different designs. This was important to prevent the designs from following a pattern, and ensuring that the entire design space was explored in depth. In total, six preliminary designs were created; each design was modeled in SolidWorks to improve the overall conception of the designs and to allow for basic static analysis. Of the six original preliminary designs, 2 were discarded, leaving 4 designs for final design selection.

Design 1

The first design was a very simple device that satisfied the client's needs. The original design, seen below in Figure 22, incorporated a circular frame with 5 contact points for optimum balance and weight distribution. The use of caster wheels would allow this device to move in any direction. The client would propel the device by pulling himself along in a motion similar to walking. The five caster wheels would mimic the movement of his current gait trainer. Wheel locks were incorporated into the caster wheels to provide stability during transfers or while working. An underarm support would keep the client upright and secure within the device, partially supporting his weight with his underarms. The sling style seat is lightweight and would form to the client's body and provide him with freedom of movement. This design utilizes indexed holes and pins in the frame to allow the device to expand and grow with the client. It is also important to note that the client would not be able transfer on his own with this device.



Figure 22: Design 1

Figure 23 shows the second iteration of Design 1, which was revised to include a pentagonal base with more clear space for the client to move his feet. A larger underarm support also provided a greater amount of back and lateral support (Figure 23).

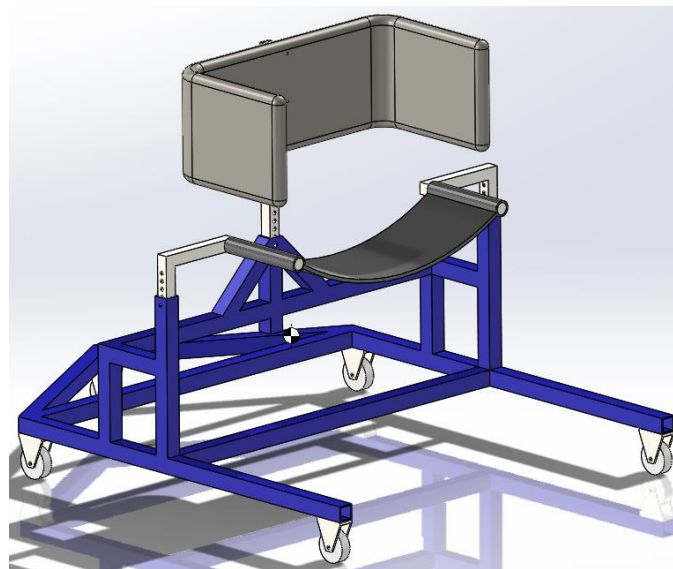


Figure 23: Design 1 Refined

Design 2

Design 2 incorporated an A-frame and six contact points with the ground. The six contact points included 4 caster wheels at the corners and two axle wheels underneath the seat (Figure 24).

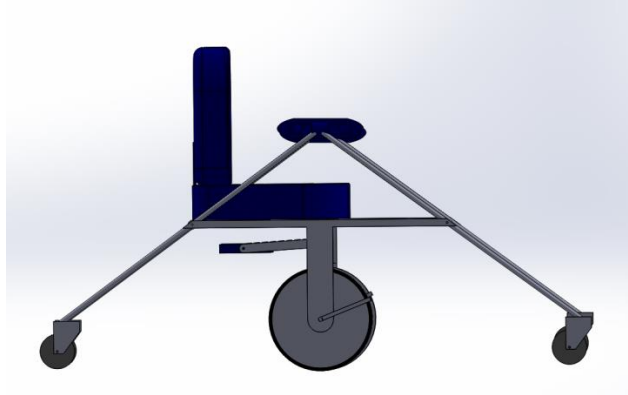


Figure 24: Design 2 Wheel Layout

By situating the axle wheels underneath the user's center of rotation, it allowed for zero-radius turns while restricting uncontrolled lateral movement. Similar to design 1, the user would use his legs to propel and steer the device. The device would be equipped with rim brakes on the axle wheels for active braking. This required the client to have an interface that could be accessed with his feet. The device would also be equipped with lockable brakes on the casters to act as parking brakes. A standard desk chair would be utilized for seating, providing comfort and blending in with the client's school. The armrests of the chair would also support the client laterally. The seat would be able to recline to allow the user to position himself differently for different activities e.g. writing versus walking. The design also included an intermediate step that would reduce the largest height that the user would need to overcome during transfers. A clamp system would be utilized to adjust the device dimensions as the user grew.



Figure 25: Design 2

This design was later revised; the frame was shortened to decrease the device footprint, and the axle wheels were made removable. This would provide the client with restricted lateral movement when needed, while giving him the option of maximum maneuverability (Figure 26).



Figure 26: Design 2 Refined

Design 3

Design 3 uses a base similar to a common office chair, with a single post in the middle of the frame. The post would incorporate a threaded mechanism for height adjustments to accommodate the client's growth. Design 3 has four contact points, all of which were caster wheels. Propulsion, active braking, and steering would be accomplished with the client's feet. Wheel locks were incorporated into the casters for parking. The design would also allow the client to tilt forward and backward, mimicking his posture in his gait trainer or while writing at his desk. Tilting could also make transfers easier. A platform seat and chest support would provide the client with the necessary underarm and lateral support, while giving him freedom of movement in his legs (Figure 27).



Figure 27 : Design 3

The refined design has a square base with an opening on one side (Figure 28). The side with the opening would give the client necessary foot space. The seat could be rotated to access the other side, which featured a pull-out desk. This desk would slide underneath the base and lock in place when not in use. The revised design included a second pivot that would allow the chest support to tilt, in addition to the seating surface. These could both be locked into discrete positions.



Figure 28: Design 3 Refined

Design 4

Design 4 was inspired by a saddle, where the client would straddle the device and propel it with his feet. The device would consist of four caster wheels and a square base, with a chest support for the client to lean against. The device would be adjustable using a scissor-lift style mechanism under the seat. Transfers would require the help of the client's aide (Figure 29).

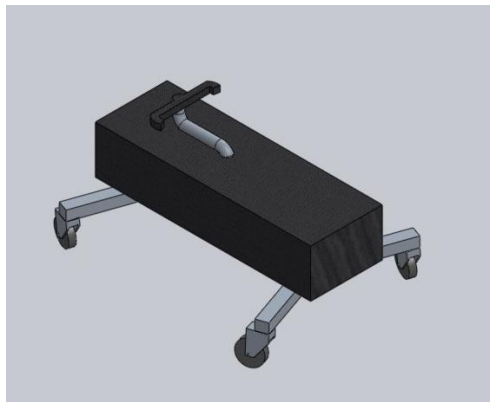


Figure 29: Design 4

This design could also double as a work station, by rotating the chest support to the side and moving the client's legs to one side of the device (Figure 30).

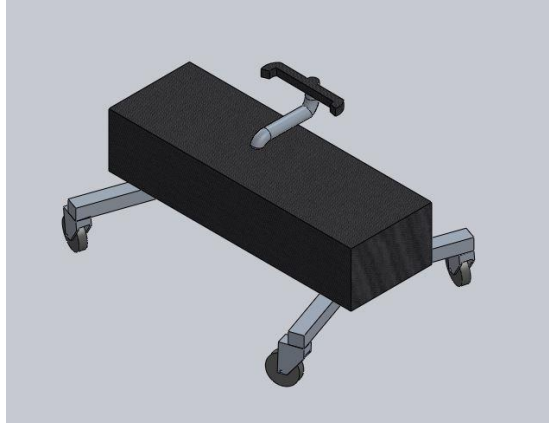


Figure 30: Design 4 Workstation

Discarded Designs

The first discarded design used a trackball for propulsion (Figure 31). This design had a bucket seat that could rotate to allow the user to either interface with the track ball or the floor, depending on the speed and control that the client desired. The design also used the combination of axle wheels and caster wheels used in design 2. The main advantage of this design was that the track ball would have translated a pushing motion into forward propulsion. This was seen as potentially easier for the client than pulling. However, the trackball was discarded because it was deemed to be inefficient, and was particularly bulky compared to the other designs.

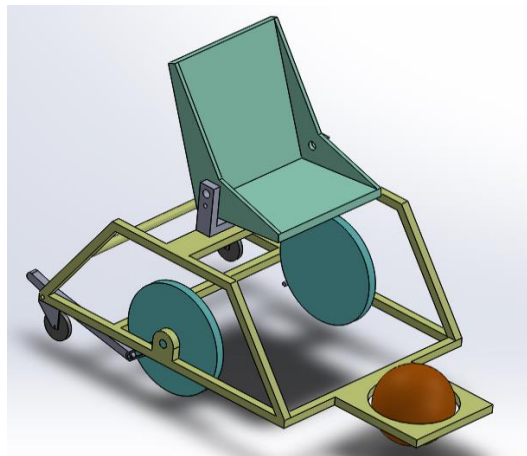


Figure 31: Trackball Design

Another design that was discarded was a “Go-Cart” type design. This design would have a bucket seat atop a square frame that would hold an electric motor to propel each wheel (Figure 32).

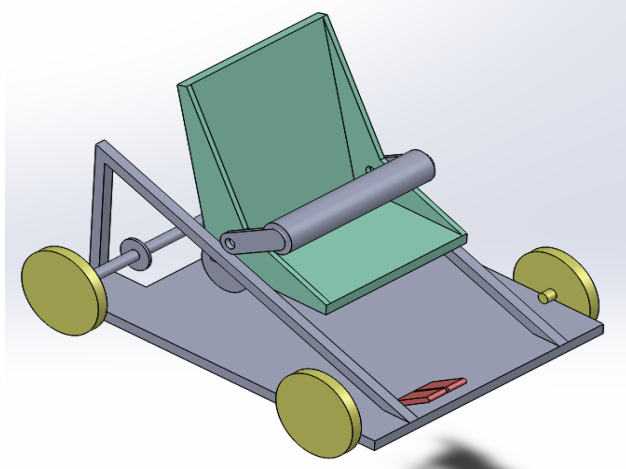


Figure 32 – Go-Cart Design

A lap bar was also included to keep the client within the bucket seat. A user interface would need to be designed to allow the client to operate the throttle, brakes, and steering. This design was ultimately discarded because it did not incorporate a zero turn radius which was considered critically important.

6.3 Design Selection

Using a decision matrix made the selection process for a final design logical and allowed for quantitative selection while avoiding bias towards any design. The matrix was created by first weighting design objectives under each function. This was achieved by using pairwise comparison charts (Table 2).

Table 2: Movement Pairwise Comparison Chart

Movement						score	weight
	durability	turning accuracy	independence	cost	stability		
durability	x	1	0	1	0	2	0.2
turning accuracy	0	x	0	1	0	1	0.1
independence	1	1	x	1	0.5	3.5	0.3
cost	0	0	0	x	0	0	0.1
stability	1	1	0.5	1	x	3.5	0.3

The pairwise comparison charts rate the relative importance of different design objectives by comparing each objective to the others one at a time. A “1” value in each cell indicates that the objective in the respective row is more important than the objective in the column, and a “0” if the column objective is more important than the row, and “0.5” if they are seen as equally important. For example, in Table 2 the intersection of the *durability* row and *turning accuracy* column has the value “1,” indicating that durability is a more important design objective than turning accuracy. Each row is summed to show the relative importance of each objective. From there, weights can be assigned to each objective corresponding to the row’s score.

Each mechanism used in the six categories (Movement, Propulsion, Braking/Locking, Safety, Seat, and Elevation) of the preliminary design receives a score on a 1-5 scale and is then multiplied by

the weight of the specifications within that category. Ideally, the concept that has the highest sum of scores should be used in the final design of the device.

In order to choose the best design to continue developing and prototyping, a decision matrix was made that considered the functions from the morphological chart (Figure 33). All of these functions appear in the decision matrix, with the exception of seat features. This was eliminated because the seat features category was seen as supplemental features to any design, and not necessarily something that differentiates designs at this stage. Each function was broken down into between 2 and 5 sub-categories to capture the purpose of each function. For example, the steering category was further broken down into; turning radius, ease of use, reliability, and precision. These aimed to relate each functional component to the design specifications (Appendix C: Decision Matrices).

		Design 1	Design 2	Design 3	Design 4
Frame	weight				
weight	0.1	4	3	4	4
strength	0.2	2	4	2	4
safety	0.3	4	4	2	4
stability	0.4	4	4	3	3
subtotal	1	3.6	3.9	2.6	3.6

Figure 33 - Sample of Decision Matrix

Through this process, Design 2 was chosen as the best design and selected for further development. Design 2 had the highest cumulative score in each category. Design 2 was very stable, and would protect the client in a collision due to the layout of the frame. While the footprint was larger than some other designs, safety was the larger concern, and design 2 was still within the design specifications. In addition, Design 2 was very directionally stable, due to the axle wheels preventing lateral movement. While the axle wheels restricted the freedom of movement slightly, they were intended to be removable for in-classroom use, where speeds would be slower.

The restraint in design 2 was a combination of the arm rests of the chair and the large back. This was similar to the setup that the client had at his desk which met his needs and worked well for him. Design 2 relied on the client to either slow with his feet, or use a small pedal to engage a bicycle-style rim-brake on the axle wheels. Both of these provided a high level of precision and allowed the client to apply the brakes with varying levels of force. Design 2 employed parking brakes similar to those seen on many wheelchairs, where a high amount of friction was applied directly to the tire to prevent its rotation. Design 2 was similar to his current chair, and easily incorporated padding to increase the level of comfort. The seat of design 2 was also adjustable to be ergonomically correct for the client. To adjust the size of the device, Design 2 used clamps and tubing similar to a bicycle seat. This mechanism was continuously variable and could easily be changed in less than 5 minutes with no tools. Design 2 also incorporated a small intermediate step to assist the client in lifting himself up into the seat. This step folded away and would not interfere with the client's propulsion.

6.5 Zero Order Prototyping

A Zero order prototype was created to mimic Design 2. The prototype was important as it demonstrated how the design would function and provided client feedback. The prototype was a scooter dolly that was equipped with four caster wheels (Figure 34).



Figure 34 – Caster Dolly

The dolly was vital in seeing how the device would move utilizing just casters. This zero order prototype was also used as a testing platform at the Norrback Avenue School to develop a better understanding of the client's abilities. The dolly was also modified with two axle wheels (Figure 35).



Figure 35 – Dolly Modified with Axle Wheels

The dolly was modified to determine if the wheel set up of two parallel axle wheels paired with four caster wheels helped to stabilize the motion, or if they would decrease functionality. The same tests were performed with both dolly setups.

6.6 Prototype Assessment

As part of the design selection process, a skills assessment was conducted to determine if the assumptions made about how the client would be able to move were accurate. The purpose of the test was to compare the four caster wheel set up with the caster and axle wheel design. The client was asked to complete three different tests on a variety of testing platforms. In these tests, he was asked to move in a straight line down a simulated school hallway; to navigate his way through a door; and to move in a figure eight around two obstacles (Figure 36). This required the client to navigate a hallway and confined space (Appendix G: Testing protocols).

Test 1: Long Distance Travel and Confined Maneuverability

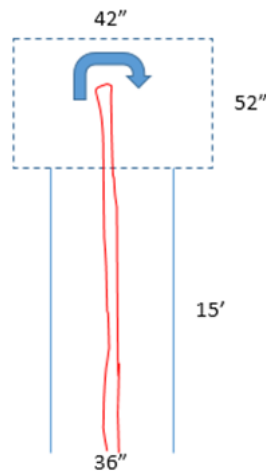


Figure 36: Testing Protocol for Long Distance and Confined Mobility Test

He repeated these tests three times overall, in his gait trainer (Figure 18); on the prototype that had four caster wheels (Figure 34); and on the prototype that had four casters wheels and two large axle wheels (Figure 35). Overall, the client's ability to navigate the obstacles and his sense of the size of his mobility device was impressive. He had very little difficulty with any of the activities, and quickly adjusted to each devices. The client is very resourceful, and seemed willing to try to learn how to use each device. When asked, he provided valuable feedback about his comfort level in the device, and ways that it could be improved.

The axle wheels provided additional stability and restricted the client's lateral motion while moving down the hallway. They were hard for him to use initially, but this might have been because he was not used to them. This confirmed that removable axle wheels were as an important design feature.

Chapter 7: Final Design

7.1 Changes Made to the Final Design

Throughout the design process, the overall design of the device changed from the preliminary models. These changes occurred as a result of concerns raised by the stress analysis on the device and to improve the overall manufacturability. There were four main design changes that occurred during the design process including: changing the shape and material of the frame; redesigning the attachment of the seat to the frame; changing the attachment of the axle wheels; and the changing the height adjustment of the chair (Figure 37). The final design image is shown without the chair attached to clearly show the seat attachment method.



Figure 37: Solidworks Models of Various Design Iterations, from Earliest (left) to Final Design (right)

One of the most important structural changes was the change in the design of the side members. The initial design (A) tried to incorporate the side members as part of the lateral support system of the device. However, it quickly became apparent that it was very difficult to create a strong, rigid structure in this arrangement. The decision was made to create a stable frame located below the device, and to make the seating an independent component. With this change, the design switched to the model shown in iteration B. This design used bent 1 inch diameter aluminum tubing to create a frame that lifted the seat off the ground, while reducing the risk of injury due to sharp corners. However, during the design analysis, these bent members raised some concerns, and were reevaluated. With the structural weakening that bending the tubing would cause, the stresses concentrated on this bend were dangerously close to the maximum tensile load of the aluminum. The bent member was changed to a straight 1 inch steel tube with a 0.12 inch wall thickness. The new design (Figure 38) was much simpler and eliminated the stress concentrations caused by the bending. Eliminating the bends of the frame lowered the overall height of the device, but the height of the cross members was increased to compensate.

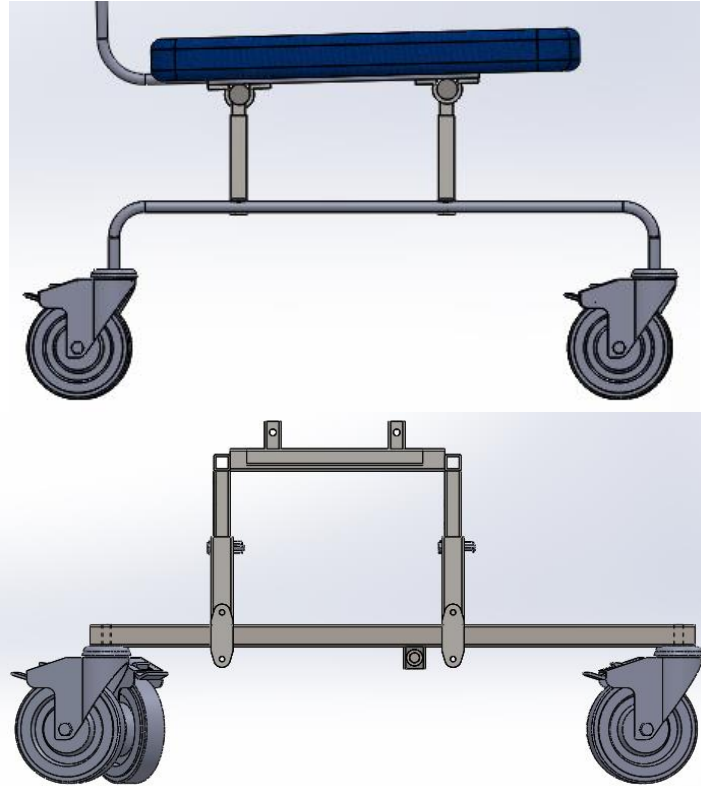


Figure 38: Original Design with Bent Frame (Top) versus Final Design (Bottom)

The original frame was held together using drilled holes and pins to secure the crossbeams to the frame. The main disadvantage to this design was that these holes became stress concentrators, increasing the chance of failure when a load was applied to the device. To eliminate these stress concentrations, the frame connections were redesigned to incorporate a clamp that would secure the cross members to the frame without damaging the existing structures. The seat is now attached by clamps that were custom designed for the device. The clamps (Figure 39) are fitted into the tubes of the cross members with approximately an inch of engagement creating a very strong hold without compromising the structural integrity of the device.

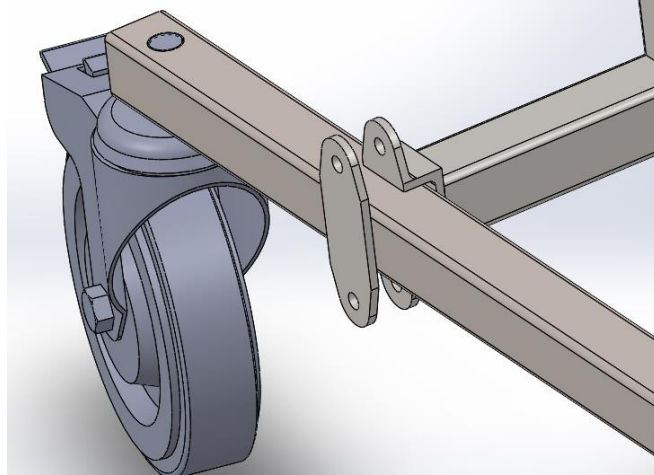


Figure 39: New Clamp

The advantages of the design change are that it allows for forward and aft adjustment of the seat, there are less stress concentrations, and it is a more secure method of attachment. The clamp is attached to the frame using 2 bolts, spacers, nuts, and a plate. The inside of the clamp uses rubber sheeting to generate greater friction for securing the crossbeams in place.

The original design had one upright in the front cross member and two in the rear. The reasoning behind this was to reduce the overall weight of the device. It was concluded that the more important attribute of the device is to ensure it is stable; therefore, the final design adds another upright to the front cross member. This allows for greater stability and more equal weight distribution through the front cross member (Figure 40).

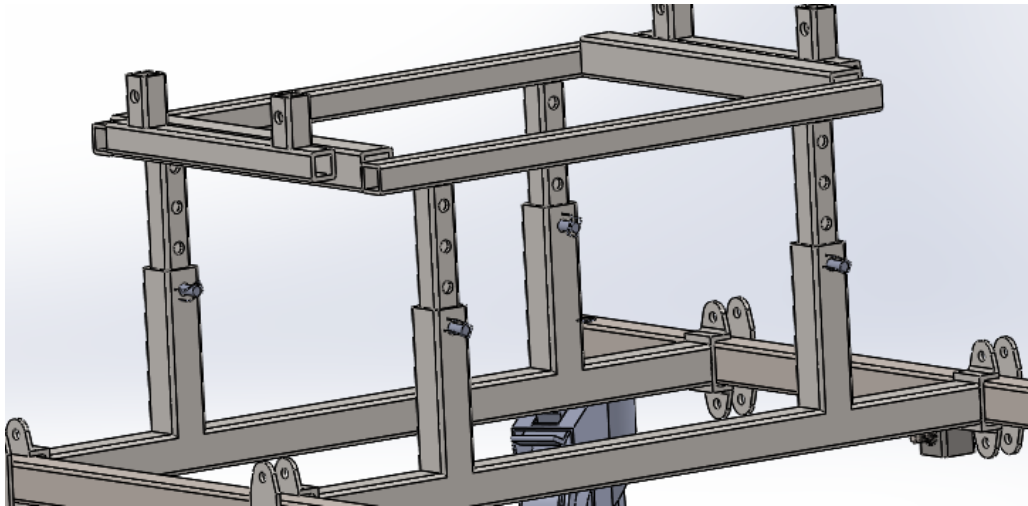


Figure 40: Upright Supports

In order to accurately depict the final design, the following terminology of the device's parts is demonstrated in Figure 41. The cross members span the width of the device and have 2 vertical seat

posts. The side members extend the length of the device and have a caster wheel mounted at either end. The cross members clamp on to the side members utilizing bolted clamps.

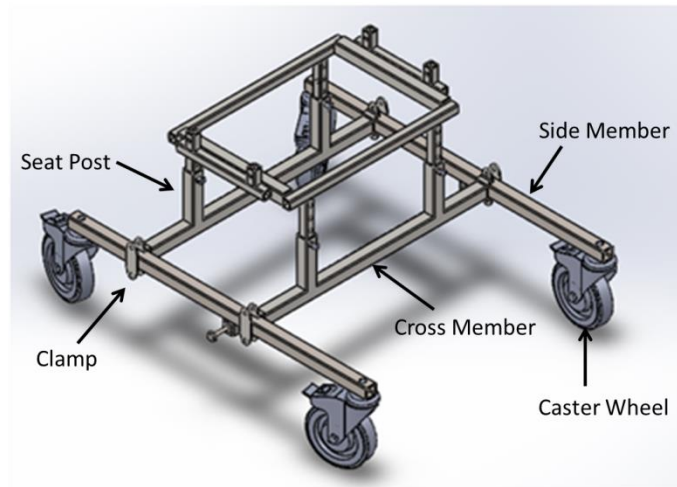


Figure 41: Device Terminology

7.2 Detailed Analysis

Given that the device will be used in a school, ensuring the device was safe was vital to the design process. The analysis of the device was conservative because the client's age and environment tend to be tough on technologies. The following sections explain the methodology of the static, dynamic, and collision analyses conducted on the device. These sections explain the process of the calculations, while Appendix I: Static and Dynamic Calculations contains the numerical results and equations. Positive X is the device right, positive Y is the device front, and positive Z is vertical (Figure 42).

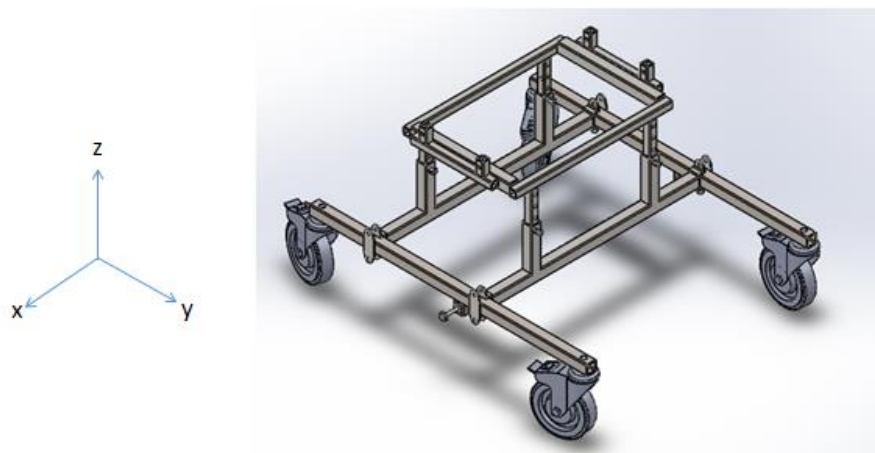


Figure 42: Device Coordinate System

7.2.1 Static Analysis

The static analysis models the most common uses of the device. This analysis assumed a predicted maximum loading of a 200 lb user, sitting on the very front or the very back of the seat. Due to the chosen bucket style seat, the assumption was made that the user would not be able to shift a considerable amount in the positive or negative x direction. The seat was assumed to be rigid, such that forces are only transferred in the Z-direction through the seat posts. As most classroom chairs are rated for 500 lb or more, it was assumed that any deflection would be negligible.

Due to the left/right symmetry, the reaction forces on the the device were found using two dimensions. Without this symmetry, the analysis would be statically indeterminate. W_1 and W_2 are two different cases of loadings. The location of W_1 demonstrates the force of the user's weight directly in the back of the seat, and W_2 represents the user's weight on the very front of the seat (Figure 43).

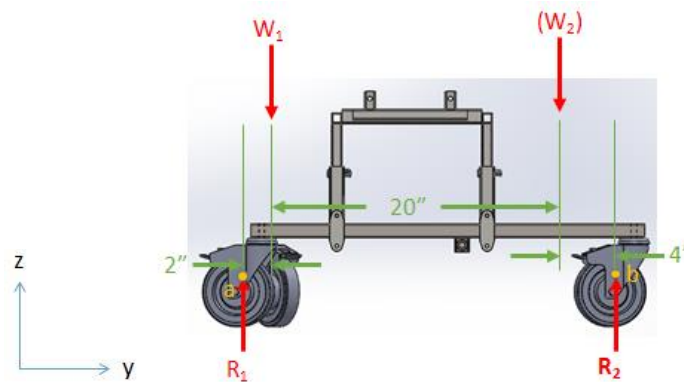


Figure 43 - Free Body Diagram for Ground Reaction Forces

Figure 43 was used to find the reaction forces up through the caster wheels. The weight of the user is demonstrated as two z-direction forces, W_1 and W_2 , which result in the ground reaction forces, R_1 and R_2 , at the axle wheels. The ground reaction forces were needed to analyze the side members of the device. Next, the internal reaction forces of the device were found, beginning in the vertical seat posts (Figure 44).

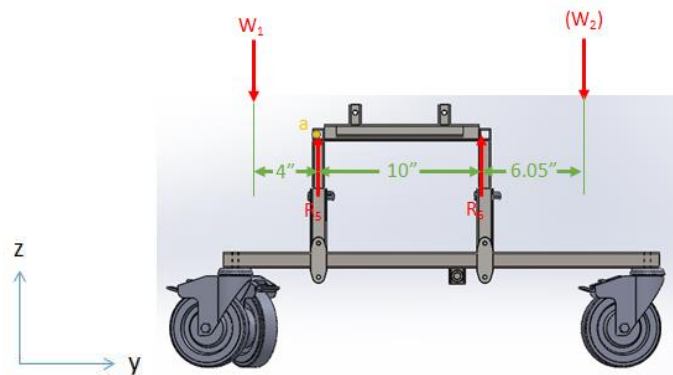


Figure 44 - Free Body Diagram for Reaction Forces at Seat Posts

The forces in the seat posts, R_5 and R_6 , were calculated in order to find the reaction forces, R_{RR} and R_{LR} at the attachment of the cross member and the side member (Figure 45).

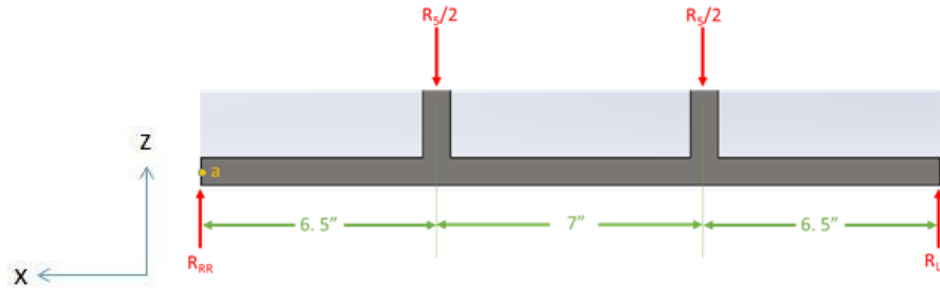


Figure 45 - Free Body Diagram for Cross Member Reaction Forces

The reaction moments paired with these forces were found using the equations in Figure 46. The two seat post loads were combined into one resultant force, P , placed on the cross member at a calculated distance from the attachment point, a .

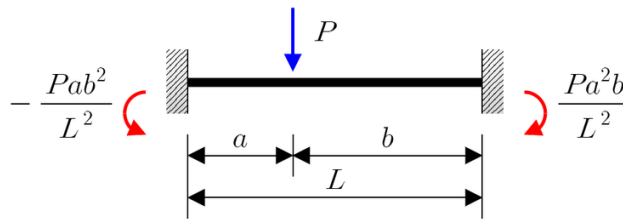


Figure 46 - Reaction Moments of Cross Member

Internal shear and moment forces were calculated at the cross member in 2 locations: between the seat posts and directly next to the left seat post (Figure 47, Figure 48 respectively). The symmetrical nature of the loading results in a stress that is the same on each side of the seat posts. This condition eliminates the need to investigate a third point (one between each reaction and applied load).

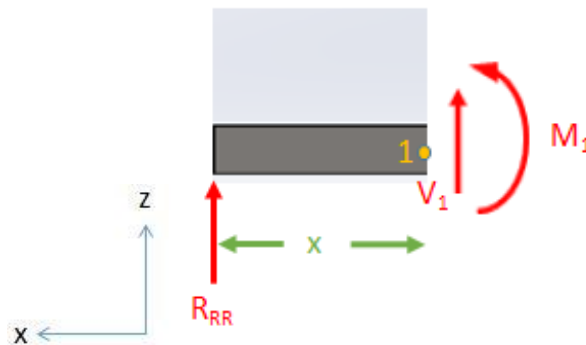


Figure 47 - First Free Body Diagram for Cross Member

The external force acting on the cross member at this point is the reaction from the side member, R_{RR} . This creates an internal shear force, V_1 , and an internal moment, M_1 .

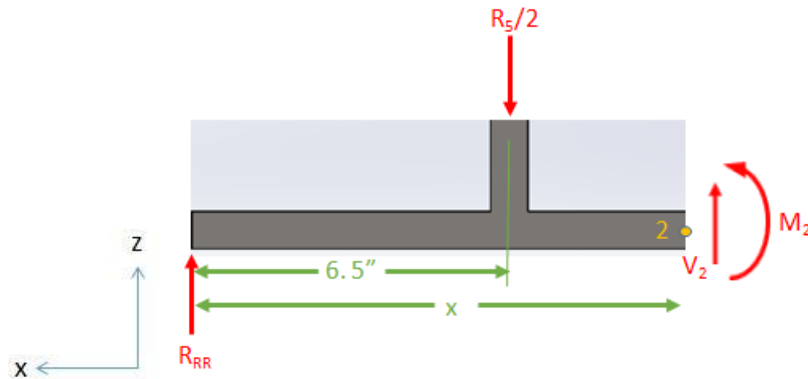


Figure 48 - Second Free Body Diagram for Cross Member

At the second point of analysis, two external forces act on the beam (Figure 49). These forces are R_{RR} , and the force of one of the seat posts, $R_5/2$. There is an internal shear, V_2 , and internal moment, M_2 , at this point.

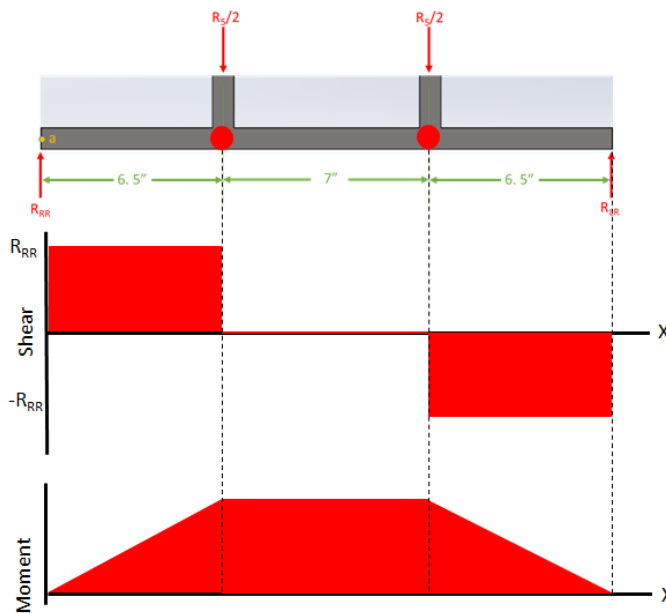


Figure 49 - Shear and Moment Diagram for Cross Members

The ground reaction forces from the caster wheels and the reaction forces from the cross member were used to calculate the internal forces in the side members. Three positions were checked for loading: the connection of the side member to the front cross member, the connection of the side member to the rear cross members, and in between the cross members (Figure 50, as points A, B, and C respectively).

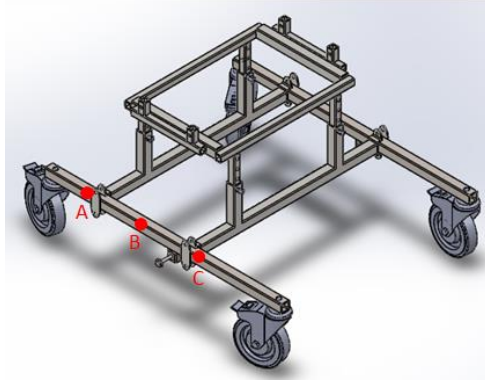


Figure 50 - 3 Points Investigated on Side Members

Due to the more complex loading of these members, three dimensional analysis was required. The free body diagrams for each point (A, B, and C) are represented below in Figure 51, Figure 52, and Figure 53.

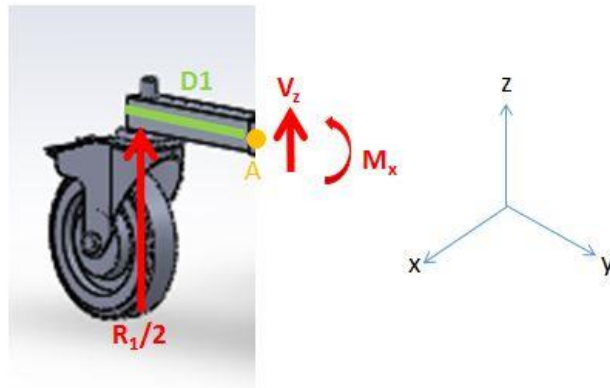


Figure 51 - FBD at Side Member Point A

The free body diagram for point A shows the only reaction force acting on the side member is the vertical force of the caster, $R_1/2$. There is only shear, V_z , in the Z and a moment, M_x around the X-axis.

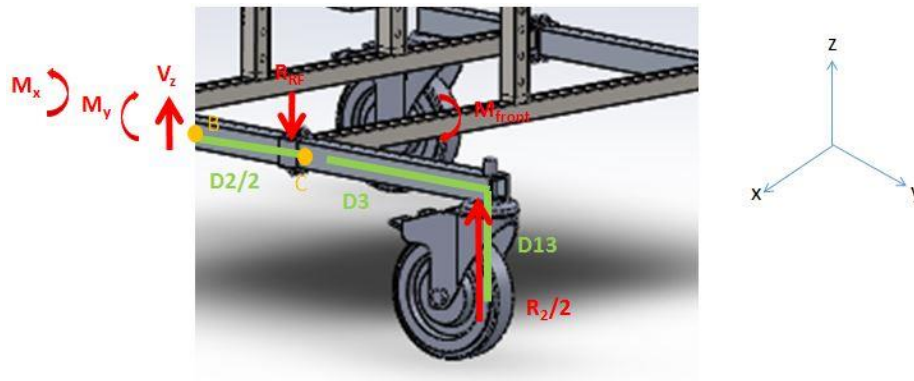


Figure 52 - FBD at Side Member Point B

At point B, there is the vertical reaction force through the caster ($R_2/2$), the downward force of the front cross member (R_{RF}), and the moment from the front cross member (M_{front}). These result in a vertical shear force (V_z), as well as moments around the X and Y axis.

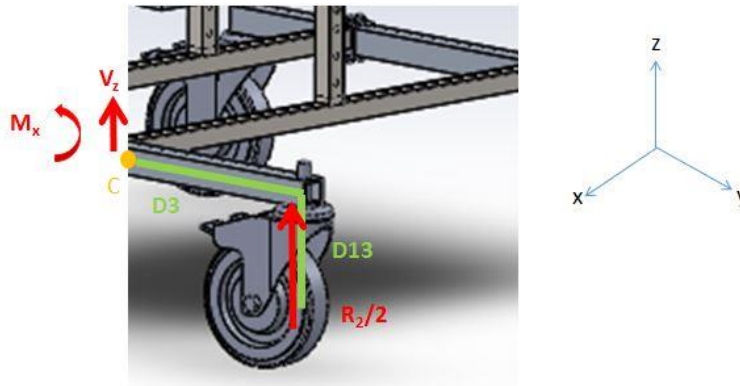


Figure 53 - FBD at Side Member Point C

The final point considered was immediately in front of the connection with the front cross member. The highest stress experienced during static loading occurred on the side member between the two cross members, and was 19 ksi. The location of the highest stress seemed counterintuitive, but was a result of two large moments acting in opposite directions on the y-axis.

7.2.2 Dynamic Loading

The dynamic loading analysis models a situation in which the client drops into his seat from a standing height. This was observed when the client transferred from the floor to a low platform. The client first stood up using the wall and then he fell onto the platform. It was assumed that the client drops from 6 inches above the seating surface. The force from this situation was simply substituted into the static loading analysis, as the forces will be the same throughout the device only larger in magnitude. The 200 lb load increases to a 352 lb load when dropped from this height, based on an impulse momentum calculation. This increases the maximum stress in the material from about 19 ksi to 35 ksi. This loading represents the absolute worst case of this dynamic scenario.

7.2.3 Collisions

Two collision scenarios were considered that could occur during the device's use. The first collision modeled the device crashing at a 45 degree angle into an obstacle at 4.4 feet per second, the average walking speed for an adult. The angle was chosen because the axle wheels prevent pure lateral motion, and a collision at 45 degrees would result in the highest lateral force on the side member. The second scenario was a head on collision of the same speed. For both collisions, it was assumed that only 1 point of the device collided with the obstacle; the very front of the frame side member. This part of the side member has the longest lever arm and would therefore see the highest stresses in a collision. The collision forces on the device for the two scenarios are represented in Figure 54, depicted by separate yellow arrows.

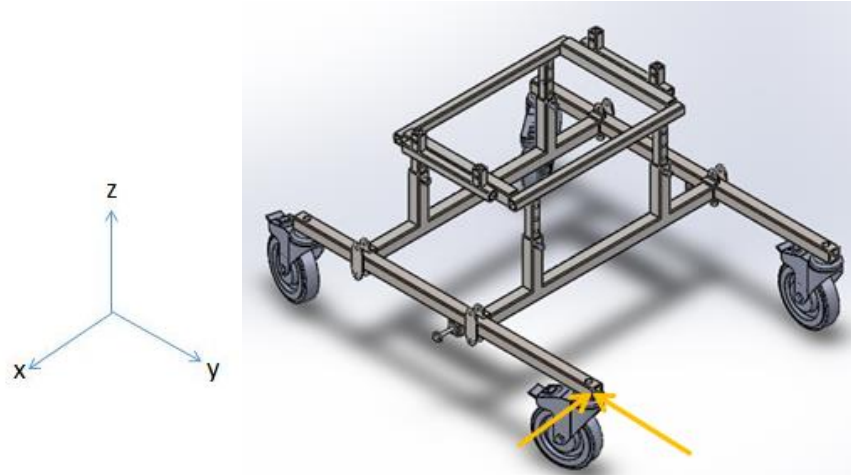


Figure 54: Location of Collision Forces

The collisions were modeled as simple impulse-momentum problems. These models took into account the change in velocity from colliding with a stationary object based on the collision time. It was assumed that in the angled collision case, the device would see a change in its x-velocity but not in its y-velocity. A coefficient of restitution of 0.5 was used to model a steel on concrete collision, representing the device colliding with a wall.

After solving for the collision force, the reaction forces and free body diagrams for the device were used to determine the Von Mises stress in the locations described in the static analysis. The vertical reaction forces through the frame were retained from the static analysis, but new FBDs were created of the side members to determine additional internal forces. The free body diagram for point A remains the same (Figure 55)

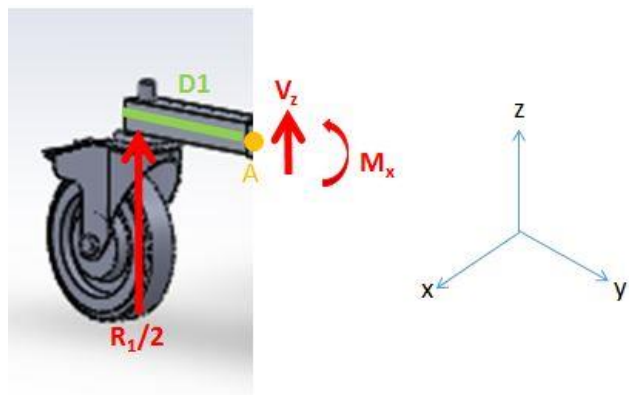


Figure 55: FBD at Side Member Point A in Side Collision

The second location, point B, experiences an additional reaction force, FF, in the X-direction for the cross members (Figure 56). This generates reaction moments in all directions.

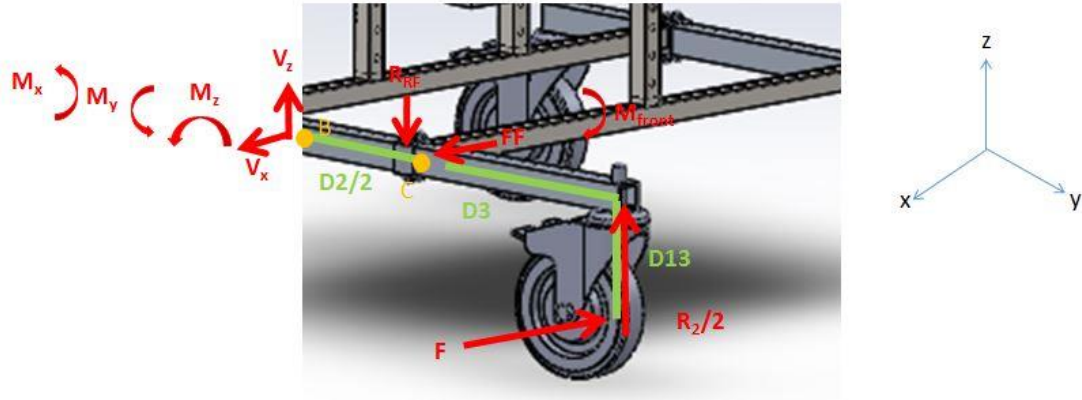


Figure 56: FBD at Side Member Point B in Side Collision

Figure 57 represents the free body diagram at point C, the point between the caster wheel and front cross member.

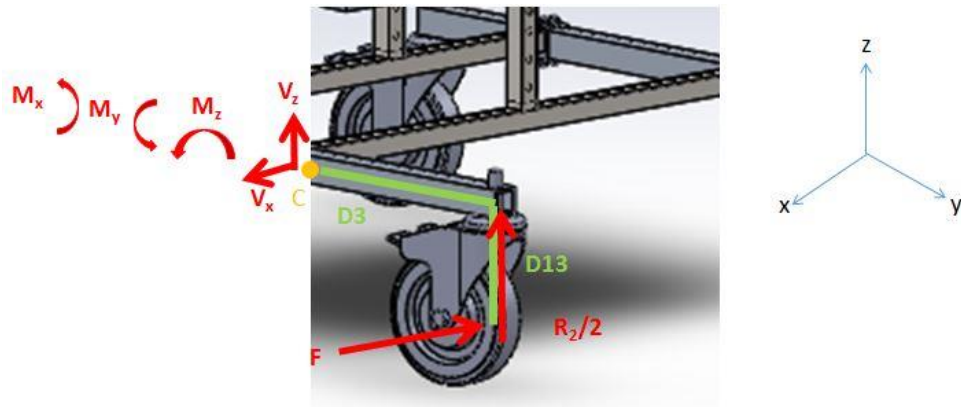


Figure 57: FBD at Side Member Point C in Side Collision

At point C the same scenario results where, moments are present in all directions. Also, a shear force in the X direction, V_x , is now apparent. Similarly, free body diagrams were created for a front collision (Figure 58, Figure 59, and Figure 60 for point A, B, and C respectively).

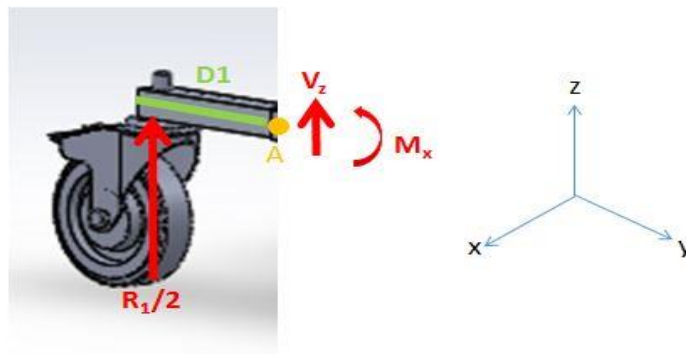


Figure 58: FBD at Side Member Point A in Front Collision

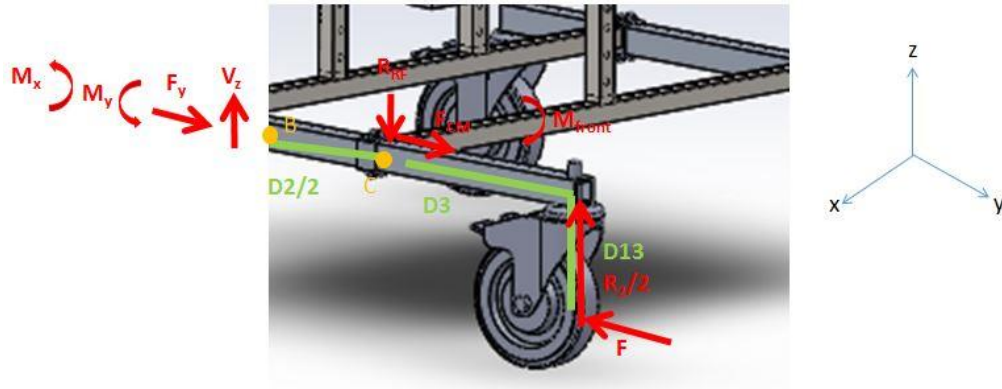


Figure 59: FBD at Side Member Point B in Front Collision

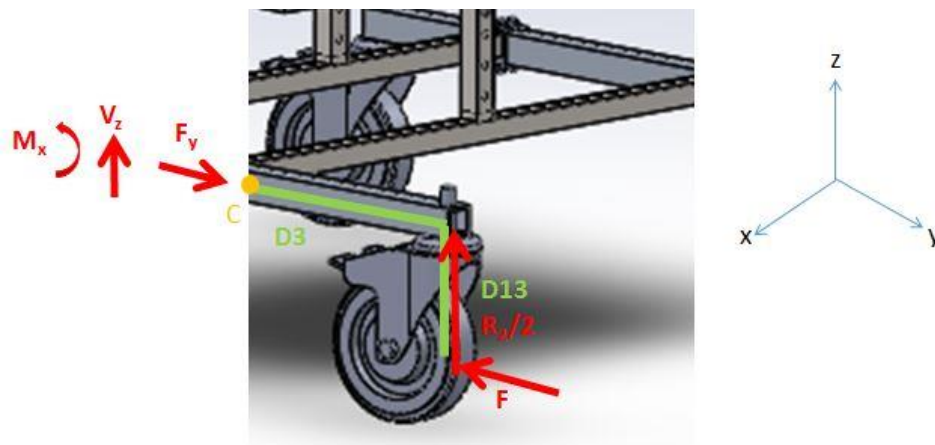


Figure 60: FBD at Side Member Point C in Front Collision

7.3 Component Selection

7.3.1 Steel Tube 0.12 inch wall thickness

1 inch and 0.75 inch square low carbon steel tubing with a 0.12 inch wall thickness was chosen for the main structural components of the device. The 1 inch tubing was used for all of the devices frame, including: the side members, crossbeams, outer seat posts, and seat attachment mechanisms. The 0.75 inch tubing is used for the inner seat posts and as part of the seat frame (Figure 61).

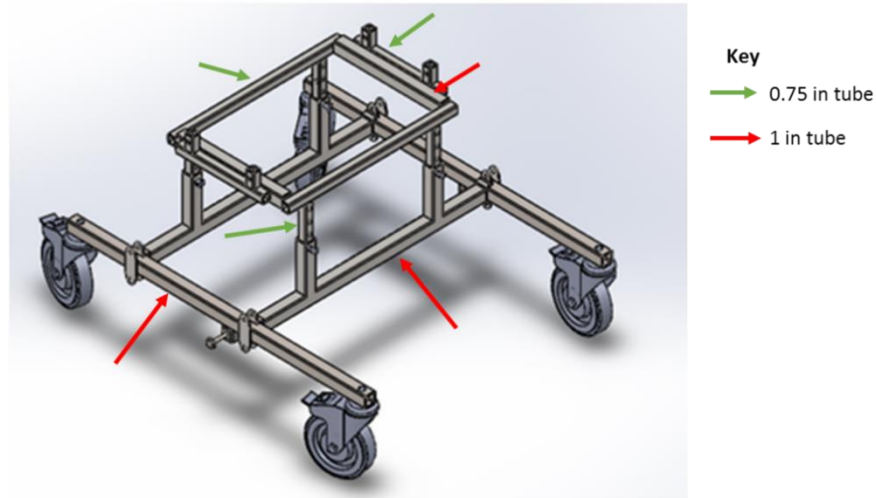


Figure 61: Location of tubing sizes

Steel was chosen because of its high yield strength of 42 ksi; which is higher than the worst case dynamic stress, 35 ksi. The frame utilizes the 1 inch tubing where the highest stresses are seen. The 1 inch tubing was also used for the seat uprights, so that the 0.75 inch tubing could fit inside and slide to allow height adjustment. Steel was heavier than alternatives, such as aluminum, but the high yield strength ensured the safety of the user.

7.3.2 Steel Stock for Frame Clamps

A 1.5 inch by 1 inch rectangular steel stock was used to fabricate clamps to connect the cross member and side member (Figure 62). A section of the clamp were custom designed with a male insert to fit inside of the 1 inch steel tube crossbeams. This insert was used to fixture the two pieces together.

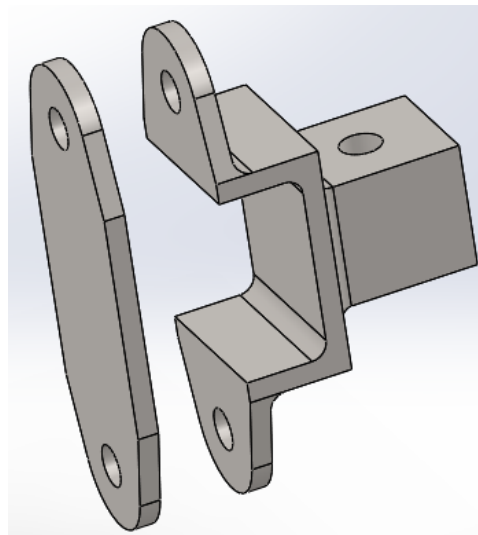


Figure 62: Framing clamp

Steel was chosen as the material to fabricate the clamps due to its high strength and manufacturability. In lieu of welding, the clamps were used to allow for forward and aft adjustment of the cross members.

7.3.3 Bucket Seat

A plastic molded bucket seat (Figure 63) was chosen because it looks natural in a school environment.



Figure 63: Ergonomic Bucket Seat

The advantages of the chair are its ergonomic design and padding, which add extra comfort for the client throughout the day. Another important feature of the seat is that its frame mounting points could be easily adapted to our design. The seat base (Figure 64), is attached to the base using the original hardware from the chair. The design considered the available lengths of materials to promote cost reduction and reduce excess materials.

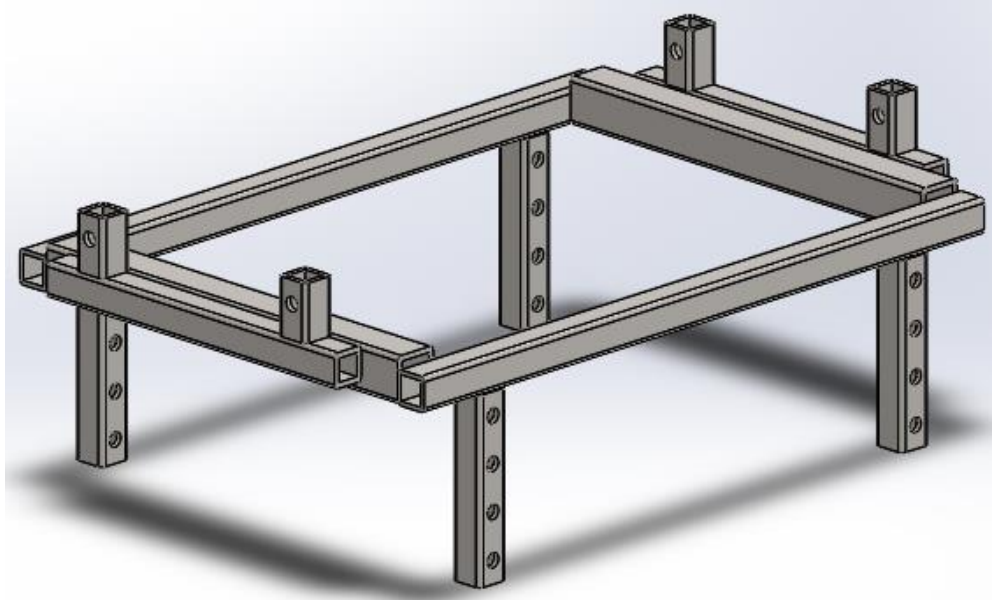


Figure 64: Seat base foundation

7.3.4 Caster Wheels

Caster wheels were chosen with a 250 lb capacity per wheel that are typically used for industrial applications, allowing for high strength and maneuverability. The caster wheels have a soft tread which is ideal for hard surfaces, such as tile. Each caster wheels has its own wheel lock that prevents rotation and swivel of the wheel.

7.3.5 Axle Wheels

The axle wheels are also made of a soft durometer material. This material allows for more fluid motion on hard surfaces.

Chapter 8: Manufacturing

Once all design and analysis was completed, the project moved into the manufacturing stage. The seat, caster wheels, and axle wheels came pre-fabricated, but the remainder of the device had to be manufactured from raw materials. The overall manufacturing of the device took about a week, and included milling, drilling, and welding.

8.1 Side Members

To construct the side members of the device, two 27.5 inch sections were cut out of a 6-foot section of the 1 inch square tubing using a chop saw. Each section had a half-inch hole drilled 1 inch from each end of the tubing for the stem of the caster wheel. The caster wheels were fixed using a locking washer, a bolt and were secured using Loctite™ thread glue to prevent loosening over time (Figure 65).



Figure 65: Exploded view of Caster Sub-Assembly

The two side members had four full caster sub-assemblies total (Figure 66). These side members comprised the outside of the frame, and were the first components completed during the manufacturing process.



Figure 66: Completed Side Frame Sub-Assemblies

8.2 Cross Members

The cross members were also made of the 1 inch steel tubing. Two 20.5 inch lengths were cut from a 6 foot length of tubing. To attach the cross members to the side framing, square brackets were needed, but they could not be found prefabricated. As a result, four clamps were milled out of 1.5 inch by 1 inch steel stock using a Haas Minimill. The clamps were custom designed using Solidworks, and the cutting path was designed in Esprit. They were designed to wrap around the thickness of the side framing, but to leave a small amount of clearance to allow for the addition of 0.125 inch foam to create a very tight seal and prevent slipping. The clamps were designed to require a press-fit into the cross members, and they were secured by drilling a 0.25 inch hole through the clamp and the crossbeam 0.5 inches from each end. This hole allowed a ¼-20 bolt, lock washer, and nut to be added to the frame creating a secure attachment point with no play. An exploded view of the connection is shown in Figure 67 and demonstrates the clamp and how it is attached to the cross member.

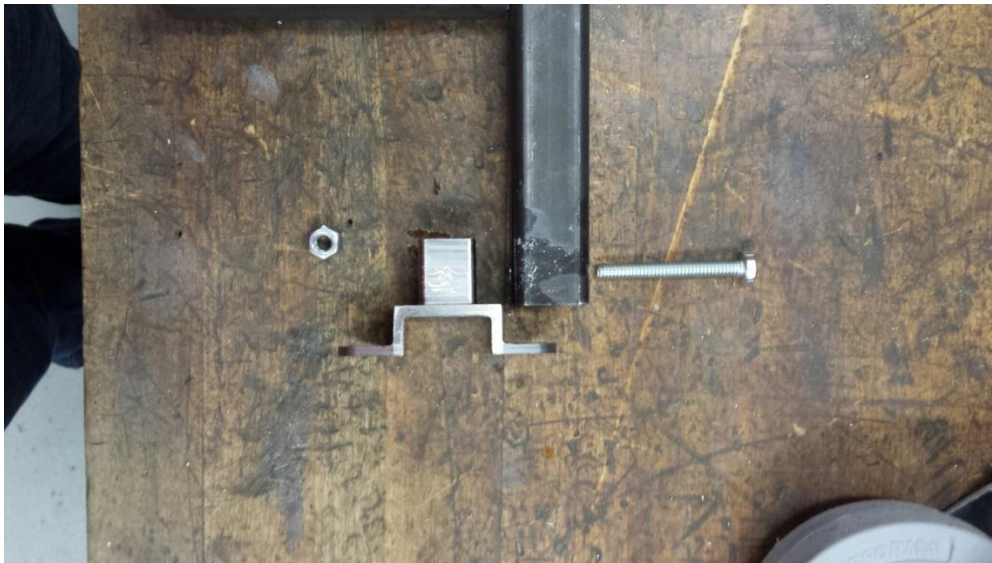


Figure 67: Clamp and Cross Member Sub-Assembly (Exploded)

The sub-assembly in Figure 68 demonstrates the completed connection.



Figure 68: Clamp Sub-Assembly (Completed)

The clamp is paired with an outer plate of 0.125 inch steel with two 0.25 inch holes drilled to accommodate the ¼-20 bolts needed to secure the cross members to the side framing. The sub assembly, shown in Figure 69, clamps the side rails firmly to the cross member creating the basic frame of the device. The addition of rubber on both inner surfaces allows the bracket to form a very tight seal and establish a secure hold with the side frame member.



Figure 69: Crossbeam Attachment to Side Frame

In order to create the adjustability of the seat, the cross members were fitted with two 4 inch sections of the 1 inch steel tubing. These sections were MIG welded perpendicular to the cross members and a 0.375 inch hole was drilled 0.5 inches from the top. The uprights are centered 11 inches from one another on each cross member. The other component of the adjustability included a section of the seat

base. The seat base had sections of 0.75 inch steel tubing cut into 4 inch sections. These sections fit into the 1 inch uprights with 0.01 inch of clearance, so they needed a grease to make the movement fluid. The 0.75 inch tubing had four 0.25 inch holes drilled 1 inch apart from each other to provide the height adjustment. Using quick-release pins through the uprights, the seat height was adjustable by 4 inches from 14 inches, the typical seat height for an elementary school chair, to 18 inches, the average height that a high school student would sit (Figure 70).

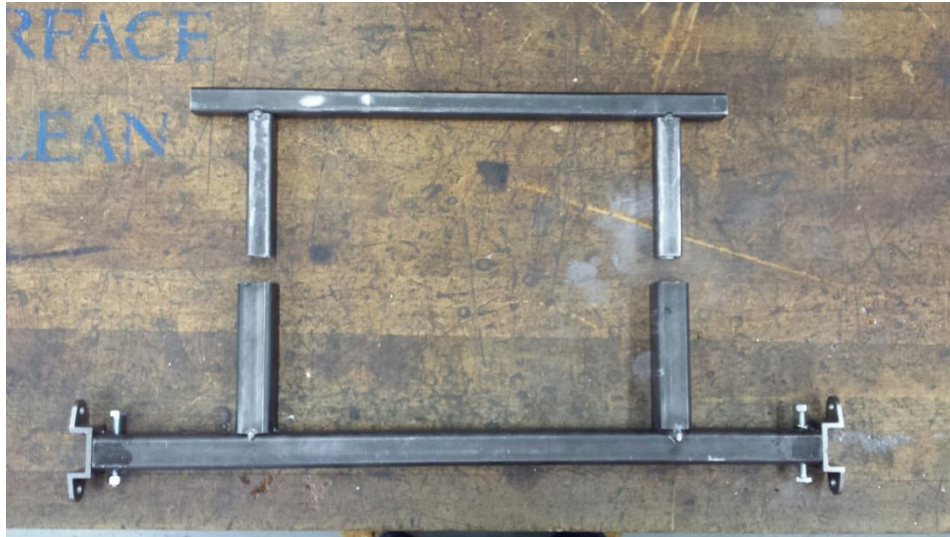


Figure 70: Height Adjustment Sub-Assembly

Once the first cross member assembly was completed, a second identical cross member was created. Once the two side members and the two cross members were completed, they were bolted together creating the device's frame. The completed frame (Figure 71) is very sturdy. The machined brackets and rubber created an extremely rigid frame. Figure 70 also demonstrates the pins inserted into the bottom part of the adjustability.



Figure 71: Completed Frame with Cross Members

8.3 Seat Framing

The seat that we ordered came completed with its own frame and legs. However, In order to attach the seat to the device's frame, the original legs had to be removed. The existing holes in the seat were adapted to be used with the device's design. To ensure the stability of the seat, a rectangular frame was created (Figure 72).



Figure 72: Seat Frame Ready for Welding

This frame is composed of 0.75 inch steel tubing for the long section of the frame, and 1 inch steel tubing for the smaller side members. A difference in size occurred because the chair had existing contours which made it impossible to construct the frame entirely out of the 1" tubing. This frame was welded together and extra care was taken to make sure that everything was level and squared off. This was especially important because this seat frame had to interface with the lower vertical posts to allow the uprights to slide for the seat height adjustment. An intermediate step of the welding is shown in Figure 73.

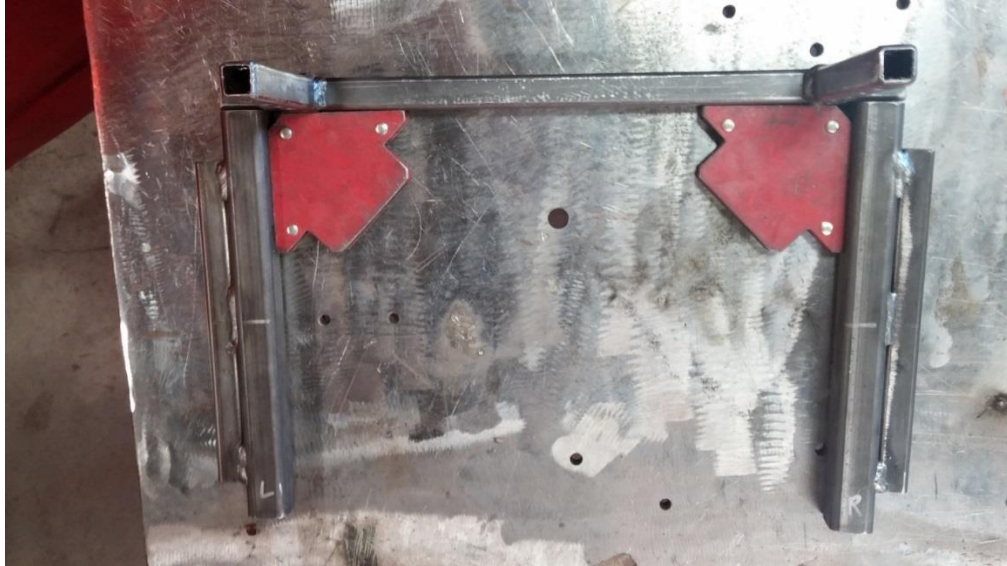


Figure 73: Seat Frame Welding Assembly

The existing holes in the seat were slightly recessed, which meant that it would be difficult to attach the square frame directly to the chair. As previously mentioned, the contour of the seat prevented the frame from sitting flush against the bolt holes, so a small vertical offset had to be designed. To interface with the seat, four small posts were made out of 0.75 inch tubing and were welded to the top of this rectangular frame. These posts were drilled to allow for a bolt to be placed through the existing holes in the seat and tightened down. The entire seat base assembly was attached to the seat using 0.3125 inch bolts through the pre-existing bolt holes (Figure 74). Once the seat frame assembly was complete, it was connected with the bottom section creating the completed device frame.



Figure 74: Plastic Molded Seat

8.4 Axle Wheels

The device also incorporates two axle wheels on the side members which are used to give the device additional stability by preventing lateral motion. These wheels are centered on the chair's center of rotation which ensures a zero-turning radius. To attach the axle wheels, 1.25 inch steel tubing was cut into a two 3 inch sections. This section of tubing slipped over the 1 inch side members allowing the wheel location to be adjusted. A section of 1 inch tubing was welded vertically onto this sliding mechanism and a hole for the axle was drilled through the 1 inch tubing. The axle was secured using a lock washer and a 0.5 inch nut on the axle. In order to hold the wheel securely in place, rubber was used to shim the outer tubing, and a 0.25 inch nut was welded onto the 1.25 inch piece so that a thumb screw could be used to lock it into position. This method was chosen because it allows the position of the axle wheel to be shifted if the user has any problems with the location (Figure 75).



Figure 75: Axle Wheel Attachment

8.5 Armrests and Seatbelt

Once the entire frame was completed, the secondary accessories had to be attached. The seatbelt and armrests were an easy addition to the overall device frame. Although the student doesn't have use of his arms, the armrests are height adjustable and well-padded to provide the client lateral support while he is seated and moving in the device. These arm rests were attached to the existing seat frame through three drilled holes. The armrests were then attached using three ¼-20 bolts through the corresponding spots on the seat support. The device also has a seatbelt which is used to keep the client in the seat throughout his day. The seat belt is attached through the same holes that attach the chair to the manufactured frame. The seat belt is a replacement car seatbelt, and comes with attachment plates and hardware which were used to secure it to the chair. The completed device, with armrests and seatbelt attached, is shown in Figure 76.



Figure 76: Device with Armrests

8.6 Safety Precautions

Once the device was completely manufactured, it was important that safety precautions were taken to address any areas of concern. All sharp edges and burrs were carefully removed, leaving any hard corners rounded off, and no pinch points were left on the frame. Any protruding nuts or bolts were trimmed, smoothed down, and covered with rubber caps to reduce the risk of injury. The clamps were covered by foam pipe insulation which eliminated any hard edges, and provided padding in the event that someone fell on the device or kicked it.

8.7 Full Device

The completed device is pictured below. Once all changes were made, the bare metal was coated in a Rustoleum™ protective paint to prevent rusting, and ensure the longevity of the device. The paint was blue because it was the client's favorite color and would help to ensure he like the appearance of the device (Figure 77).



Figure 77: Completed, painted device

Chapter 9: Verification and Testing

Once the design and fabrication of the device was completed, the design had to undergo verification to ensure that the design specifications were met. Once all specifications were met, the device was taken to the school to begin testing by the client.

9.1 Safety and Stability

1. *A Braking and Locking Mechanism* – The device’s caster wheels have locks which prevent the wheel from spinning, and also prevent rotation of the entire caster. The device is unable to move when two of the caster wheels are locked, but up to four can be locked for added safety. For active braking, the chair is designed to be stopped by the user’s feet contacting the ground. The device was able to stay stationary on a 14 degree incline with two caster wheels locks activated.
2. *The device must be able to support the weight of a 200 lb human* – The device was loaded with 200 lbs of weight and left overnight to see if any damage occurred. There was no damage after 24 hours of continuous loading, so the chair was deemed to support up to 200 lbs safely.
3. *Device should not tip over at a 14 degree incline per wheelchair safety standards* – The device was loaded with 200 lbs in the seat, a 40 lb backpack was hung on the back, and the chair was inclined up to 14 degrees. The chair had no tipping up to 14 degrees in all directions.
4. *Device should not tip in the event that the device collides with another object while travelling at 1.5 times the normal walking speed (7.5 feet per second)* – Although this was not tested with the actual device, to prevent damage, the CG analysis (Appendix H: Center of Gravity Calculations) indicated that the device would not tip as long as the CG was less than a foot and a half above the ground. The device’s CG is only about seven inches off the ground, meaning that it should have a safety factor of about two in this collision case.
5. *The center of gravity (CG) should be less than 75% the total height of the device* – The device’s CG is approximately 7 inches off the ground, which is approximately 50% of the total height of the device.
6. *The Device’s CG should sit within its contact points, with the floor, when viewed from above* - The Device’s CG is approximately in the middle of the device, meaning that it has about 10 inches in any direction before the device would be at risk of tipping.

9.2 Maneuverability

1. *The device should be no wider than 28”* – The device is 27.5 inches wide at the widest point.
2. *Must be less than 38” long* – The device is 28 inches long

3. *The device must be able to have zero-turning capabilities* – The Fixed axle wheels are aligned with the device's center of rotation ensuring that the device will have a zero-turning radius. These wheels are also adjustable to allow the center of rotation to move as needed.
4. *The device should weigh less than 50 pounds* – The device weighs 45 pounds
5. *The device must allow the client to self-propel* – The device requires the user to pull himself through the school using his legs, encouraging healthy muscle development, particularly in the hamstrings.

9.3 Adaptability

1. *The seat height should adjust to be the same as the average seat height for a school chair* – The device's seat height can adjust from 14 inches to 17 inches at 1 inch increments.
2. *While sitting, a person's calves should be perpendicular to the ground* - The adjustable height of the device will ensure that the client is always able to sit in this position. The lowest setting was chosen based on the client's current shank measurement, and the maximum height was chosen based on his projected growth due to anthropometric data.
3. *The seat must be large enough to accommodate the client as he grows from 8 years old up into high school* – The seat comfortably seats adult males ranging in age from 8 to 22. This range should encompass his growth over the next few years.
4. *The device is designed to last for several years so the materials it is constructed from must be able to survive 6-7 years of use* – Steel is an extremely robust material, and will be able to withstand the abuse that the device may see over the next few years.

9.4 Comfort

1. *The client must be supported in an anatomically correct position* – The chair that is used in the device is designed to be an ergonomic seating system, holding the user in an anatomically correct position. A lumbar support was also added to increase the comfort and support of the chair.
2. *The client must be laterally supported to prevent him falling out of the seat during normal activity* – The addition of the armrests prevents the client from falling out of the device. The seatbelt also allows the student to move around freely in the device but prevents him from falling out of it.
3. *The client must be supported in multiple positions or postures to allow him to shift his weight which will prevent pressure sores* - The student is able to move freely in the device while still being held safely by the seatbelt and the armrests.

4. *The device should be comfortable enough to sit in for 4 hours without discomfort* – The client has used the device for two weeks of continuous use in the school, and when asked about how it felt he said “It’s more comfortable than my gait trainer! Do I have to get out?” The seat’s padding and the addition of the lumbar support should allow continuous use without any discomfort.

9.5 Miscellaneous

1. *With little financial input from the team members, the device should be under the allotted budget* – The device costs \$450 for all manufacturing, prototyping and development. This left approximately \$30 in the budget.
2. The device should facilitate physical activity on behalf of the client in order to help promote healthy development.
3. *The device should be lightweight and able to be lifted by 1 person.* Heavy lifting standards indicate that anything over 50 pounds should be lifted by more than one person to prevent injury. The device weighs 45 pounds which is under this limit. It is able to be moved by one person, and can even be lifted into a car or truck in the case that it needs to be transported.
4. *The device should not diminish the functionality of, or otherwise detract, from the usefulness of his modified desk and accessible laptop keyboard* – The client is able to interface with these device as well as, or better than, he was able to before using the device. The mobility device holds him in a position that allows him to easily access these assistive technologies.
5. *The client’s favorite color is blue, and he requested that the device be blue in color* – Everything except the physical chair of the device has been painted blue.

All of the design specifications were met, indicating that the design was successful. Once the device was verified, the device was taken to the school to begin testing and use by the client.

9.6 Testing

On the initial trip to the school with the device, the client was asked to repeat the tests he conducted at the start of the project, this time using the new device. After only a short time, he was able to easily complete all tests that were created, and repeatedly asked for more difficult tests. The client was asked to navigate a series of obstacle courses to demonstrate his maneuverability (Appendix G: Testing protocols). Once he was comfortable, he was allowed to take the device out into the school and interact with the doors, elevators, and other obstacles he would see throughout his day. The initial testing was so successful that the device was left at the school for the client’s use for two continuous weeks. After those two weeks, the client had no problems, and was very comfortable using the device in his day to day activities. This indicated that the device was extremely successful, and the device was left at the school for his continuous use over the next few years.

Chapter 10: Conclusions and Future Work

The device was very successful in meeting the client's needs. The device enables him to be more independent in his school day, and also encourages him to improvise and learn new ways to do things. After only using the device for a week, the client was able to do everything expected of him, and greatly adapted to the device. In addition to the device meeting his needs, it was important to ensure that he enjoyed the device.

The design gives the client increased dependence throughout his entire school day. He can use the device to navigate through hallways, bathrooms, and in the tight spaces of the classroom. This prevents the student from scooting along the floor as he had done in the past and therefore makes his day much more hygienic. The device can also be used as the client's desk chair in the classroom. This eliminates the need for him to transfer into a common desk chair. The client also has a pencil box outfitted to the device that he can store pencils for use at his desk. Another aspect that increases the independence of the user is his ability to enter and exit the device unassisted with the exception of the seat belt. The client can also exit the device and adjust the armrests as needed with his feet, to suite his liking.

The other very important success in this device is that it encourages physical activity and muscle development for the client. As the device requires the client to shuffle his feet beneath himself, it creates a physical type of mobility that both his physical therapist and aide wanted to see out of the device.

Another successful attribute of the device is that it replaces the need for his other existing such as the stroller and gait trainer. The device completely eliminates the need for the stroller within the building, as it was used to get him from class to class. Transfers in and out of devices are also reduced as he needs fewer devices to take him through his daily activities. The client will still have to use the gait trainer to use outdoors for activities such as recess, as the device is designed for indoor use only.

Compared to the devices he currently uses, the designed device is much more inexpensive as represented in Table 3.

Table 3: Prices of Devices

Device	Price
Final Assistive Mobility Design	\$450
Rifton Pacer™ Gait Trainer	\$610+ (Base Frame Only)
Permobile™ Power-chair	\$6,000
Convoid™ Adult Stroller	\$1,800

Overall, the client thoroughly enjoys the device and even shows it off to his fellow classmates (Figure 76).



Figure 78: The Client in the Device

Some quotes from the client in regards to the device include:

- “I like it, it’s really good and it looks like you put a lot of work into it.”
- “Do I have to get out?”
- “It’s like it [the device] reads my mind!”
- “I like it better than my gait trainer”
- “It feels like it weighs one pound!”
- “I can actually use this in the classroom and at my desk?”
- “This is way too easy [to use].”

Though the client is satisfied with the device, future work could be done to improve the design. One addition could include spring loaded, or shock absorbing, caster wheels, to ensure all wheels are in contact with the floor at all times. A different wheel configuration that also allows for the restriction of lateral movement but creates a zero turn radius could be investigated to further reduce the size of the device. All terrain wheels would also be a useful addition to the device so he could use it for outdoor scenarios, such as recess. One useful attribute that could be looked into is a mechanism that allows for the client to stand while in the device. This would entirely eliminate the need for any other device throughout his school day, and eliminate any transfers.

Bibliography

- "AAB Rules and Regulations (PDF)." *AAB Rules and Regulations (PDF)*. N.p., n.d. Web. 03 Oct. 2013. <http://www.mass.gov/eopss/consumer-prot-and-bus-lic/license-type/aab/aab-rules-and-regulations-pdf.html>.
- "Adaptive Mobility." *Adaptive Mobility Positioning Blog by Rifton*. N.p., n.d. Web. 03 Oct. 2013. <<http://www.rifton.com/adaptive-mobility-blog/use-of-pacer-gait-trainer-1/>>.
- "amcsupport.org | Arthrogryposis Multiplex Congenita Support, Inc." *AMCSUPPORT.ORG | Arthrogryposis Multiplex Congenita Support, Inc.* N.p., n.d. Web. 17 Oct. 2013
- "Arthrogryposis Multiplex Congenita Support, Inc." *AMCSUPPORT.ORG*. N.p., n.d. Web. 02 Oct. 2013.
- "Arthrogryposis." *Shriners Hospitals for Children* -. N.p., n.d. Web. 02 Oct. 2013. <http://www.shrinershospitalsforchildren.org/CareAndTreatment/Orthopaedics/Arthrogryposis.aspx>
- "Disability Stats and Facts." *Disability Funders Network*. 2012 N.p., n.d. Web. 16 Oct. 2013. <http://www.disabilityfunders.org/disability-stats-and-facts>
- "History of Accessible Facility Design." *WBDG*. N.p., n.d. Web. 03 Oct. 2013. <http://www.wbdg.org/design/accessible_history.php>.
- "Rifton Pacer Gait Trainers." *Rifton Pacer Gait Trainer, Fully Adjustable, Durable Mobility Device*. N.p., n.d. Web. 10 Oct. 2013.
- Frost, H.M. "Wolff's Law and bone's structural adaption to mechanical usage: an overview for clinicians" *Angle Orthod*. 1994; 64(3): 175-188.
- Chen, Harold, MD. "Arthrogryposis." *Medscape*. Ed. Bruce Buehler, MD. N.p., 15 Feb. 2013. Web. 20 Sept. 2013. <<http://emedicine.medscape.com/article/941917-overview>>.
- Cooper, Rory A., Hisaichi Ohnabe, and Douglas A. Hobson. *An Introduction to Rehabilitation Engineering*. Boca Raton: Taylor & Francis, 2007. Print.
- Hesse, S., D. Uhlenbrock, C. Werner, and A. Bardeleben. "A Mechanized Gait Trainer for Restoring Gait in Nonambulatory Subjects☆." *Archives of Physical Medicine and Rehabilitation* 81.9 (2000): 1158-161. Print.
- Kenealy. 2013. [Interview].
- Nichols, Trisha, "Natural history study of arthrogryposis multiplex congenita, amyoplasia type" (2011). UT GSBS Dissertations and Theses (Open Access). Paper 150.

- Schiller JS, Lucas JW, Peregoy JA. "Summary health statistics for U.S. adults: National Health Interview Survey, 2011." National Center for Health Statistics. *Vital Health Stat* 10(256). 2012
- Sobaszekiewicz Merck, Nora Lee. "The Effects of a Wheelchair on Social Interaction." *SJSU Scholarworks* (1996): n. pag. Web. 10 Oct. 2013.
<http://scholarworks.sjsu.edu/cgi/viewcontent.cgi?article=2261&context=etd_theses>.
- Staff, Mayo Clinic. *Mayo Clinic*. Mayo Foundation for Medical Education and Research, 19 Feb. 2011. Web. 03 Oct. 2013. <http://www.mayoclinic.com/health/walker/HA00060>.
- Staheli, L. T. (1998). *Arthrogryposis: A text atlas*. New York: Cambridge University Press.
- Van Der Woude, L.H.V, H.E.J. Veeger, A.J. Dallmeijer, T.W.J. Janssen, and L.A Rozendaal. "Biomechanics and Physiology in Active Manual Wheelchair Propulsion." *Medical Engineering & Physics* 23.10 (2001): 713-33. Print.

Appendices

Appendix A: Photos of the Client's Classroom and Devices



Figure 79: The Student's Stroller



Figure 80: Back view of the Stroller



Figure 81: The Specialized Desk Setup



Figure 82: A second view of the Desk



Figure 83: The Student's Specialized Keyboard



Figure 84: A Shot of the Current Classroom Setup

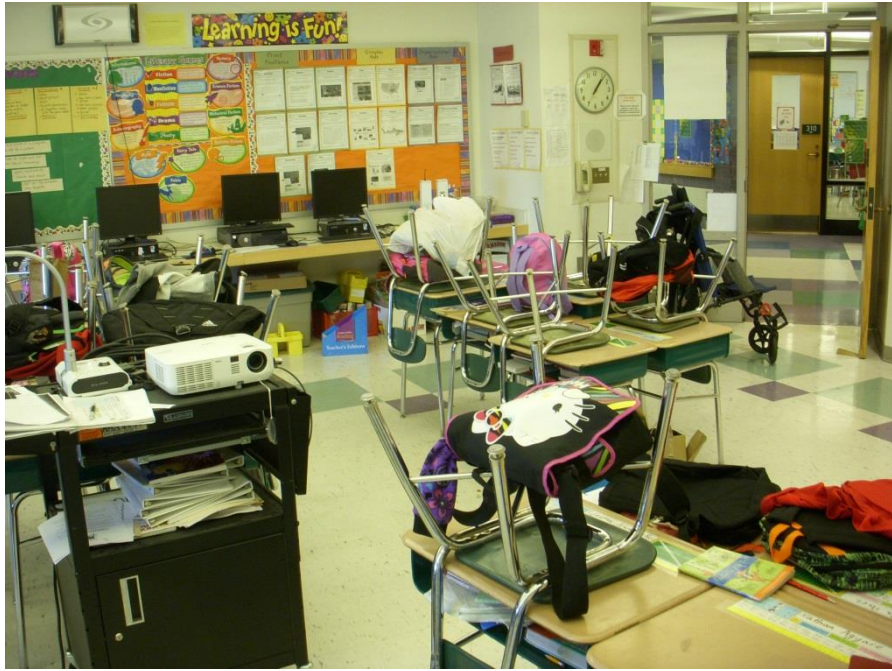


Figure 85: Another view of the student's classroom

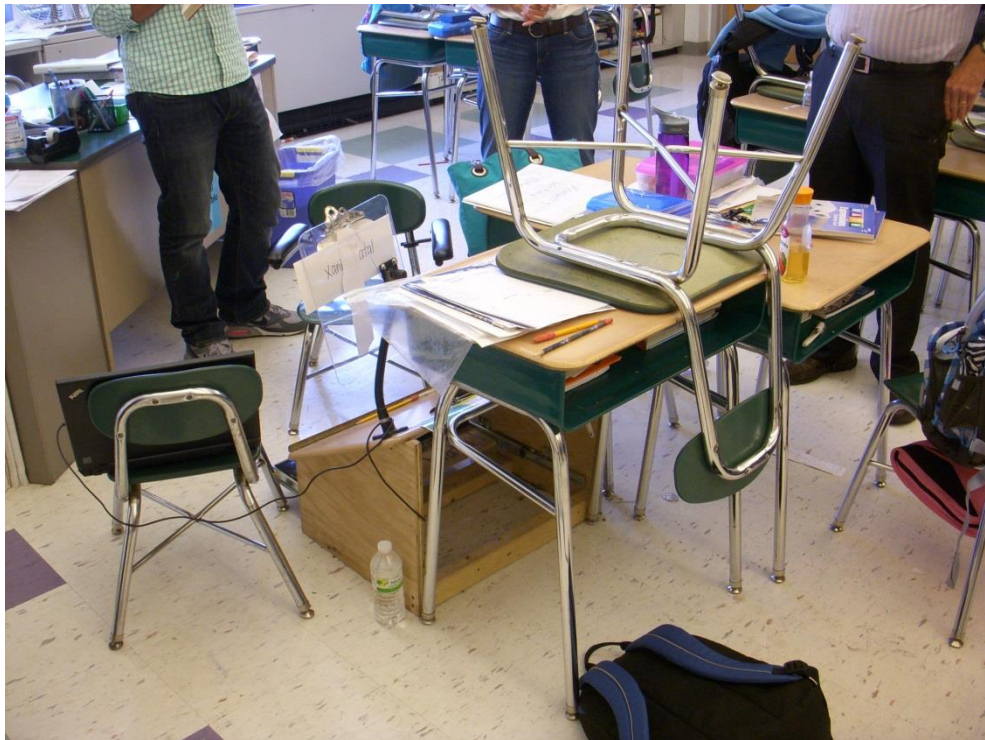


Figure 86: This image shows the limited space behind the student's desk

Appendix B: Functional Decomposition of the Student’s School Activities

School Activity	Required functions
Writing	Leg access to modified desk, take weight off of feet, Must be able to reach his workspace
Laptop	Leg access to modified desk, take weight off of feet, Must be able to reach his workspace, the ability to see the screen
Group Work	Sitting at a similar elevation to his peers, the ability to move through the class, access to a workspace, ability to remain stationary
Restroom	Access to sink to wash hands (feet), access to toilet, usable by aide for other bathroom functions
Cafeteria	Move long distances, proximity to table, get food, sit at table height
Gym Class	Outside of the Design Space
Recess	Outside of the Design Space
Going to and from bus	Outside of the Design Space
White board work	Navigate tight spaces, remain stationary, reach board
Moving between classes	Walk side-by-side with peers, walk at similar speed, stop and go safely, turning
Using the elevator	Push buttons, tight turning radius/backwards motion, navigate changes in floor surface, remain stationary
Social interactions	Sit at a similar elevation, move at a similar speed, move facing forwards

Figure 87: Functional Decomposition of School Activities

Appendix C: Decision Matrices

		Design 1	Design 2	Design 3	Design 4
Frame	weight				
weight	0.1	4	3	4	4
strength	0.2	2	4	2	4
safety	0.3	4	4	2	4
stability	0.4	4	4	3	3
subtotal	1	3.6	3.9	2.6	3.6
Contact Points					
stability	0.4	4	4	3	4
footprint size	0.2	2	3	4	2
collision safety	0.4	4	4	3	3
subtotal	1	3.6	3.8	3.2	3.2
Movement					
directional stability	0.5	4	5	3	4
freedom of movement	0.5	4	4	4	4
subtotal	1	4	4.5	3.5	4
Propulsion					
efficiency	0.2	3	4	4	4
speed	0.1	3	3	3	4
health	0.3	3	3	4	4
maneuverability	0.4	4	4	3	3
subtotal	1	3.4	3.6	3.5	3.6
Steering					
turning radius	0.1	5	5	5	5
ease of use	0.3	4	3	3	2
reliability	0.2	4	4	4	3
precision	0.4	3	3	4	3
subtotal	1	3.7	3.4	3.8	2.9
Active Braking					
ease of use	0.2	4	4	4	4
effectiveness	0.3	3	4	3	3
reliability	0.4	4	4	4	4
control over braking power	0.1	4	4	4	4
subtotal	1	3.7	4	3.7	3.7

Figure 88: First 6 Categories of the Decision Matrix

Parking Brake						
reliability	0.4	4	4	4	4	4
ease of use	0.2	2	3	2	2	2
locking	0.4	4	4	4	4	4
subtotal	1	3.6	3.8	3.6	3.6	3.6
Restraint						
comfort	0.2	3	4	4	2	2
safety	0.4	3	2	4	3	3
freedom of movement	0.2	3	4	2	2	2
ease of use	0.1	4	4	2	4	4
adjustability	0.1	3	3	4	3	3
subtotal	1	3.1	3.1	3.4	2.7	2.7
Seat						
comfort	0.4	4	5	2	2	2
adjustability	0.2	4	3	4	3	3
support	0.4	1	4	3	2	2
subtotal	1	2.8	4.2	2.8	2.2	2.2
Adjustability						
ease of use	0.1	4	4	3	3	3
durability	0.1	5	3	3	4	4
stability	0.3	4	3	3	4	4
range of adjustment	0.2	3	4	5	3	3
subtotal	1	2.7	2.4	2.5	2.5	2.5
Transfer						
ease of use	0.1	2	4	2	3	3
stability	0.4	2	4	3	3	3
independence	0.1	3	4	2	2	2
subtotal	1	1.3	2.4	1.6	1.7	1.7
TOTAL		35.5	39.1	34.2	33.7	33.7

Figure 89: Last 5 Categories of the Decision Matrix

Appendix D: Morphological Chart

Functions of Device	Means to achieve each goal -->								
Frame	A-Frame	Circular Frame	Single Post (office Chair)	Polygonal	square	Semi circular (arch)	triangular		
Contact Points	3	4	5	6					
Movement	caster wheels	single axel wheels	independent fixed axle wheel	caster/axle					
Propulsion	electric motor	track ball	eliptical	pedals	walking				
Steering	leaning	foot movement	rudder	handlebar/steering wheel	zero-turn bars	independent propulsion			
Active Braking	disk brakes	bike brakes	pressure on wheels	clutch system	friction brake	footbrake			
Parking Brake	wheel locks	friction pegs	lifting wheels off ground	wheel friction pads					
Restraint	lap bar	lab belt	torso belt	chest wrap	arm rest	underarm suport	no restraint		
Seat	bucket seat	platform	desk chair	sling					
Seat Features	reclining	standing	pivoting	rotating					
Adjustability	pushpins and tubes	fiction/pressure lock	threaded/screw	gears	ratcheting				
Transfer	ramp/slide	pulley	lower to floor	physical ability	tiliting chair	Aide	intermediate step	linkage	separate docking station

Figure 90: Morphological Chart for Design 1

Functions of Device	Means to achieve each goal -->								
Frame	A-Frame	Circular Frame	Single Post (office Chair)	Polygonal	square	Semi circular (arch)	triangular		
Contact Points	3	4	5	6					
Movement	caster wheels	single axel wheels	independent fixed axle wheel	caster/axle					
Propulsion	electric motor	track ball	eliptical	pedals	walking				
Steering	leaning	foot movement	rudder	handlebar/steering wheel	zero-turn bars	independent propulsion			
Active Braking	disk brakes	bike brakes	pressure on wheels	clutch system	friction brake	footbrake			
Parking Brake	wheel locks	friction pegs	lifting wheels off ground						
Restraint	lap bar	lab belt	torso belt	chest wrap	arm rest	underarm suport	no restraint		
Seat	bucket seat	platform	desk chair	sling					
Seat Features	reclining	standing	pivoting	rotating					
Adjustability	pushpins and tubes	fiction/pressure lock	threaded/screw	gears	ratcheting				
Transfer	ramp/slide	pulley	lower to floor	physical ability	tiliting chair	Aide	intermediate step	linkage	separate docking station

Figure 91: Morphological Chart for Design 2

Functions of Device	Means to achieve each goal -->						
Frame	A-Frame	Circular Frame	Single Post (office Chair)	Polygonal	square	Semi circular (arch)	triangular
Contact Points	3	4	5	6			
Movement	caster wheels	single axel wheels	independent fixed axle wheel	caster/axle			
Propulsion	electric motor	track ball	eliptical	pedals	walking	pushing	
Steering	leaning	foot movement	rudder	handlebar/steering wheel	zero-turn bars	independent propulsion	
Active Braking	disk brakes	bike brakes	pressure on wheels	clutch system	friction brake	footbrake	
Parking Brake	wheel locks	friction pegs	lifting wheels off ground				
Restraint	lap bar	lab belt	torso belt	chest wrap	arm rest	underarm suport	no restraint
Seat	bucket seat	platform	desk chair	sling			
Seat Features	reclining	standing	pivoting	rotating			
Adjustability	pushpins and tubes	fiction/pressure lock	threaded/screw	gears	ratcheting		
Transfer	ramp/slide	pulley	lower to floor	physical ability	tilting chair	Aide	intermediate step

Figure 92: Morphological Chart for Design 3

Functions of Device	Means to achieve each goal -->						
Frame	A-Frame	Circular Frame	Single Post (office Chair)	Polygonal	square	Semi circular (arch)	triangular
Contact Points	3	4	5	6			
Movement	caster wheels	single axel wheels	independent fixed axle wheel	caster/axle			
Propulsion	electric motor	track ball	eliptical	pedals	walking		
Steering	leaning	foot movement	rudder	handlebar/steering wheel	zero-turn bars	independent propulsion	
Active Braking	disk brakes	bike brakes	pressure on wheels	clutch system	friction brake	footbrake	
Parking Brake	wheel locks	friction pegs	lifting wheels off ground				
Restraint	lap bar	lab belt	torso belt	chest wrap	arm rest	underarm suport	no restraint
Seat	bucket seat	platform	desk chair	sling			
Seat Features	reclining	standing	pivoting	rotating			
Adjustability	pushpins and tubes	fiction/pressure lock	threaded/screw	gears	ratcheting		
Transfer	ramp/slide	pulley	lower to floor	physical ability	tilting chair	Aide	intermediate step linkage separate docking station

Figure 93: Morphological Chart for Design 4

Functions of Device	Means to achieve each goal -->									
Frame	A-Frame	Circular Frame	Single Post (office Chair)	Polygonal	square	Semi circular (arch)	triangular			
Contact Points	3	4	5	6						
Movement	caster wheels	single axel wheels	independent fixed axle wheel	caster/axle						
Propulsion	electric motor	track ball	eliptical	pedals	walking					
Steering	leaning	foot movement	rudder	handlebar/steering wheel	zero-turn bars	independent propulsion				
Active Braking	disk brakes	bike brakes	pressure on wheels	clutch system	friction brake	footbrake				
Parking Brake	wheel locks	friction pegs	lifting wheels off ground							
Restraint	lap bar	lab belt	torso belt	chest wrap	arm rest	underarm suport	no restraint			
Seat	bucket seat	platform	desk chair	sling						
Seat Features	reclining	standing	pivoting	rotating						
Adjustability	pushpins and tubes	fiction/pressure lock	threaded/screw	gears	ratcheting					
Transfer	ramp/slide	pulley	lower to floor	physical ability	tiliting chair	Aide	intermediate step	linkage	separate docking station	

Figure 94: Morphological Chart for Track Ball Design (Discarded)

Functions of Device	Means to achieve each goal -->									
Frame	A-Frame	Circular Frame	Single Post (office Chair)	Polygonal	square	Semi circular (arch)	triangular			
Contact Points	3	4	5	6						
Movement	caster wheels	single axel wheels	independent fixed axle wheel	caster/axle						
Propulsion	electric motor	track ball	eliptical	pedals	walking					
Steering	leaning	foot movement	rudder	handlebar/steering wheel	zero-turn bars	independent propulsion				
Active Braking	disk brakes	bike brakes	pressure on wheels	clutch system	friction brake	footbrake				
Parking Brake	wheel locks	friction pegs	lifting wheels off ground							
Restraint	lap bar	lab belt	torso belt	chest wrap	arm rest	underarm suport	no restraint			
Seat	bucket seat	platform	desk chair	sling						
Seat Features	reclining	standing	pivoting	rotating	no extra feature					
Adjustability	pushpins and tubes	fiction/pressure lock	threaded/screw	gears	ratcheting					
Transfer	ramp/slide	pulley	lower to floor	physical ability	tiliting chair	Aide	intermediate step	linkage	separate docking station	

Figure 95: Morphological Chart for Go-Cart Design (Discarded)

Appendix E: Contact Point Analysis

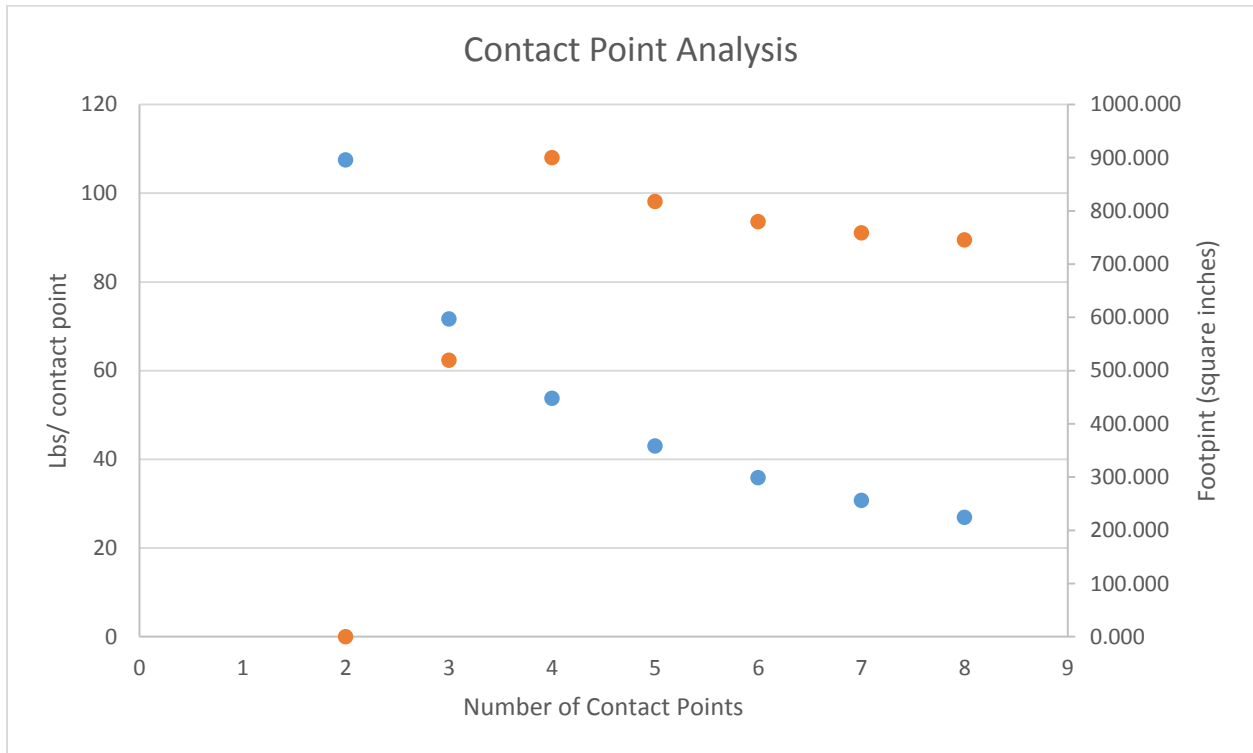


Figure 96: Weight Distribution Proportional to Contact Points

Appendix F: Preliminary Design Sketches

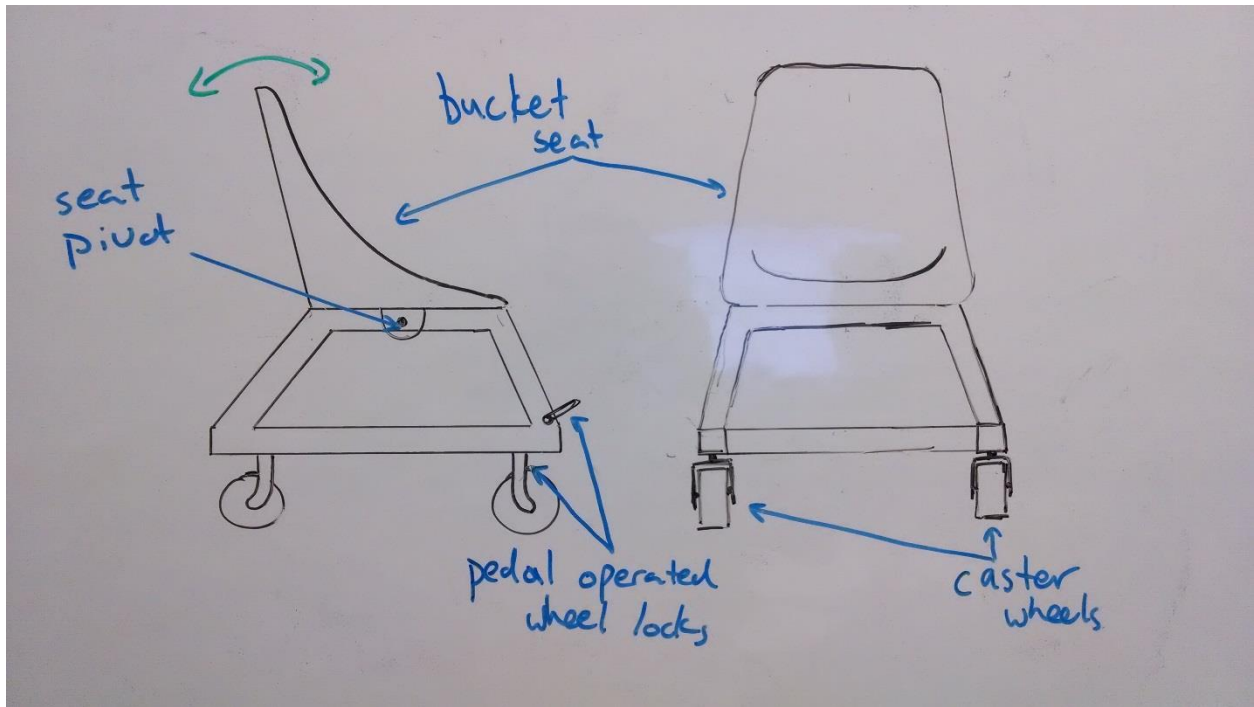


Figure 97: Hand Sketch of Preliminary Design 1

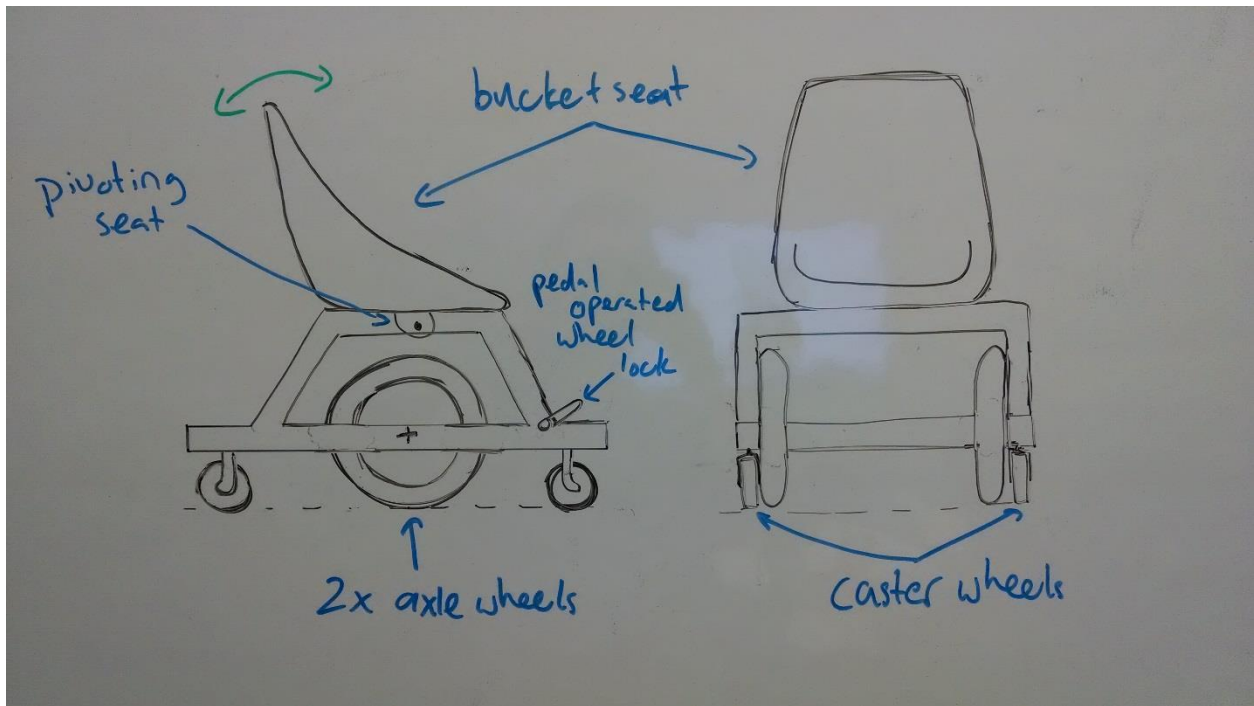


Figure 98: Hand Sketch of Preliminary Design 2

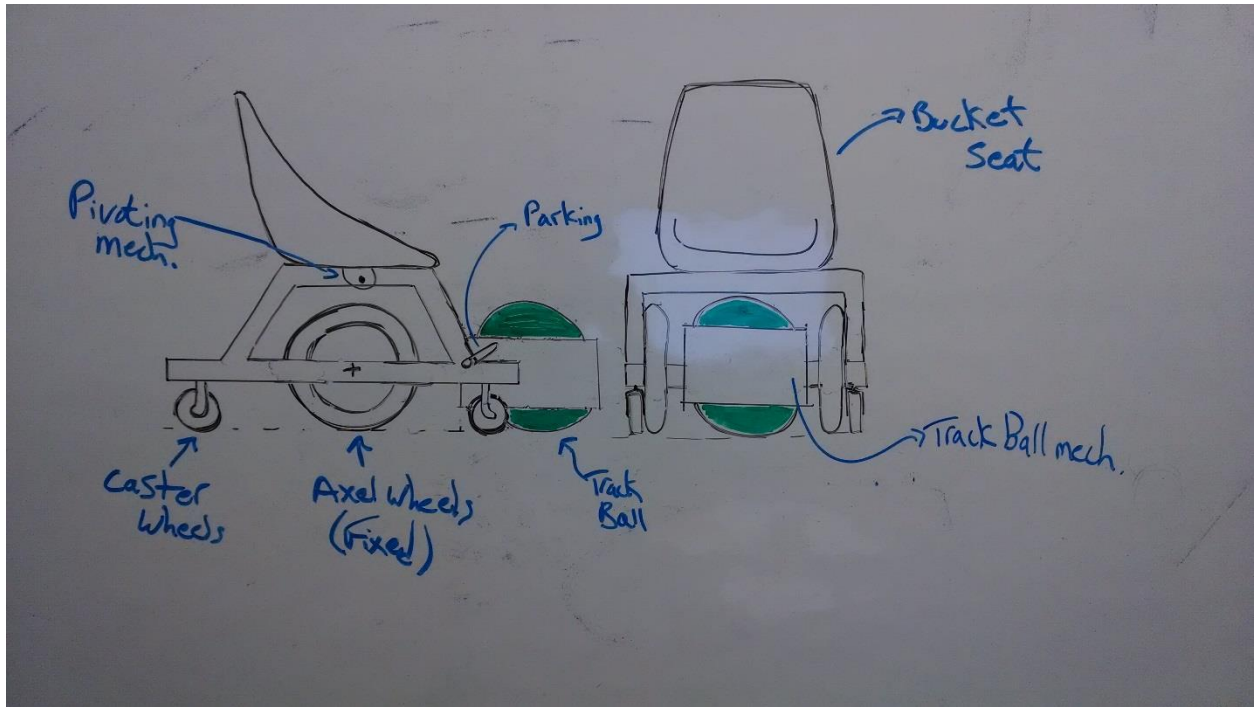


Figure 99: Hand Sketch of Track Ball Design

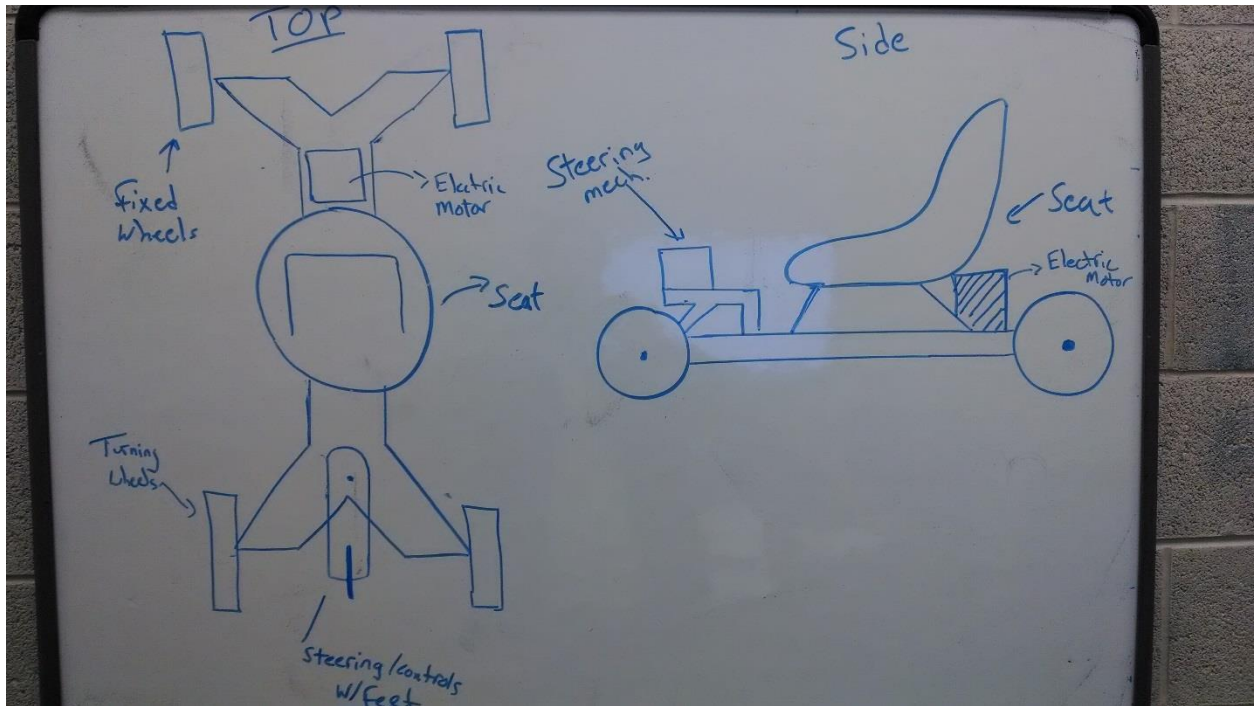


Figure 100: Hand sketch of Go-Kart Design

Appendix G: Testing protocols

Test 1: Long Distance Travel and Confined Maneuverability

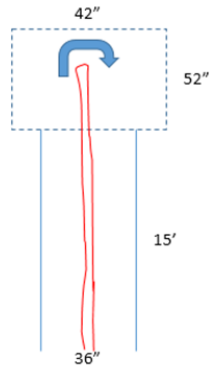


Figure 101 – Testing Protocol for Long Distance and Confined Mobility Test

Test 2: Targeting a Doorway

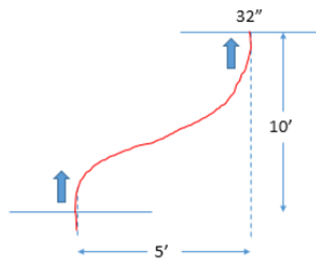


Figure 102: Testing Protocol for Targeting a Doorway Test

Test 3: Tight Maneuverability

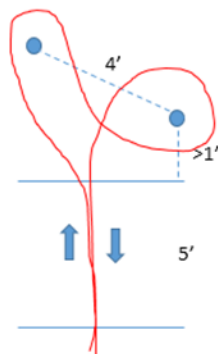


Figure 103: Testing Protocol for Tight Maneuverability Testing

Appendix H: Center of Gravity Calculations

To link the center of gravity with base height Figure 104 below was created to illustrate the geometry of the situation. The device will be statically stable until the center of gravity falls outside of the contact points with the ground. In this figure, the center of gravity is labeled "CG," and has a vertical line traced to the ground in red. Horizontal is represented by the dashed line, while the two solid lines represents the base width and the base height, tilted an angle θ from horizontal and vertical respectively.

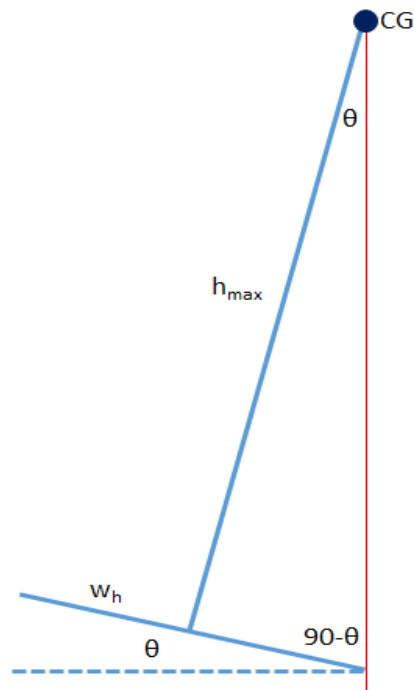


Figure 104: Calculation of Maximum Center of Gravity Height with a Defined Base Dimension

Using the triangular geometry of the situation, the following equation was written.

$$\tan(90 - \theta) = \frac{h_{max}}{w_{half}}$$

Here, h_{max} is the maximum height of the center of gravity, w_{half} is half of the base width, and θ is the slope angle. This equation can be rearranged to solve directly for the center of gravity height as a function of angle and base width as shown below.

$$h_{max} = w_{half} * \tan(90 - \theta)$$

Using the maximum tilt angle of 14 degrees, the maximum height of the center of gravity for a 28 inch base dimension is 56 inches. Dynamic situations were investigated next. Figure 105 illustrates a basic collision.

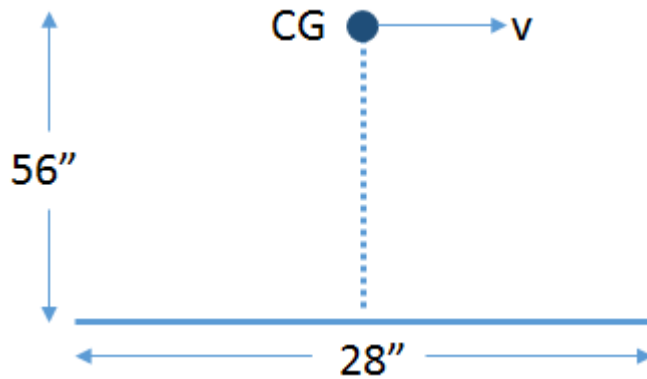


Figure 105: Simple Collision Model

The dimensions in this graphic were taken from the static calculations as a starting point. The center of gravity is again represented by the dot labeled “CG,” and the device is shown to be moving to the right with velocity “v.” The impulse-momentum relationship was used to model the collision and solve for the resultant force from colliding with an immovable object such as a wall.

$$m\Delta v = F\Delta t$$

$$F = \frac{m\Delta v}{\Delta t}$$

For the initial calculation, the velocity was taken as the average walking speed of a human, 4.4 feet per second. To determine the approximate collision time, an experiment was conducted. Using slow-motion video, a chair was filmed colliding with a wall, with a stopwatch in the frame for reference. A still shot from this video can be seen in Figure 106 below.



Figure 106: Still Shot from Slow Motion Video

Using a known length and the collision time from the video, it was determined that the chair collided with the wall while traveling 4.398 feet per second. This is less than 0.5% error and was determined accurate enough for the calculations. The collision took place over 0.36 based on the

footage. With the student’s projected weight at 115 pounds and the maximum weight of the device restricted to 50 pounds, the total weight used for the calculation was 165 pounds.

$$\text{pound force} = \text{pound mass} * 32.2 \text{ feet/second}$$

The equation was used to convert 165 pound-force to 5.12 pound-mass for use in the impulse equation. Solving the impulse equation with the known mass, velocity change, and time change, a force of 62.5 pounds was calculated. Using this force, a force diagram was created, seen below in Figure 107.

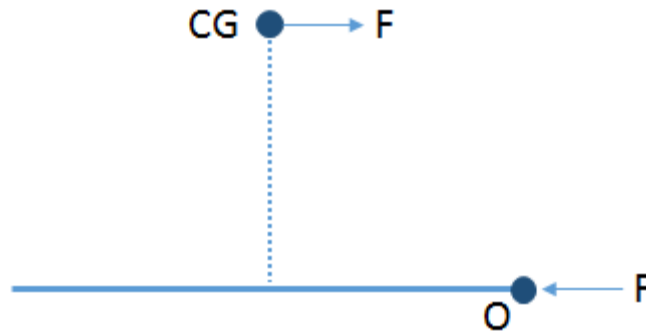


Figure 107: Collision Forces

Here, the collision occurs at point O, which represents the outermost edge or point of the device. The impulse will impart a force, calculated to be 62.5 pounds. It can be seen from the diagram in Figure 107 that summing the forces in the horizontal direction leads to the results that an equal force will act in the opposite direction on the center of gravity. The forces acting on the center of gravity, height h above the collision point, will impart a torque about point O, illustrated in Figure 108 below.

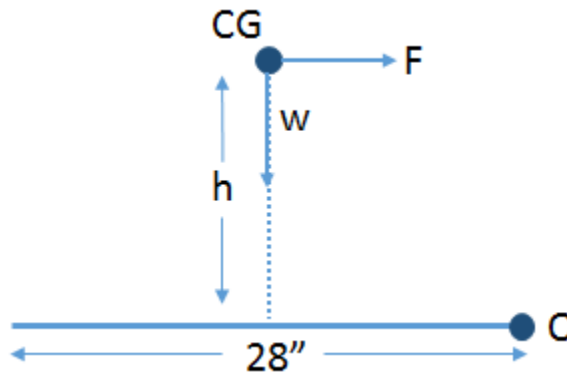


Figure 108: Collision Moments

Using the diagram in Figure 108 to sum the moments about point O, the following equation was developed.

$$\sum M_O = F * h - W * w_{half} = 0$$

In this equation, F represents the force acting on the center of gravity, h represents the height of the center of gravity, W represents the gravitational force on the center of gravity, and w_{half} represents half the width of the base. To ensure the greatest stability, the sum of the moments was set to zero. By setting the sum of moments equal to zero, it is guaranteed that the device will not tip, and therefore all contact points will remain on the ground. Solving the above equation for the h will give an equation for the maximum height.

$$h = \frac{W * w_{half}}{F}$$

By solving the impulse equation for a range of collision velocities and base widths, Figure 109 below was generated.

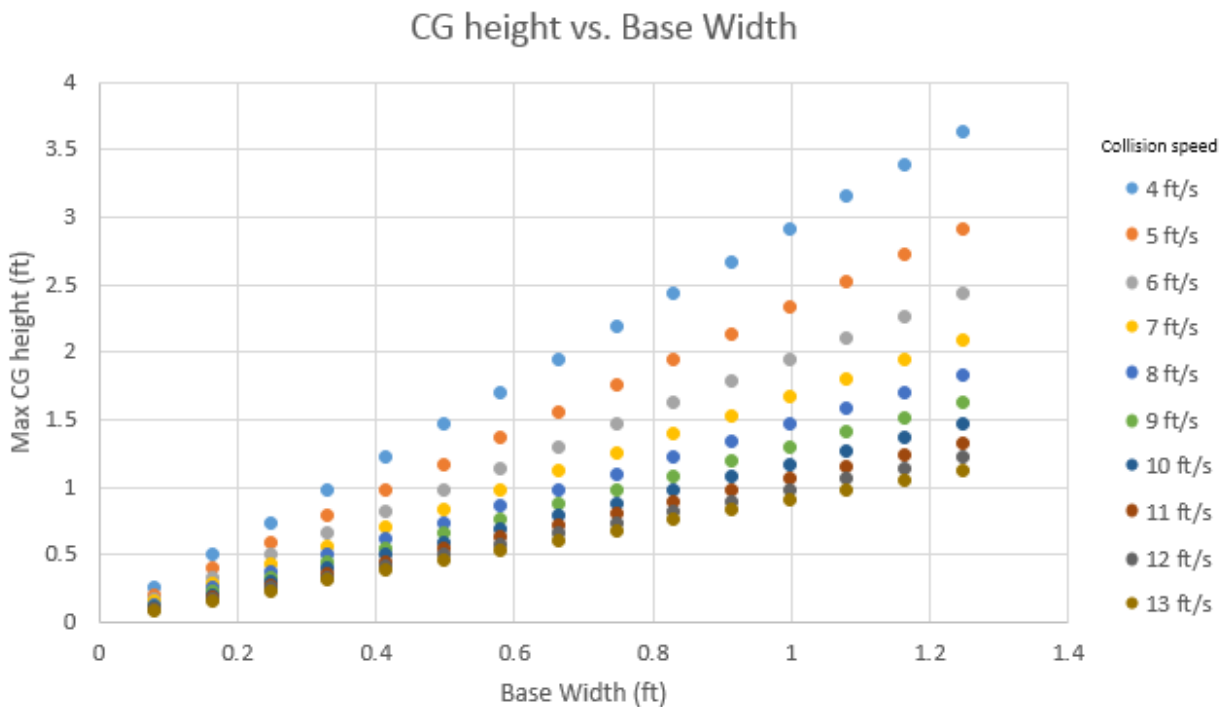


Figure 109: Center of Gravity Heights versus Base Width for Varying Velocities

Using this chart, the maximum center of gravity height for any practical combination of base widths and maximum velocities can be determined. The selected maximum allowable speed of 7 ft/s is illustrated by the purple dots above.

Center of Gravity Shift Due to User Movement

One of the bigger concerns with stability is ensuring that the device is always stable, regardless of the static or dynamic conditions. The previous section discussed the requirements due to the possibility of dynamic collisions, and this section will explain the effect of the center of gravity for various body positions in the device.

The center of gravity for the student/device system will shift as the student leans forwards, backwards, or side to side. The position of his legs (extended vs. feet on the ground) will also affect the

center of gravity location. A study was conducted to look at the effect of various positions, based on anthropometric data and the student's current and projected measurements.

Five body positions were analyzed: standing upright; sitting with a forward lean and feet on the ground; sitting with a forward lean and legs extended; sitting with a sideways lean and feet on the ground; and sitting with a sideways lean and legs extended. These can be seen below in Figure 104 through Figure 114.

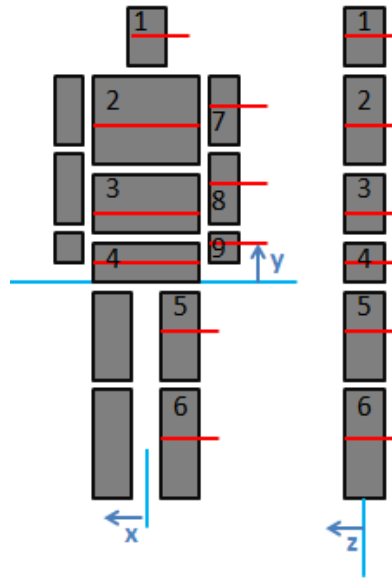


Figure 110: Standing Position for CG Approximation

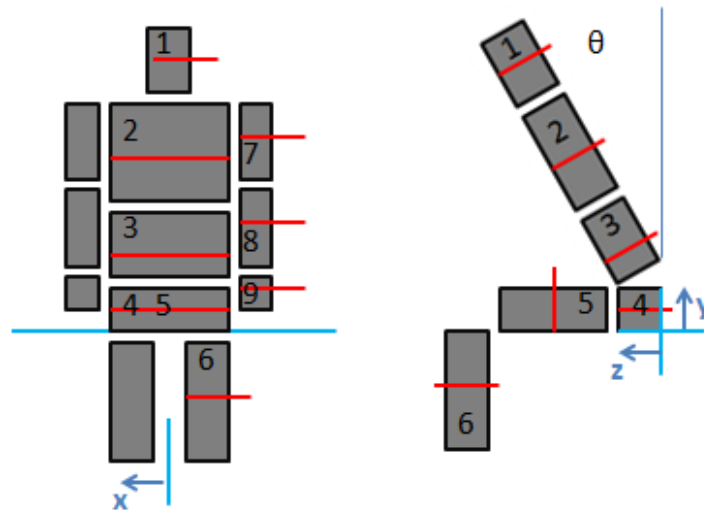


Figure 111: Forward Lean with Feet on Ground for CG Approximation

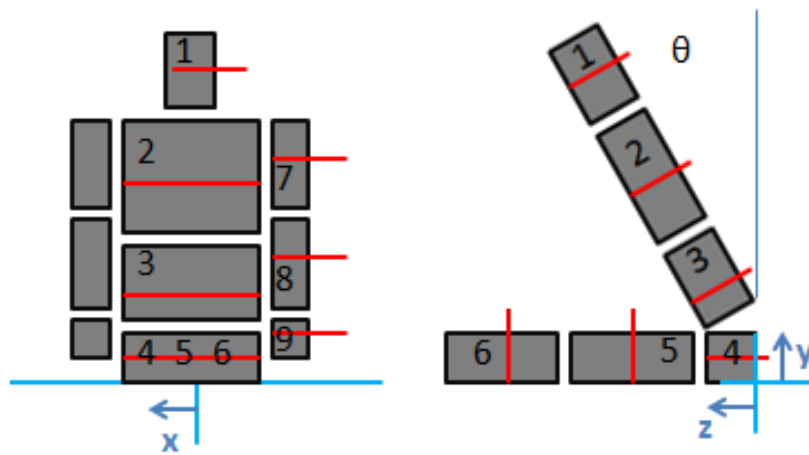


Figure 112: Forward Lean with Legs Extended for CG Approximation

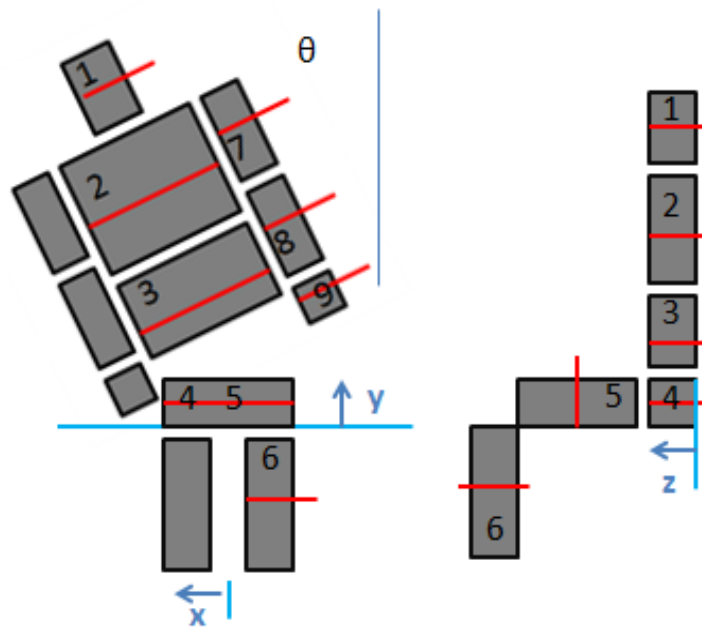


Figure 113: Sideways Lean with Feet on Ground for CG Approximation

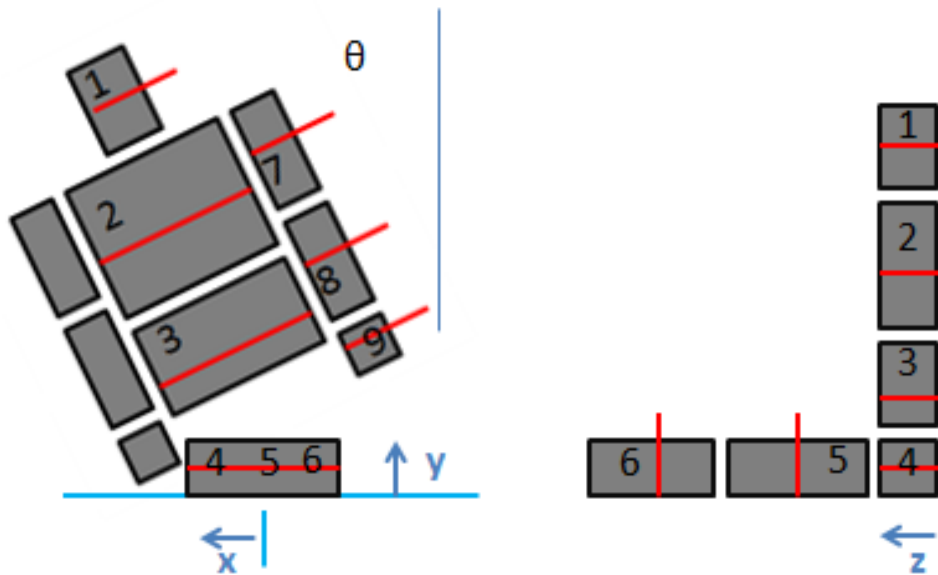


Figure 114: Sideways Lean with Legs Extended for CG Approximation

Anthropometric data required for these center of gravity approximations included the segmental length, weight, and center of gravity location as a percent of the student's current and projected measurements, for the head and neck (1), thorax (2), abdomen (3), pelvis (4), thigh (5), lower leg and foot (6), upper arm (7), forearm (8), and hand (9). It can be seen in the illustrations that the x-axis bisects the body left and right, the y-axis bisects the body horizontally below the pelvis, and the z-axis runs vertically along the back. The red lines in the above figures represent the longitudinal locations of each segment's individual center of gravity.

The total body center of mass was located along each axis using the center of mass equations shown below for the x, y, and z directions.

$$x_{cm} = \frac{\sum_{i=1}^9 m_i x_i}{\sum_{i=1}^9 m_i}$$

$$y_{cm} = \frac{\sum_{i=1}^9 m_i y_i}{\sum_{i=1}^9 m_i}$$

$$z_{cm} = \frac{\sum_{i=1}^9 m_i z_i}{\sum_{i=1}^9 m_i}$$

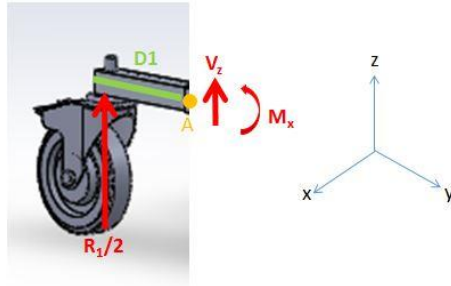
The m_i terms represent the mass of each individual segment, while the x_i , y_i , and z_i terms represent the location of each segment's center of gravity. This was found using anthropometric data, which gave the proximal and distal locations of each segment's center of gravity. Overall, the data showed that a lean angle of 90 degrees from vertical only changed the CG of the body by about 6 inches in the direction of lean. The results of this exercise can be seen in Figure 115.

Appendix I: Static and Dynamic Calculations

Static

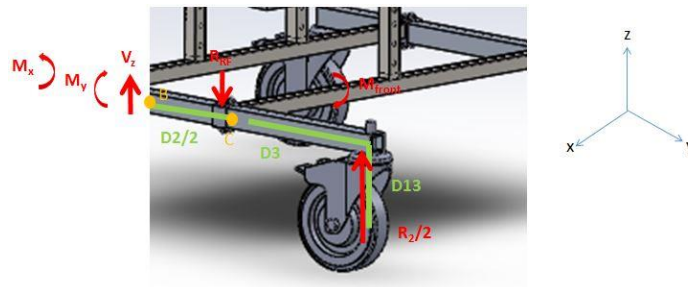
Internal forces are calculated by summing the forces and moments at each point in each coordinate direction (x,y,z).

Point A



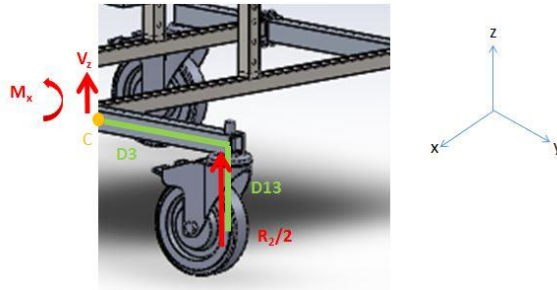
$$\begin{aligned} \sum F_x = 0 &= V_x \\ V_x &= 0 \\ \sum F_y = 0 &= V_y \\ V_y &= 0 \\ \sum F_z = 0 &= V_z + \frac{R_1}{2} \\ V_z &= -\frac{R_1}{2} \\ \sum M_{xA} = 0 &= M_x + \frac{R_1}{2} d_1 \\ M_x &= -\frac{R_1}{2} d_1 \\ \sum M_{yA} = 0 &= M_y \\ M_y &= 0 \\ \sum M_{zA} = 0 &= M_z \\ M_z &= 0 \end{aligned}$$

Point B



$$\begin{aligned} \sum F_x = 0 &= V_x \\ V_x &= 0 \\ \sum F_y = 0 &= V_y \\ V_y &= 0 \\ \sum F_z = 0 &= V_z + \frac{R_2}{2} - R_{RF} \\ V_z &= R_{RF} - \frac{R_2}{2} \\ \sum M_{xB} = 0 &= M_x + \frac{R_2}{2} \left(\frac{d_2}{2} + d_3 \right) - R_{RF} \left(\frac{d_2}{2} \right) \\ M_x &= R_{RF} \left(\frac{d_2}{2} \right) - \frac{R_2}{2} \left(\frac{d_2}{2} + d_3 \right) \\ \sum M_{yB} = 0 &= M_y - M_{front} \\ M_y &= M_{front} \\ \sum M_{zB} = 0 &= M_z \\ M_z &= 0 \end{aligned}$$

Point C



$$\begin{aligned} \sum F_x = 0 &= V_x \\ V_x &= 0 \\ \sum F_y = 0 &= V_y \\ V_y &= 0 \\ \sum F_z = 0 &= V_z + \frac{R_2}{2} \\ V_z &= -\frac{R_2}{2} \\ \sum M_{xC} = 0 &= M_x + \frac{R_2}{2} (d_3) \\ M_x &= -\frac{R_2}{2} (d_3) \\ \sum M_{yC} = 0 &= M_y \\ M_y &= 0 \\ \sum M_{zC} = 0 &= M_z \\ M_z &= 0 \end{aligned}$$

Dynamic Loading

For dynamic loading, it is assumed that the user falls from a height of 6 inches into the seat. Final velocity after freefall is found and substituted into impulse-momentum to find collision force. The force of this impact is substituted into the static loading calculations as the user's weight.

$$v_f^2 = v_i^2 + 2ad$$
$$v_f = \sqrt{2ad} = 5.67 \text{ ft/s}$$

The maximum user weight (200 lbs) is divided by gravitational acceleration (32.2 feet per second) to get the mass. Collision time is assumed to be 0.1 seconds.

$$F\Delta t = m(v_u - v_f)$$
$$F = \frac{m(v_u - v_f)}{\Delta t} = 352 \text{ lb}$$

Collisions

Internal forces are calculated by summing the forces and moments at each point. The collision force was calculated using a coefficient of restitution (assumed to be 0.5) and impulse-momentum (assumed collision time of 0.36 seconds). The velocity before the collision is assumed to be average adult walking speed (4.4 feet per second).

For the angled collision case, the change in velocity from the collision is purely in the x-direction. The x-velocity is a function of the collision angle, and is found using trigonometry.

$$v_{u,x} = v * \sin(\theta)$$
$$C_R = \frac{-v_{f,x}}{v_{u,x}}$$
$$v_{f,x} = -1.56 \text{ ft/s}$$

Impulse-Momentum is used to find collision force. The mass is assumed to include the combined maximum user and device weights (200 lbs and 50 lbs respectively) divided by gravitational acceleration (32.2 feet per second).

$$F\Delta t = m(v_{u,x} - v_{f,x})$$
$$F = \frac{m(v_{u,x} - v_{f,x})}{\Delta t} = 129 \text{ lb}$$

For the front collision case, coefficient of restitution is used again to find collision velocity.

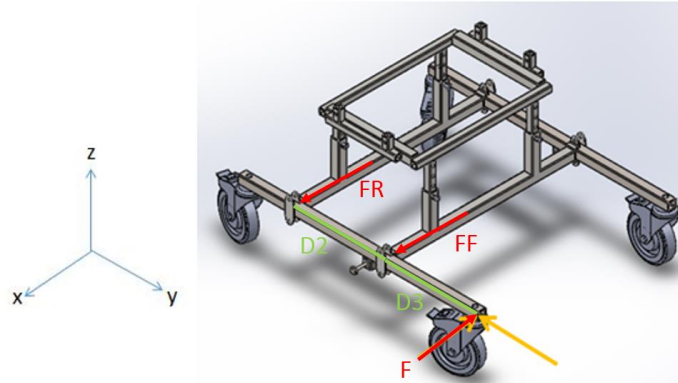
$$C_R = \frac{-v_f}{v_u}$$
$$v_f = -2.2 \text{ ft/s}$$

Impulse-Momentum is used again to find collision force.

$$F\Delta t = m(v_u - v_f)$$
$$F = \frac{m(v_u - v_f)}{\Delta t} = 142 \text{ lb}$$

Side Collision

First, the reaction forces in the cross members are calculated.



$$\sum M_a = F(d_2 + d_3) - FF(d_2) = 0$$

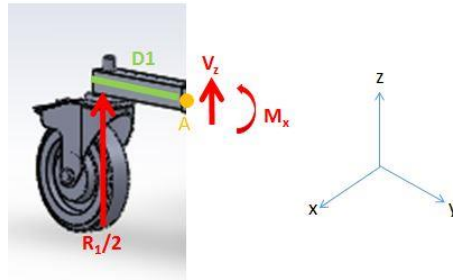
$$FF = \frac{F(d_2 + d_3)}{(d_2)}$$

$$\sum F_y = FF + FR - F = 0$$

$$FR = F - \frac{F(d_2 + d_3)}{d_2}$$

Next, internal forces are calculated by summing the forces and moments at each point.

POINT A



$$\sum F_x = 0 = V_x$$

$$V_x = 0$$

$$\sum F_y = 0 = V_y$$

$$V_y = 0$$

$$\sum F_z = 0 = V_z + \frac{R_1}{2}$$

$$V_z = -\frac{R_1}{2}$$

$$\sum M_{xA} = 0 = M_x + \frac{R_1}{2} d_1$$

$$M_x = -\frac{R_1}{2} d_1$$

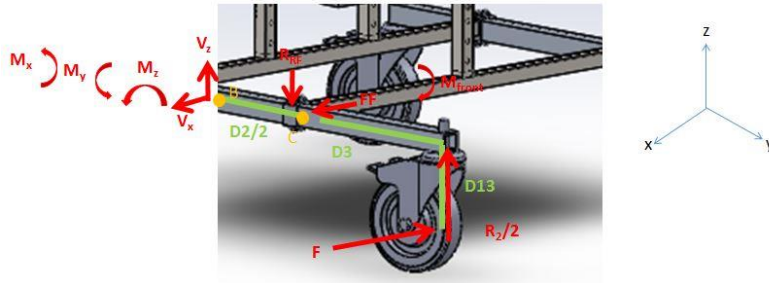
$$\sum M_{yA} = 0 = M_y$$

$$M_y = 0$$

$$\sum M_{zA} = 0 = M_z$$

$$M_z = 0$$

POINT B



$$\sum F_x = 0 = V_x + FF - F$$

$$V_x = F - FF$$

$$\sum F_y = 0 = V_y$$

$$V_y = 0$$

$$\sum F_z = 0 = V_z + \frac{R_2}{2} - R_{RF}$$

$$V_z = R_{RF} - \frac{R_2}{2}$$

$$\sum M_{xB} = 0 = M_x + \frac{R_2}{2} \left(\frac{d_2}{2} + d_3 \right) - R_{RF} \left(\frac{d_2}{2} \right)$$

$$M_x = R_{RF} \left(\frac{d_2}{2} \right) - \frac{R_2}{2} \left(\frac{d_2}{2} + d_3 \right)$$

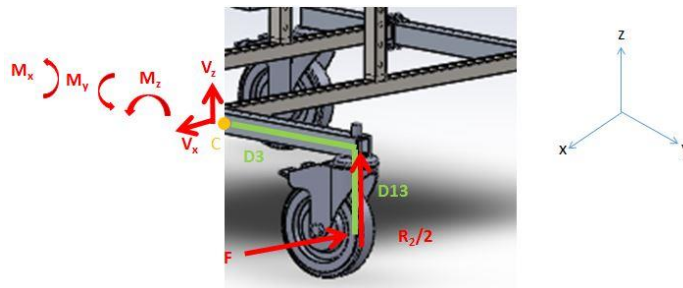
$$\sum M_{yB} = 0 = M_y + F(d_{13}) - M_{front}$$

$$M_y = M_{front} - F(d_{13})$$

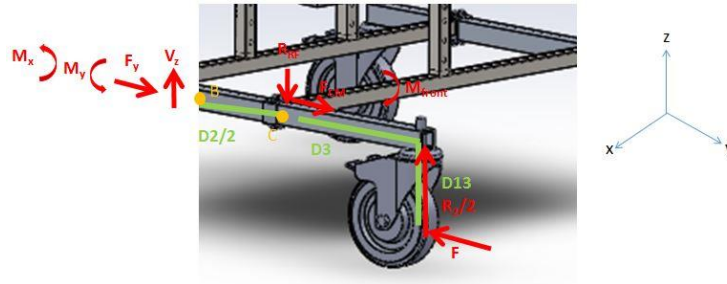
$$\sum M_{zB} = 0 = M_z + F \left(\frac{d_2}{2} + d_3 \right) - FF \left(\frac{d_2}{2} \right)$$

$$M_z = FF \left(\frac{d_2}{2} \right) - F \left(\frac{d_2}{2} + d_3 \right)$$

POINT C



Point B



$$\sum F_x = 0 = V_x$$

$$V_x = 0$$

*It is assumed that the collision force (F) is absorbed entirely by the front cross member (F_{CM})

$$\sum F_y = 0 = F_y + F_{CM} - F$$

$$F_y = 0$$

$$\sum F_z = 0 = V_z + \frac{R_2}{2} - R_{RF}$$

$$V_z = R_{RF} - \frac{R_2}{2}$$

$$\sum M_{xB} = 0 = M_x + \frac{R_2}{2} \left(\frac{d_2}{2} + d_3 \right) - R_{RF} \left(\frac{d_2}{2} \right) - F(d_{13})$$

$$M_x = R_{RF} \left(\frac{d_2}{2} \right) + F(d_{13}) - \frac{R_2}{2} \left(\frac{d_2}{2} + d_3 \right)$$

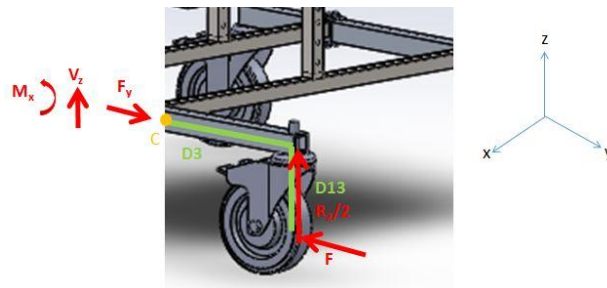
$$\sum M_{yB} = 0 = M_y - M_{front}$$

$$M_y = M_{front}$$

$$\sum M_{zB} = 0 = M_z$$

$$M_z = 0$$

Point C



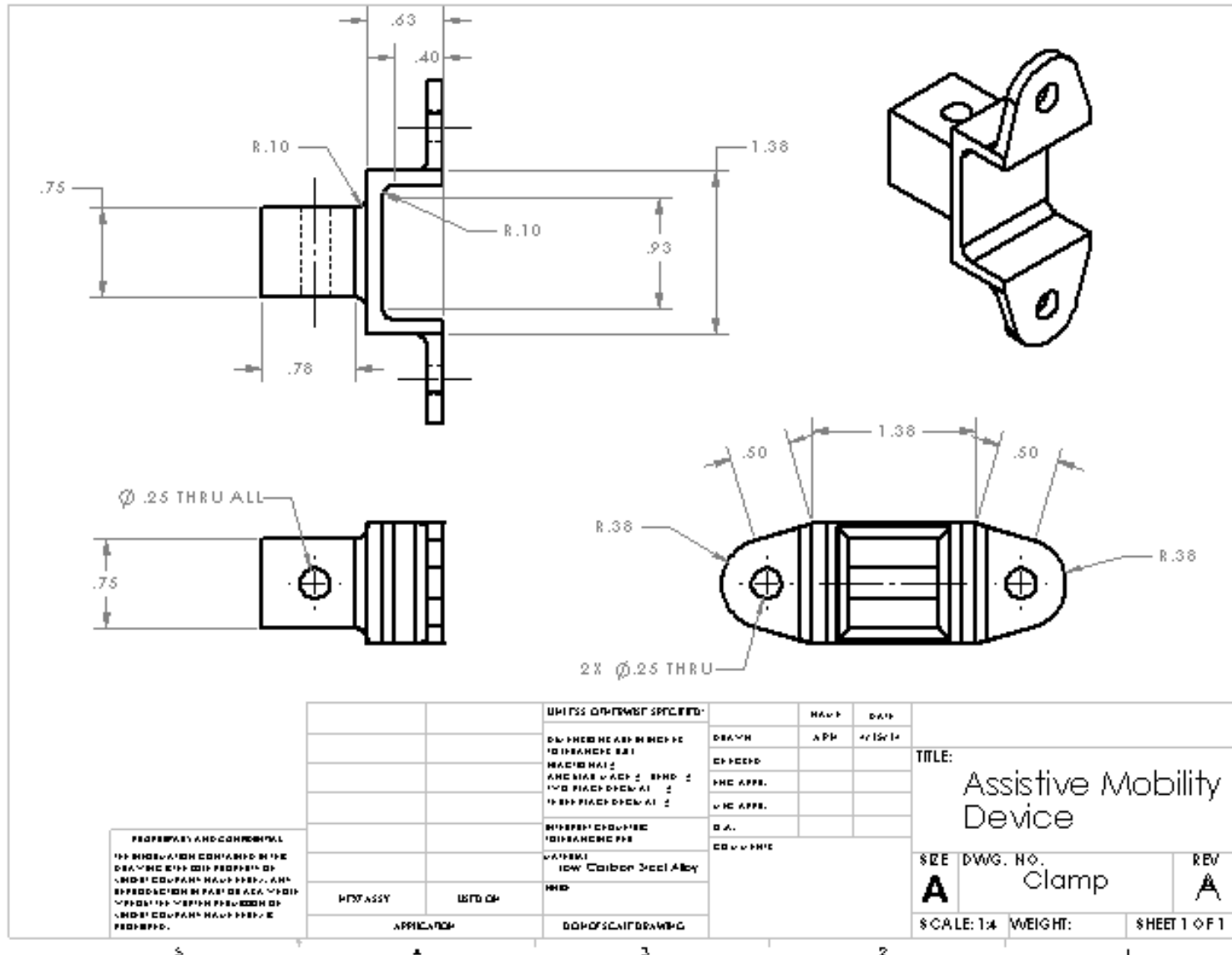
$$\sum F_x = 0 = V_x$$

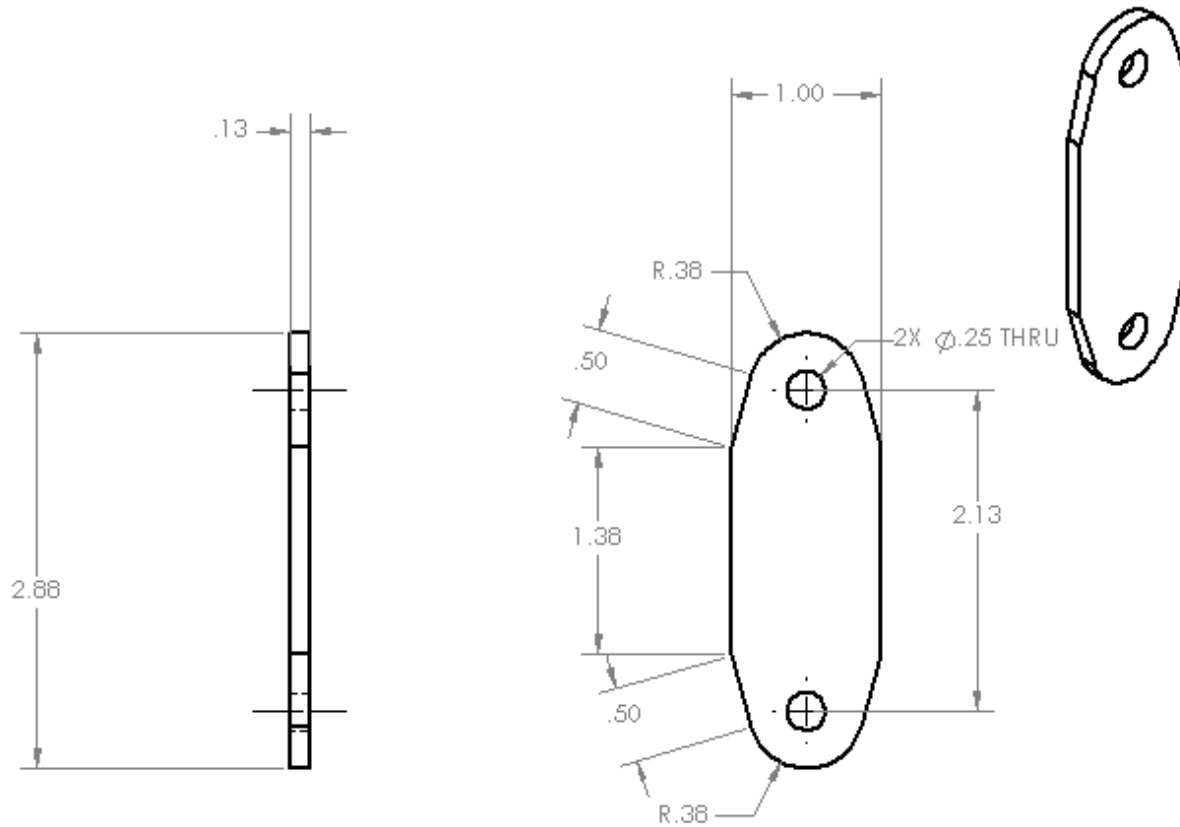
$$V_x = 0$$

$$\sum F_y = 0 = F_y - F$$

$$F_y = F$$

$$\begin{aligned} \sum F_z = 0 &= V_z + \frac{R_2}{2} \\ V_z &= -\frac{R_2}{2} \\ \sum M_{xC} = 0 &= M_x + \frac{R_2}{2}(d_3) - F(d_{13}) \\ M_x &= F(d_{13}) - \frac{R_2}{2}(d_3) \\ \sum M_{yC} = 0 &= M_y \\ M_y &= 0 \\ \sum M_{zC} = 0 &= M_z \\ M_z &= 0 \end{aligned}$$





PROPRIETARY AND CONFIDENTIAL
 THE INFORMATION CONTAINED IN THIS
 DRAWING IS THE SOLE PROPERTY OF
 CHRYSLER COMPANY. ANY REPRODUCTION
 OR TRANSMISSION IN ANY FORM OR BY
 ANY MEANS WITHOUT THE WRITTEN
 PERMISSION OF CHRYSLER COMPANY IS
 PROHIBITED.

		UNLESS OTHERWISE SPECIFIED:		DATE	DATE	TITLE: Assistive Mobility Device	
		DIMENSIONS ARE IN INCHES FRACTIONS: 0/16		DRAWN	APP		SIZE DWG. NO. REV A Clamp Side A
		DECIMALS: 0.0001		CHECKED			
		ANGULARS: MAX 2 1/2		ENG APPR			
		TWO PLACE DECIMALS		MFG APPR			
		THREE PLACE DECIMALS		D.A.			
		DIFFERENT DIMENSIONS FOR DRAWING SET:		COMMENTS:		SCALE: 1:4 WEIGHT: SHEET 1 OF 1	
		MATERIAL: Low Carbon Steel Alloy					
NEXT ASSY		USED ON					
APPLICATION		DO NOT SCALE DRAWING					

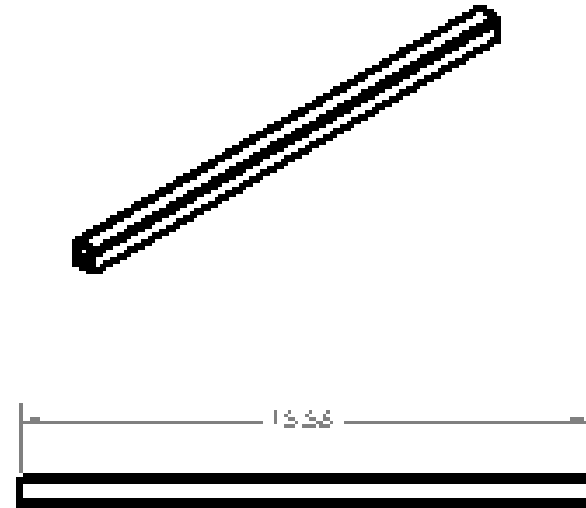
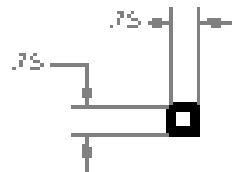
5

4

3

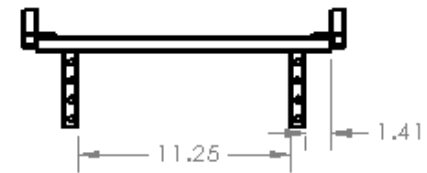
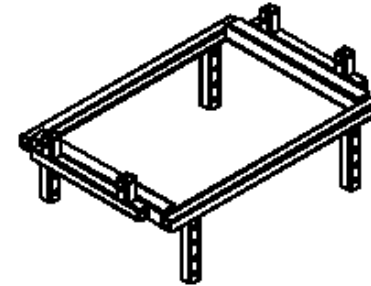
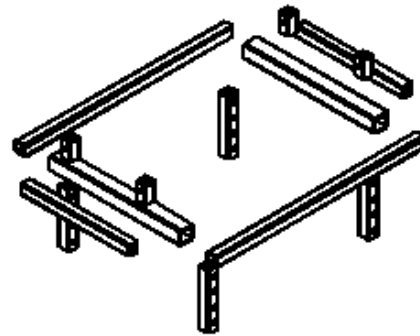
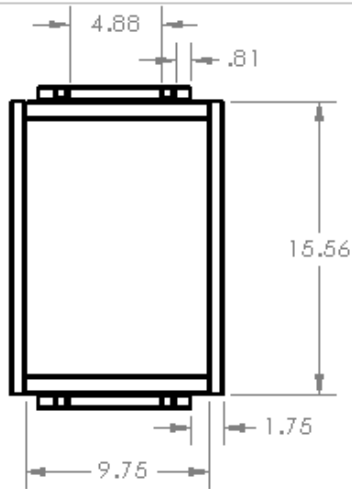
2

1



THIS DRAWING AND ALL DIMENSIONS
 THEREON ARE THE PROPERTY OF
 THE UNIVERSITY OF MICHIGAN
 AND ARE NOT TO BE REPRODUCED
 OR TRANSMITTED IN ANY FORM
 OR BY ANY MEANS, ELECTRONIC
 OR MECHANICAL, INCLUDING
 PHOTOCOPYING, RECORDING,
 OR BY ANY INFORMATION
 STORAGE AND RETRIEVAL
 SYSTEM, WITHOUT PERMISSION
 IN WRITING FROM THE
 UNIVERSITY OF MICHIGAN
 LIBRARY SERVICES

		UNIVERSITY OF MICHIGAN		DATE	REV	
		DESIGNED BY: [Name]	REV 01	08/11	001	
		CHECKED BY: [Name]				
		APPROVED BY: [Name]				
		DATE: [Date]				
		PROJECT: [Project Name]				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				
		SCALE:				
		BY:				
		CHECKED BY:				
		DATE:				
		PROJECT:				
		DRAWING NO.:				
		TITLE:				



PROPRIETARY AND CONFIDENTIAL
 THE INFORMATION CONTAINED IN THIS
 DRAWING IS THE SOLE PROPERTY OF
 CSE-SEAT COMPANY. ANY REPRODUCTION
 IN PART OR AS A WHOLE WITHOUT THE
 WRITTEN PERMISSION OF CSE-SEAT
 COMPANY IS PROHIBITED.

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	TITLE: Assistive Mobility Device	
		DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MMACH ± BEND ± THIRD PLACE DECIMAL ± THREE PLACE DECIMAL ±		DRAWN			SIZE DWG. NO. REV A Seat Subframe
		MATERIAL		CHECKED			
		FINISH		ENG. APPR.			
41X1 ASSY	4378 04	PROPERTY & CONTROL FOLLOWING DEPT:		MFG APPR.			
APPLICATION		DO NOT SCALE DRAWING		COMMENTS:			

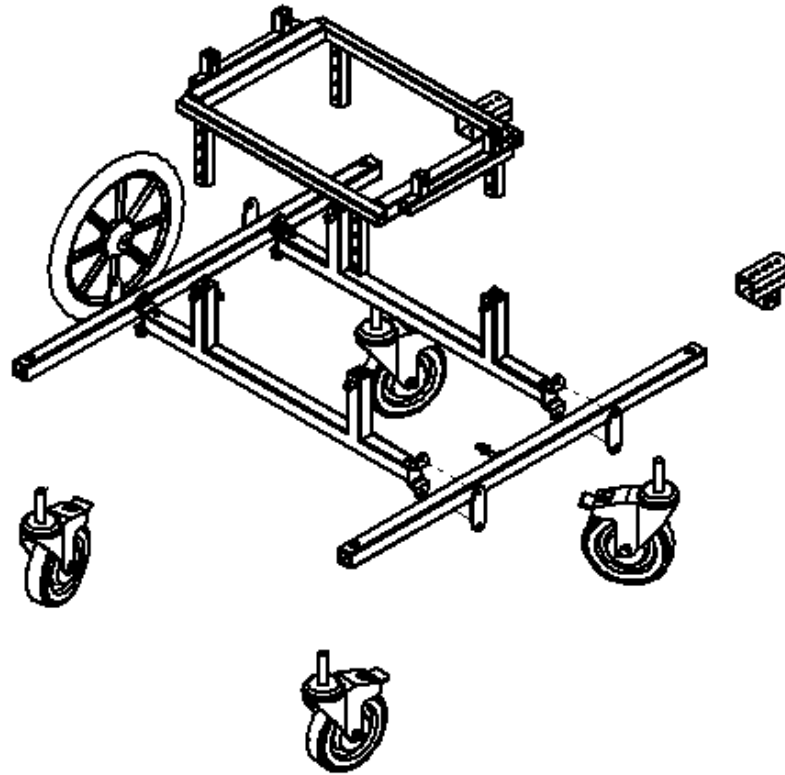
5

4

3

2

1



PROPRIETARY AND CONFIDENTIAL
 THE INFORMATION CONTAINED IN THIS
 DRAWING IS THE SOLE PROPERTY OF
 CHESTNUT COMPANY HAMBURG. ANY
 REPRODUCTION IN PART OR AS A WHOLE
 WITHOUT THE WRITTEN PERMISSION OF
 CHESTNUT COMPANY HAMBURG IS
 PROHIBITED.

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE		
		DIMENSIONS ARE IN INCHES		DRAWN		TITLE:	
		TOLERANCES:		CHECKED		Assistive Mobility Device	
		FRACTIONAL: ±		ENG APPR.		REV	
		ANGULAR: MACH ± BEND ±		MIC APPR.		A Frame Assembly	
		TWO PLACE DECIMAL ±		O.A.		SCALE: 1:4 WEIGHT: SHEET 1 OF 1	
		THREE PLACE DECIMAL ±		COMMENTS:			
		DIFFERENT GEOMETRIC TOLERANCING PER MATERIAL					
NEXT ASSY		ASSEMBLY					
APPLICATION		DO NOT SCALE DRAWING					

5

4

3

2

1

mm