Designing and Testing a Safe and Adjustable Bicycle for a Child with Achondroplasia

A Major Qualifying Project

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Abstract

In the current bicycle market, there are no affordable options that fit the physical needs of those with achondroplasia, the most common form of dwarfism. This problem greatly affects children as it does not allow them to participate in valuable activities that other children are able to participate in. The goal of this project was to design a bicycle for a 6-year-old child with achondroplasia that maintains the appearance of an average bicycle while catering to her proportions and biomechanics. The bicycle was made to be adjustable to be used throughout childhood growth while maintaining biomechanical efficiency, with safety prioritized and verified. The client tested the final prototype and felt enthusiasm about her ability to ride the bicycle comfortably.

Executive Summary

I. INTRODUCTION

Children with achondroplasia, a common form of dwarfism, have different biomechanics and proportions than an average child. Therefore, average children's bicycles rarely fit the needs of children with achondroplasia, and there are limited affordable custom options available. This has resulted in many children with achondroplasia feeling left out because they can't ride bicycles like other kids their age. To solve this problem, alterations were made to a commercial children's bicycle from Walmart to fit the specific needs of a six-year-old girl with achondroplasia.

II. LITERATURE REVIEW

A. Achondroplasia

Achondroplasia is the most common form of dwarfism in humans [1]. This genetic condition slows the growth of cartilage and bone, especially in the long limb bones, leading to characteristics such as a disproportionate short stature, long trunk, frontal bossing of the head, lumbar lordosis, bowlegs, and reduced muscle strength.

B. Current Bicycle Market

There are very limited options for bicycles that fit children with achondroplasia, none being affordable. One company, Islabikes, designs bicycles for people with dwarfism. However, one children's bicycle from this company costs upwards of $420 [2]. Strider, another bicycle company, offers customizable bicycles for $250-900 [3]. When compared to the average cost of a commercial children's bicycle, $50-200, the prices for Islabikes' and Strider's bicycles are very steep. This lack of accessibility creates a divide for children with dwarfism who want to ride bicycles with their peers, as the physical barriers they face can lead to a feeling of isolation and a lack of inclusion [4].

III. CLIENT STATEMENT

Design, prototype, and test a custom bicycle that fits the physical and social needs of a child with achondroplasia. This device will be comfortable and adjustable for the user to accommodate the child's growth.

IV. DESIGN PROCESS

Six design criteria were created to help gauge the specific needs of the client. The criteria were then ranked by the client's parents and are listed below in order of importance, starting with most important:

1. Comfortable and efficient
2. Adjustable
3. Lightweight and transportable & Visually resembles a standard bicycle
4. Durable
5. Used for daily leisurely riding

   As the bicycle was created, these criteria were prioritized.

V. DESIGN VERIFICATION

A. Bicycle Frame

One of the major modifications the team hoped to make to the bicycle frame was removing the top bar of the bicycle frame, transforming it into a step-through frame. To ensure this operation retained the safety of an average bicycle, finite element analysis (FEA) and mechanical testing were performed to prove the bicycle's integrity after modification.

A commercial 12-inch children's bicycle was purchased from Walmart and modeled in SolidWorks. The model was then imported into Ansys to conduct FEA simulation. Two conditions were modeled: starting riding and riding on a flat surface. The same was performed for the bicycle frame with the top bar removed, and the equivalent von-Mises stress results compared. Figure 1 displays an example of the results obtained from FEA for the original frame.

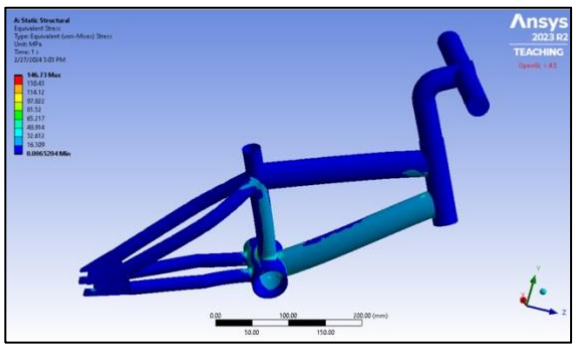

Figure 1. Equivalent von-Mises stress simulation results for the bicycle frame with the top bar under the starting riding conditions.

Following FEA simulation, mechanical testing was performed to validate the simulation results and thereby prove the bicycle will be safe without the top bar under expected riding conditions. Strain gauges were placed in three locations on each of the bicycle frames, and the bicycles were loaded with weight (90 lbs. on the seat and 25lbs on each handlebar). Then, the strain values from this testing were compared to the Ansys results to determine accuracy. It was found that in most locations, the mechanical testing yielded results on the same order of magnitude as the Ansys simulation results; however, in a few locations, the strain was greater than expected. While further testing would help generate a more complete conclusion, due to the lack of visible damage or deformation from the heavy loading used in mechanical testing of the bicycle, it was concluded that removing the top bar is a safe modification to make.

B. Pedal Crank

Another modification the team hoped to make was the addition of two holes in each of the pedal cranks, which would allow the client to either shorten or lengthen the pedal crank depending on what fits her best. This adjustability accommodates the client's growth through her childhood. To ensure that the incorporation of extra holes would not threaten the structural integrity of the bicycle pedals, FEA was performed.

The pedal crank from a commercial 12-inch children's bicycle was modeled in SolidWorks. Two CAD models were created: one of a pedal crank with no modifications and one of a pedal crank with two additional holes added. The models were then imported into Ansys, with loads applied reflecting the client standing up while riding. The equivalent von-Mises stress results of both models were compared by calculating the safety factor.

The pedal crank without modifications had a safety factor of 4.14 while the pedal crank with the two holes had a safety factor of 2.63. Based on prior research articles, with a safety factor of above 2.22 for a bicycle, it is deemed safe to use [5]. Therefore, it was concluded that adding the two additional holes to the bicycle pedal cranks would not threaten the structural integrity of the bicycle pedals and was a safe modification to make.

VI. FINAL DESIGN

The final design of the bicycle is shown in Figure 2. Four main components were modified from the purchased bicycle frame to fit the client's needs.

- Frame
  - The top bar of the frame was removed to create a step-through bicycle. This allows easier access for getting on and off the bicycle.
- Pedals
  - Two new holes were added to the pedals to allow for the crank length to be shortened and adjusted as the client grows.
- Handlebars
  - The handlebars were lowered by two inches by switching the handlebars for a set from a different bicycle to make them more comfortable for the client to reach.
- Seat
  - The seat was lowered by an additional half inch from the lowest point by moving the rear reflector.

Figure 2. Final bicycle design with completed modifications.

VII. DISCUSSION

The results of the analysis proved that all modifications made to the bicycle were able to be done safely. All stresses in the modified bicycle simulation were lower than the yield strength of the material, with these results verified through physical testing. In addition, the bicycle met the design goals of the project. When riding the modified bicycle, the client demonstrated her comfort with the design through her ease and interest in continuing riding. The handlebars, seat height, and pedal crank length can all be adjusted to accommodate the user's future growth.

VIII. CONCLUSIONS AND RECOMMENDATIONS

The client tested the final prototype and was able to ride the bicycle comfortably and safely. This proves that bicycles can be made more accessible for children with disabilities such as achondroplasia. By making all children's bicycles adjustable by component, companies can sell bicycles to the average child, while still designing them to fit the physical needs of children with disabilities. By designing bicycles with this need in mind, all children will be able to participate in bicycle riding, which will lead to psychological and physical benefits.

Due to lack of time, a way to embark onto the bicycle without the training wheels on was not addressed. The client is currently able to step on the pedals to reach the seat, however, future improvements would allow her to do so without utilizing the pedals.

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Chapter 1: Introduction

Many people face difficulties and hardships throughout their lives. Yet, for individuals with physical disabilities, inaccessible environments cause these challenges to arise more frequently and have a greater impact. For instance, a flight of stairs to enter a building, a feature that someone without a physical disability would find easy to navigate, can make a building inaccessible for a disabled person if there is no accompanying ramp. This can lead to feelings of exclusion and isolation, potentially causing mental distress as well. Having a non-inclusive environment and a lack of adaptive devices, additionally, can add to this feeling of isolation.

One example of a physical disability is achondroplasia, the most common form of dwarfism. This condition affects the growth of the bones in the legs and arms, causing a short stature, long torso, lumbar lordosis, bowlegs, and several other symptoms. Because of these physical differences from the average population, everyday activities such as bicycle riding are not accessible. Often, people with achondroplasia are unable to reach the handlebars and pedals of commercial bicycles, due to their shorter inseam and arm length. If individuals with this condition were to purchase a custom bicycle that fits their body dimensions properly, it could cost up to $900, a very expensive price for the average person.

However, bicycle riding is something that many adults and children partake in. Not only is bicycle riding a popular social activity, but research has shown that exercise is an important factor in improving mental health and psychological functions too [6]. The inability to be included in activities such as bicycle riding can thus cause strain on individuals with disabilities.

This project focuses on creating an adaptive bicycle for a 6-year-old child with achondroplasia. Modifications were made to a commercial bicycle purchased from Walmart to fit the physical and societal needs of this child, allowing her to be able to comfortably partake in bicycle riding with her friends and family.

Chapter 2: Literature Review

2.1 Achondroplasia

Achondroplasia is the most common form of dwarfism in humans, affecting about 1 in 10,000 of births [1]. This genetic condition slows the growth of cartilage and bone, especially in the long limb bones (i.e. the bones in the arms and legs) of the human body. Individuals with achondroplasia are often identified by their short stature, long trunk, and genu varum. Other common phenotypes of achondroplasia include, but are not limited to, excessive lumbar lordosis, frontal bossing of the head, hypotonia, hyper extensibility of joints, and spinal stenosis [7].

2.1.1 Height and Weight in Achondroplasia

One of the main identifiers of people with achondroplasia is their short stature. In a research study published in the 2023 *Calcified Tissue International* journal, researchers found that the height of the subjects in the achondroplasia group were statistically significantly lower than the subjects in the control group [8]. The mean height for the achondroplasia group was 126.5cm versus the mean height of the control group of 162.0cm [8]. These values are shown in Figure 3.

	Control ($n = 21$)	ACH ($n = 10$)	p value
Evaluation age (years old)	15.7 (12.1–38.7)	15.0 (11.7–23.4)	0.819
Gender			>0.999
Male	76.2% (16/21)	80.8% (8/10)	
Female	23.8% (5/21)	20.0% (2/10)	
Height (cm)	162.0 (145.8–168.7)	126.5 (115.3–136.8)	**$<$0.001**
Z-score of height	-0.40 ± 0.73	-5.38 ± 1.13	**$<$0.001**
Weight (kg)	48.90 ± 14.09	40.16 ± 14.43	0.120
Z-score of weight	-0.17 ± 0.87	-1.38 ± 1.18	**0.003**

P value in bold represents a statistically significant difference

ACH achondroplasia

Figure 3. Anthropometric values between a control group and achondroplasia groups. [8]

This difference in height and weight also shows up in childhood growth. In a study conducted in 2007 with 17 patients having a mean age of 11.8 +/- 3.3 years, researchers found that the mean height of these children varied by almost 6 standard deviations lower than the average population of the same age [9]. However, their mean sitting height only varied by about 2 standard deviations below the age-matched population, numerically showing the trait of shorter legs of people with achondroplasia [9]. As for weight differences, their research showed that the weight varied by about 1.5 standard deviations lower than the average population [9]. These results from the study, shown in Figure 4, were similar to the *Calcified Tissue International* study described previously. These values were important to the design and analysis of this project in order to accurately model the loads on the bicycle that the client will exert. By understanding the difference in weight and height of the population with achondroplasia, the bicycle would be better catered to the body dimensions of the client.

	Achondroplasia mean ± SD (range)	*Z*-Score mean ± SD	Reference values mean ± SD (range)
Height (m)	118.0 ± 9.93 (90.0–125.5)	−5.77 ± 0.98	150.70 ± 14.19† (126.71–172.07)
Sitting height (cm)	72.29 ± 7.50 (51.50–82.0)	−2.18 ± 1.49	79.50 ± 6.84† (69.84–90.88)
Arm span (cm)	104.0 ± 10.78 (86.0–121.0)	−6.39 ± 1.02	150.73 ± 14.64† (126.95–173.60)
Head circumference (cm)	56.68 ± 1.90 (52.0–59.5)	1.88 ± 1.13	54.05 ± 0.99† (52.19–55.41)
Weight (kg)	31.19 ± 10.48 (19.10–55.60)	−1.53 ± 0.89	40.01 ± 11.58† (24.34–59.82)

Figure 4. Anthropometric measurements of children with achondroplasia, compared with age-matched values of a reference group. [9]

Another recent research study worked to create growth curves of US children (under 18 years old) with achondroplasia to help with further research and clinical understanding of achondroplasia [10]. Researchers used data collected from four US skeletal dysplasia centers to construct age vs. height, age vs. weight, height vs. weight, and age vs. head circumference curves for both females and males from birth through 18 years [10]. The age versus height and age versus weight curves for 2- to 18-year-old females with achondroplasia are shown in Figures 5 and 6 below, respectively. These values are useful metrics in predicting the client's growth throughout her childhood.

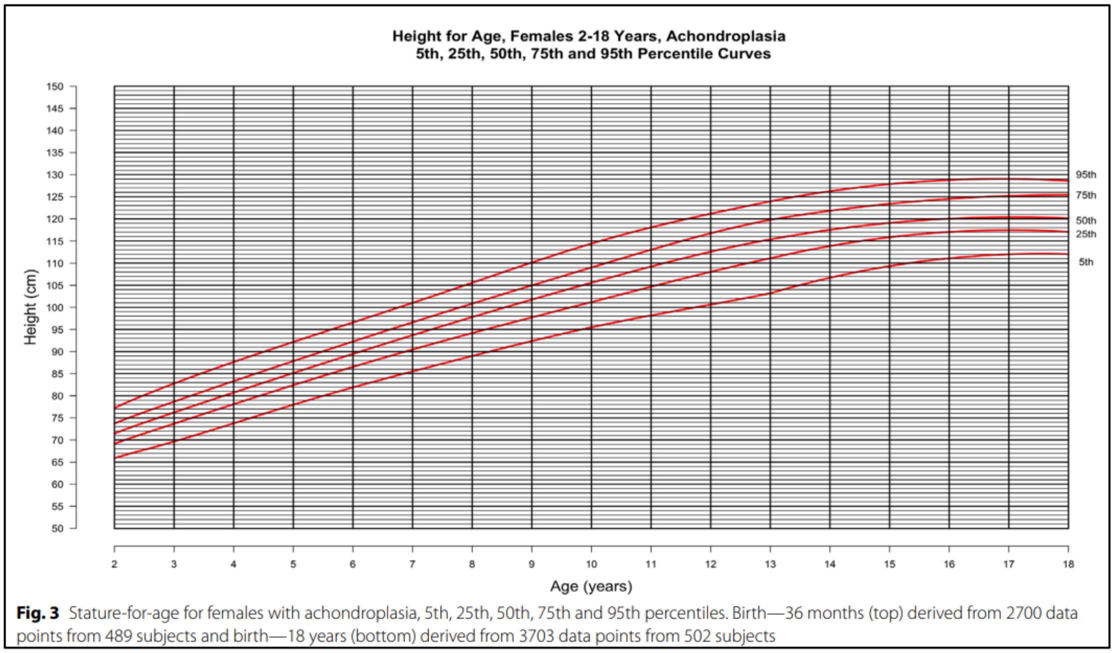


Figure 5. Age versus height curves for females with achondroplasia ranging in age from 2 to 18 years old. The 5th, 25th, 50th, 75th, and 95th percentiles are displayed in the graph. [10]

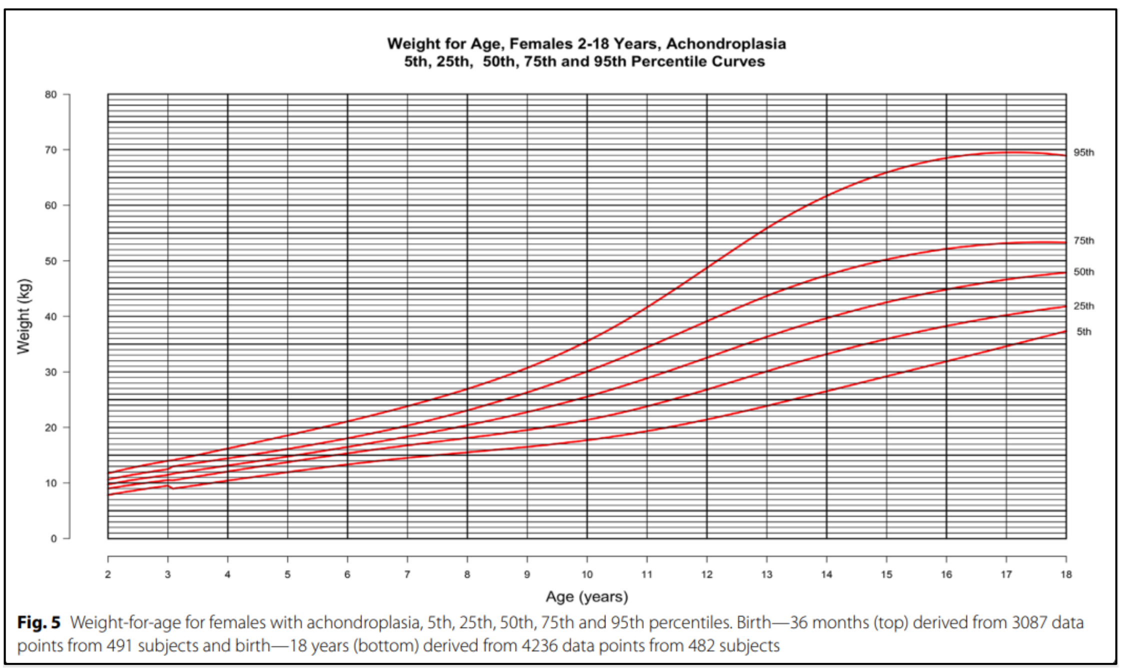


Figure 6. Age versus weight curves for females with achondroplasia ranging in age from 2 to 18 years old. The 5th, 25th, 50th, 75th, and 95th percentiles are displayed in the graph. [10]

2.1.2 Muscle Strength in Achondroplasia

The muscle strength of people with achondroplasia is a topic that hasn't been widely studied yet. One 2007 research study found that for most muscle groups, the muscle strength in children with achondroplasia was significantly less than the average age-matched population [9].

To quantify muscle strength, researchers used a hand-held Dynameter to find strength in Newtons. The results for this study are shown in Figure 7. The strength in the hip flexors, dorsal extensors of the wrist, knee extensors, and dorsal flexors of the foot are all significantly lower than the referenced population of children. The article hypothesizes that this difference may be due to a "decrease in muscle mass, by reduced neuromuscular coordination, or by altered biomechanics" [9]. Since a trait of those with achondroplasia is shorter bones, having a relatively average length of the muscles and tissues surrounding the shorter length of bones may lead to weak muscle tone, or hypotonia, in their body [9].

Table III. Muscle Strength in Children With Achondroplasia Compared With Reference Values

Muscle group	Achondroplasia mean ± SD (range)	*Z*-Score mean ± SD	Reference values mean ± SD
Shoulder abductors (Newton)	140.26 ± 50.24 (76.50–222.50)	0.36 ± 1.17	134.60 ± 38.48 (NS)
Hip flexors (Newton)	130.41 ± 36.86 (85.0–195.50)	−2.23 ± 0.60	247.06 ± 50.19*
Dorsal extensors of the wrist (Newton)	74.88 ± 32.50 (39.0–158.50)	−3.55 ± 3.33	119.0 ± 34.42*
Knee extensors (Newton)	129.12 ± 39.67 (65.50–204.0)	−2.47 ± 0.92	255.12 ± 69.43*
Dorsal flexors of the foot (Newton)	141.82 ± 35.47 (84.0–196.0)	−1.13 ± 0.70	174.29 ± 42.69*

NS, Not significant.

* $P < .01$.

Figure 7. Muscle strength in children with achondroplasia compared with reference values. [9]

2.1.3 Functional Health Status in Achondroplasia

Based on a 1998 research article in the American Journal of Medical Genetics, the most commonly reported complaint from their sample group of adults with achondroplasia was chronic back problems (41%), with "chronic allergies/sinus problems (38%), arthritis/rheumatism (33%), hearing impairment (33%), spine deformity (30%), sleeping difficulty (29%), [and] chronic neck pain (20%)" following closely [11]. These symptoms attributed to most of the overall physical health complaints of this cohort.

However, though many with achondroplasia experience skeletal dysplasia such as the symptoms described above, research studies have shown that the functional health status of adults with achondroplasia is not significantly different from the average population [11].

2.1.4 Bowleg Deformity in Achondroplasia

Bowlegs, also known as genu varum, is a condition in which the legs curve outwards at the knees. Someone who has bowlegs will have a wide gap between their knees when standing with their feet and ankles together. This misalignment can cause knee and hip pain, joint instability, some functional disability such as trouble walking or running, and a higher risk of osteoarthritis later in life [12]. An example of a child with bowlegs is shown in Figure 8.

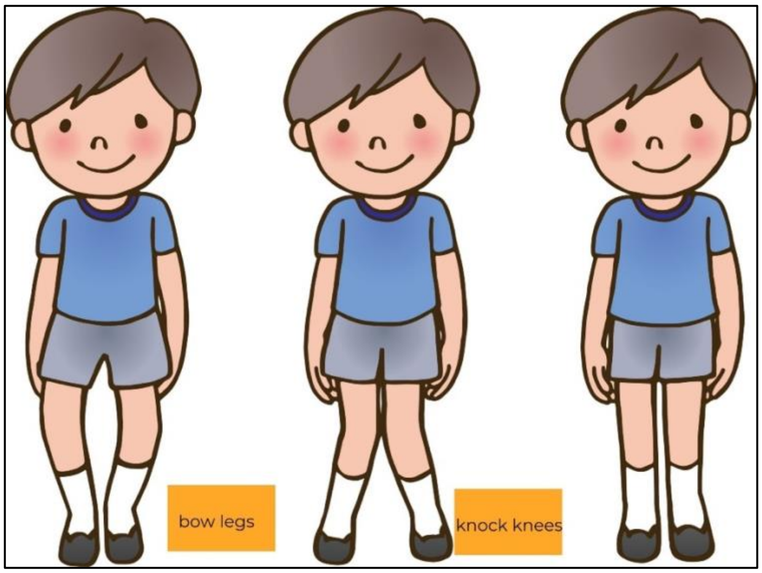


Figure 8. Figure of a child with bowlegs. [13]

For the population with achondroplasia, the frequency of having bowlegs is about 50-60% [12]. This is often a result of the fibula growing longer than the tibia. For the average person, the fibula is shorter than the tibia; the ratio of fibula length to tibia length is a constant 0.98 throughout growth [14]. However, in people with achondroplasia, the average ratio of fibula to tibia length varies throughout growth; at skeletal maturity, this ratio is about 1.08, showing that the fibula length is greater than tibia length, shown in Figure 9 below [14]. Even through several age groups of children, this trend continued to be prevalent. This difference is growth affects the relationship between these two bones, especially at the knee and ankle, often causing bowlegs. Another factor affecting bowlegs is laxity of the lateral collateral ligament, which can cause greater lateral differences in the frontal plane [12]. A person having bowlegs should be evaluated if there is concern about leg bowing affecting the individual's weight-bearing ability and ability to move properly [15]. Excessive bowing of the legs can cause pain and instability of the knee, affecting gait and other physical activities [15].

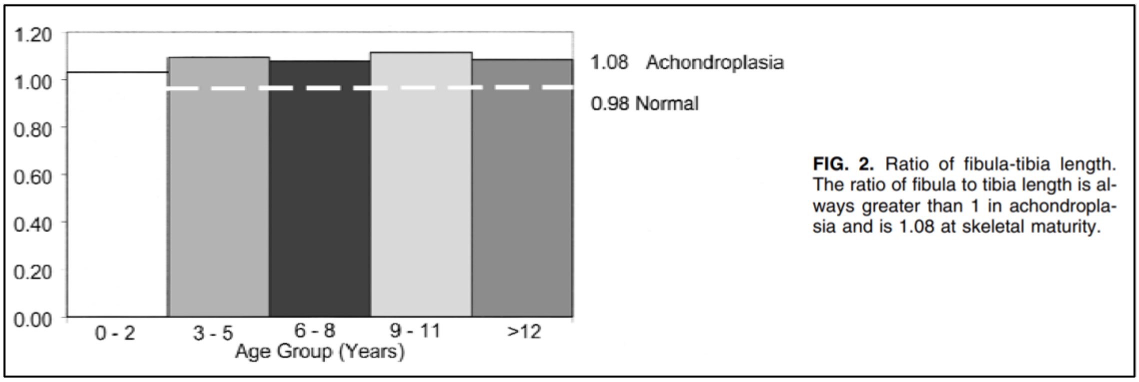


Figure 9. Ratio of fibula-tibia length. [12]

There are currently a few methods to treat bowlegs. One method is through realignment surgery, where the surgeon performs osteotomies (cutting and reshaping of the bone) of the tibia and/or fibula [12]. Lateral collateral ligament tightening can also be performed in addition to this surgery to help correct the angle of the knee. Another option to help correct bowlegs is through a brace treatment, though the impacts of this method have not been proved yet [12].

2.2 Achondroplasia and Disability

The Americans with Disabilities Act (ADA) is a federal civil rights law in the United States which prohibits discrimination against disabled people. According to the ADA, a disability is defined as “a physical or mental impairment which substantially limits one or more major life activities” [16]. Dwarfism is one such condition [17]. In fact, while they recognize the complicated and potentially negative feelings the term disabled can cause, Little People of America (a disability rights organization for people with dwarfism) encourages its members to identify as disabled due to the legal protections the identity provides them [17].

Disability is a complicated and nuanced topic which can cause a lot of negative feelings if discussed improperly. Like other minority groups the disabled community has faced a long history of discrimination and dehumanization which makes the language used to discuss disability incredibly important. The Victorian freak show had an incredibly important role in shaping modern perceptions of disabilities, including achondroplasia [18]. It is from the freak show where the term “midget” originated to describe people with proportionate dwarfism [18]. Despite its continued use in media and the entertainment industry, “midget” is a highly offensive slur and should never be used when describing achondroplasia [18]. The best place to look for guidance on appropriate terminology is from the community itself. Broadly accepted terms include “little person,” “person of short stature,” and “person with dwarfism” [19]. When referring to medical conditions that cause short stature (achondroplasia being the most common), the appropriate term is “dwarfism” [20]. Additionally, the label of dwarf is accepted by most members of the community [19]. However, it is important to recognize that the disabled community is broad and diverse and as such, there is not one form of language that is preferable in every case [21]. Thus, it is important to ask the disabled individual which forms of language they prefer.

2.3 Psychology and Recreational Needs

Most individuals encounter challenges and adversities at various points in their lives. However, for those with disabilities, inaccessibility causes these obstacles to be more recurrent and carry a more significant impact. According to Leaf Complex Care, there are three main factors that affect the mental health of people with physical disabilities: social constraints, loneliness and isolation, and lack of integrated care [22]. Society tends to form unjust stereotypes and prejudice against people with physical limitations, making it more difficult to achieve equal social inclusion in their community. Due to these barriers people with physical disabilities will often become isolated, either because they feel constrained or because of the lack of inclusion. This leads to them experiencing some stress, anxiety, depression, and/or posttraumatic stress disorder [22]. Lack of inclusion can include factors such as a non-accessible physical environment and the lack of adaptive devices [23]. The lack of bicycles available for people with forms of dwarfism is an example of the lack of accessibility and inclusion for individuals with disabilities.

Along with feeling like they do not fit in, the lack of accessible bicycles for children with achondroplasia can also prevent them from exercising. In all people, exercise improves anxiety, stress, and depression, along with psychological, physiological, and immunological functions [6].People with physical disabilities are already at a higher risk for some of these disorders, and exercise is especially important for this population.

2.4 Current Bicycle Market

Currently, there are few companies that sell bicycles specifically designed for children with dwarfism. One bicycle company, called Islabikes, is based in the United Kingdom and focuses on selling bicycles to children with dwarfism [2]. In 2020, the company received requests from individuals with dwarfism to design a bicycle that would suit their needs. This sparked an investigation by Islabikes to figure out how to design a bicycle that supports people with restricted growth. Often, commercial children's bikes do not fit these children's needs because their body proportions are different than the average person, as previously discussed. Since these people did not have access to bicycles that meet their needs, some lacked the desire to participate in cycling.

Islabikes launched four designs to address this problem: two for adults with dwarfism and two for children with dwarfism. The Joni 20 and the Joni 24 are two versions of the first bicycle model for adults with dwarfism, as can be seen in Figure 10 [2]. These bicycles are currently being sold for about $950.

Figure 10. Joni 20 (left) and Joni 24 (right). [2]

Their children's bicycles cost about $420, but are still expensive, especially for children who will most likely end up outgrowing this bicycle. Based on the bicycles sold on Walmart.com, typical children's bicycles range from about $50 to $200 [24]. These two models sold by Islabikes are called Cnoc 14 Small Dwarfism and Cnoc 16 Dwarfism, as shown in Figure 11 [2]. Each of these models are built for people of different measurements.

Figure 11. Cnoc 14 Small Dwarfism (left) and Cnoc 16 Dwarfism (right). [2]

Cnoc 14 Small Dwarfism is designed for a child of an approximate minimum height of 90 centimeters (about 2.95 ft), a minimum inside leg length of 30 centimeters (about 11.81 in), and a maximum inside leg length of 35 centimeters (about 1.15 ft) [2]. Cnoc 16 Dwarfism is designed for a child of an approximate minimum height of 102 centimeters (about 3.35 ft), a minimum inside leg length of 36 centimeters (about 1.18 ft), and a maximum inside leg length of 40 centimeters (about 1.31 ft) [2]. The main differences between these four bicycles and an average bicycle are mostly all in the frame design. These bicycles position people in an upright riding position and offer an "ultra-low step-over which offers excellent foot clearance when getting on and off" [2]. Since initially researching these bicycles, Islabikes has paused sales of these models, meaning that these are not even currently available for children with achondroplasia to purchase.

There are also companies that offer custom bicycle designs, such as a company called Strider. These bicycles can be customized by model, frame color, handlebar type, wheel type, and accessories [3]. These custom design websites are very beneficial in finding the best combinations. These bicycles range in price from about $250 to $900 [3]. Due to the limited amount of bicycle options for children with achondroplasia, people have had to alter commercial children's bicycles themselves or use bicycles that do not fit every physical and environmental need for the children. Therefore, it is essential that proper modifications are made to bicycles to accommodate the needs of those with achondroplasia while also maintaining appropriate safety guidelines.

2.4 Bicycle Components

There are over 20 components in a typical commercial bicycle. There are many different types of bicycles, such as mountain bicycles, racing bicycles, or the typical everyday recreation bicycles. Despite their differences, these bicycles share common core components, while also incorporating specialized parts tailored to their intended use. The image below shows the key components found in most average bicycles.

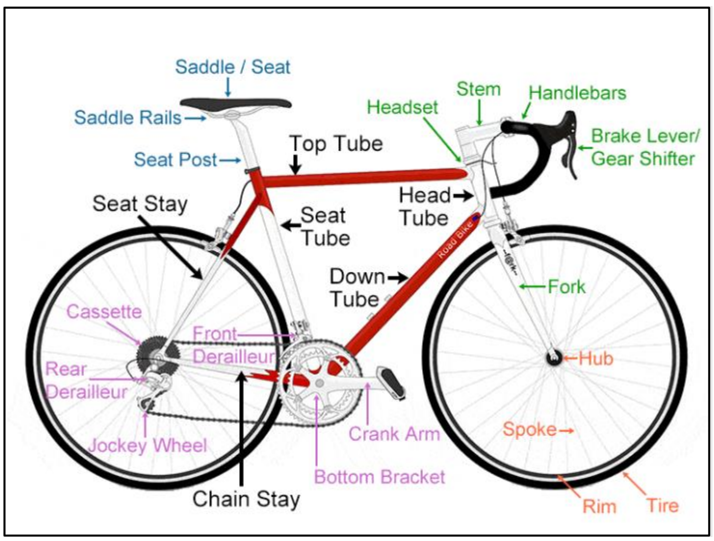


Figure 12. Diagram of typical bicycle components. [25]

As seen in Figure 12, bicycles are broken down into five main sections: frame (black), front (green), wheel (orange), back (purple), and seat (blue). Each section hosts components that serve a purpose for the bicycle.

The bicycle frame typically includes the top tube, head tube, down tube, seat tube, seat stays, and chain stays. The top tube, also referred to as the crossbar, runs parallel to the ground to support the bicycle frame, however, some bicycles omit this component to ensure easy mounting and dismounting for the user. The head tube allows for the steering of the front wheels as it connects the handlebars to the wheel fork while the down tube, the thickest part of the frame, connects from the head tube to the pedals for structure and stability. The final tube, the seat tube, is the host of the seat post, which is how the seat/saddle is adjusted. Lastly, two sets of stays, the seat stays and chain stays, respectively connect the seat to the rear wheel axle and pedal to the side of the rear wheel.

The front of the bicycle includes the fork, headset, stem, handlebars, brake levers, and brakes. The fork (Figure 13) is the connection point between the front wheel and the frame.

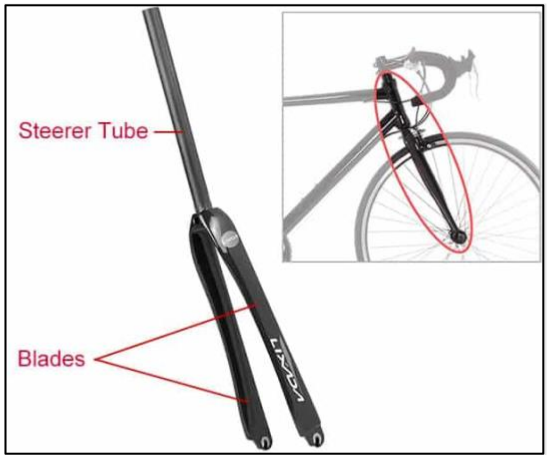


Figure 13. Bicycle fork. [25]

The fork also connects to the headset, a set of components inside the head tube that allows the handlebars to turn the front wheel. Next, the stem holds the handlebars and is the connection point between the handlebars and the fork. Handlebars are essential to steering the bicycle. Lastly, the brake levers control the braking system, allowing the rider to slow down the bicycle.

The center of the bicycle wheel section, often called the hub, includes the axle, bearings, and hub shell. Within the wheel, there are rims (the metal frame that supports the tire), the tires themselves, and the valves for inflating them. The hub and rim are connected by many spokes.

The back of the bicycle includes components responsible for propelling the wheels. Pedals are where the rider's feet sit while riding, with the crankset being the part turned by the rider's legs. The crank set moves around the bottom bracket and turns the chain rings which in turn moves the chain (Figure 14).

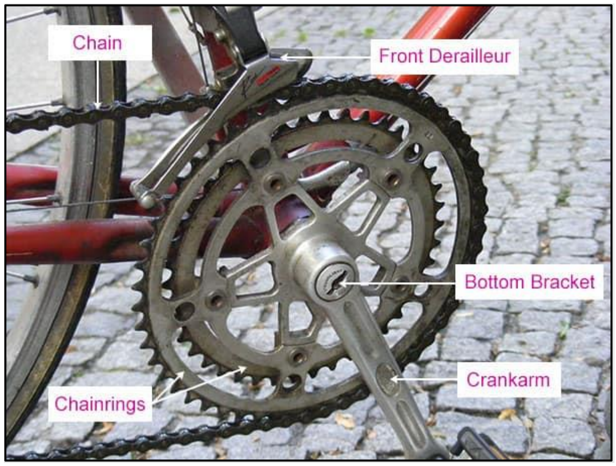


Figure 14. Back components of a bicycle. [25]

The chain transfers the power supplied by the user to the rear wheel which causes the bicycle to move. Additional components in this section pertain only to bicycles equipped with gears.

The seat is the simplest of the sections, only made up of the saddle itself, saddle rails, saddle clamp, and seat post. The saddle is where the user will sit on the bicycle, while the saddle rails are what support and hold the saddle in place. The seat post allows for vertical adjustment, ensuring rider's comfort [25].

2.5 Bicycle Sizing

While various bicycles share many common components, they exhibit a wide range of shapes and sizes tailored to individual requirements. Bicycle components are adaptable to cater to different customer needs. People ride bicycles throughout their life, so it is crucial to offer sizes to all different people.

One place where this is evident is the children's bicycle industry. Children grow fast, so there needs to be many different sizes of bicycles on the market for them to choose from. Because of this, there needs to be some sizing standard in place for children to refer to when buying bicycles. Luckily, organizations have done research on this and have found correlations of the sizes of bicycles that work best for different sized children of average height.

According to an article titled "Ultimate Guide to Kids Bike Sizes", children's bicycles often have a very similar frame size to one another. However, where these bicycles are different is their wheel size. Children's bicycles typically range from wheel sizes of 12 inches to 24 inches [26]. Table 1 serves as a sizing chart for children's bicycles. By knowing a child's inseam height and overall height, the proper wheel size for them can be determined.

Table 1. Sizing chart for children's bicycles. [26]

Wheel Size	Age	Height	Inseam
12”	2-3	2’10”-3’4”	14-17”
14”	3-4	3’1”-3’7”	16-20”
16”	4-5	3’7”-4’0”	18-22”
18”	5-6	3’9”-4’3”	20-24”
20”	5-8	4’0”-4’5”	22-25”
24”	7-11	4’5”-4’9”	24-28”

Other aspects of children’s bicycles that change with bicycle size are the stand over height (the distance between the ground and top of the top tube) and the seat post height (the height of the seat measured from the ground up), as these are dependent on the child’s inseam and total height. This is because the inseam height must be greater than both the stand over and seat post height. If this were not true, the child would not be able to comfortably stand over the bicycle or sit on the bicycle. Therefore, it is vital to have those measurements before purchasing a children’s bicycle [26].

2.6 Biomechanics

As any child, children with achondroplasia will outgrow things such as their bicycle. It is important to consider the growth patterns of children with achondroplasia versus those of an average child. Table 2 shows the average growth of a female child with achondroplasia for sitting height. Similar charts for arm span and average leg length growth were obtained from the same source [27].

Table 2. Descriptive statistics for sitting height for age 2 to 20 years. [27]

Descriptive statistics for sitting height for age, 2 to 20 years (for calculation of z-scores; L=l)				
	Girls			
Age (years)	n	Mean	SD	CV
2	49	50	1.4	2.80%
3	62	53.4	1.7	3.20%
4	65	56.2	2.1	3.70%
5	57	58.7	2.4	4.00%
6	44	61.4	2.6	4.20%
7	40	64	2.8	4.30%
8	47	66.3	2.8	4.30%
9	42	68.4	2.9	4.20%

10	41	70.6	3	4.30%
11	36	72,7	3.2	4.40%
12	30	75	3.4	4.50%
13	32	77.5	3.5	4.50%
14	22	79.6	3.5	4.30%
15	26	81.2	3.3	4.00%
16	17	82.2	3	3.70%
17	17	82.9	2.8	3.40%
18	12	83.2	2.7	3.30%
19	10	83.4	2.7	3.20%
20	34	83.5	2.7	3.20%

These charts show that the average sitting height of a female child with achondroplasia will increase by approximately 24.8 centimeters from ages 5 to 20, a 44% increase. Average leg length increases by approximately 14 centimeters, or 51%, and arm span increases by approximately 32.3 centimeters, or 41.5%, from ages 5 to 20. Females with average growth patterns were found to grow in sitting height by about 31 centimeters or 54% and in leg length by about 30 centimeters or 60% from the same ages [28]. This is more than a two-fold increase in growth between the two. However, both data sets have a similar percentage of growth. For both children with achondroplasia and without, the adjustability of a bicycle is important as they age from child to teenager to young adult.

Muscle strength and power output in individuals with achondroplasia is generally less than those with an average growth pattern. Throughout multiple studies of both children and adults with achondroplasia, muscle strength is shown to be weaker across most muscle groups. Another study specific to the vastus lateralis, a muscle compartment located in the outside thigh region, showed that adults with achondroplasia had a 53% smaller muscle volume, and produced 29% less force [29].

The positioning of the rider's body will determine how efficient a bicycle is. Efficiency is especially important for people with achondroplasia since they already have a disadvantage in muscle strength and power output. The first component that affects body position is the saddle and its height. To be the most biomechanically efficient, the rider often has their knee positioned at around a 25- to 35-degree angle between the thigh and calf at maximum extension. Figure 15 shows a diagram of how to measure knee angle of a bicycle rider.

Figure 15. How to measure for knee angle. [30]

The second component is handlebar position. For comfortable riding, handlebars should be placed at a height that prevents the rider from bending too far forward and allows them to bike in an upright position. There are no set measurements for this and will depend on what is most comfortable for the user. The third component is pedal and cleat position. The ball of the foot should be located right above the pivot arm, or the center of the pedal to produce as much force as possible into the pedal. This is something that is hard to control without clip-in pedals, but generally any comfortable foot position will be sufficient [31].

A large part of balancing on a bicycle comes from the rider maintaining a center of mass at a point equally distant and over the two wheels [32]. This is commonly referred to as the rider-bicycle system center of mass, or COM. The rider-bicycle system COM is maintained by both the steering and body movements relative to the bicycle. Body movements are used at a much higher percentage of the time when moving at higher speeds, and steering is used more at lower speeds. However, both are still used to some degree at all speeds. While turning, there are inherent forces that will cause a bicycle to continue in a straight line. These are called centrifugal forces. Body movements are used to negate the centrifugal forces. The name of the force caused by these body movements is called centripetal force. To not fall while turning on a bicycle, the torques exerted by both the centripetal and centrifugal forces must be equal. Both torques can be calculated using distance from the ground to the biker's center of mass, velocity of the bicycle, the circle radius of the turn, and the mass of the bicycle and rider. The equations for both centrifugal and centripetal torques are below:

$$(1)\ T_{Centrifugal} = (mv^2/R) * Cos\ \Theta * L$$

$$(2)\ T_{Centripetal} = (mg) * Sin\ \Theta * L$$

Where: m = mass of the rider & bicycle, v = velocity of the rider & bicycle, Θ = lean angle, L = distance from ground to rider-bicycle COM, R = turn radius, g = force of gravity

When these forces are set equal to each other, lean angle can be calculated in a simpler way:

$$(3)\ Tan\ \Theta = (v^2/Rg)$$

As seen in equation 3, lean angle is entirely dependent on velocity and turn radius. Figure 16 shows a diagram to help better understand the system.

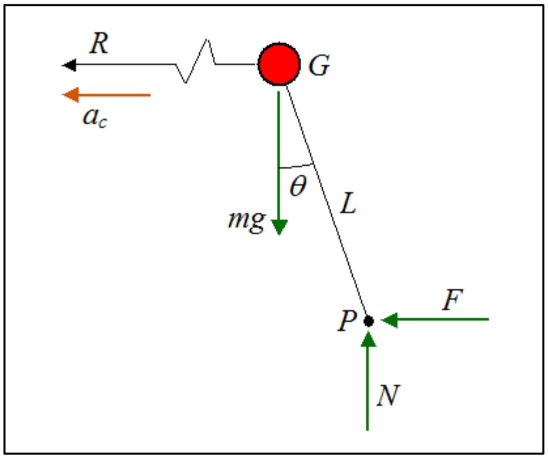


Figure 16. Bicycle turning system. [33]

Chapter 3: Project Strategy

3.1 Initial Client Statement

"Design, prototype, and test a custom bicycle that fits the physical and social needs of a child with achondroplasia. This device will be comfortable and adjustable for the user to accommodate the child's growth."

3.2 Design Requirements (Technical)

To accomplish the goal in the client statement, various design requirements had to be achieved. A bicycle had to be created that:

1. Visually resembled a standard two-wheel bicycle to allow the user to feel and look like an average child while riding.
    a. Assessment: User interviews, matches definition of standard two-wheel bicycle
2. Had detachable training wheels for when the user wanted to remove them.
3. Was structurally safe and durable.
    a. Assessment: Mechanical testing.
4. Accommodated the growth of the child until at least age 12.
    a. Assessment: Bicycle components were adjustable enough to fit the measurements of an average 12-year-old child with achondroplasia based on growth charts.
5. Was physically comfortable for the user to ride.
    a. User was able to propel forwards effectively and efficiently.
    b. Was intuitive and had easy-to-access user controls (e.g. easy to activate brakes, pedals and handles could be easily reached).
    c. User could easily get on and off without risk of tipping/tripping.
        i. Assessment: Observations, user interviews, motion capture of user riding bicycle.
6. Was lightweight and easy to transport.
    a. Assessment: Bicycle weighed about the same as an average children's bicycle (<25 lbs.).
7. Could be used for daily leisurely riding on a variety of outdoor surfaces such as gravel, dirt, and pavement and did not present any extra safety challenges on top of those of average bicycle.
    a. Assessment: Mechanical testing.

To fully understand the safety requirements that bicycles need to have, it was extremely important to research the Code of Federal Regulations.

3.3 Design Requirements (Standards)

The Code of Federal Regulations (CFR) explains specific requirements for bicycles to ensure safety. These standards are broken down into sections: mechanical, fork and frame, braking system, steering system, pedal, chain and chain guards, tire wheels and wheel hubs, seats, reflectors, and additional requirements. Due to the CFR, if a bicycle fails any of the requirements below that are associated with these pieces, it is banned under the Federal Hazardous Substances Act [34].

3.3.1 Mechanical

If assembly is required, an adult of average intelligence and ability must be able to assemble the bicycle. There must be no unfinished cut metal edges or sharp parts on the bicycle that may inflict an injury on the rider, and all burrs or feathering must be removed. Additionally, all screws, bolts, and nuts must be fully secured and cannot loosen, break, or fail during testing. When the bicycle undergoes testing, there may not be a visible break in any steering, wheel, pedal, crank, or braking system component [34].

3.3.2 Fork and Frame

The bicycle fork and frame assembly must not break or bend if a force of 200 lbf is applied. A test must be run with the fork where a force is applied until the fork bends 2 ½ inches. After it is bent 2 ½ inches, there must be no sign of fracture [34]. This test was not completed because a fork was taken from a different commercial bicycle that has already passed this safety testing.

3.3.3 Braking System

Bicycles must have rear-wheel brakes or both front-wheel and rear-wheel brakes. The braking system must be fully secured to the bicycle frame. If a bicycle seat is higher than 22 inches off the ground when it is in its lowest position, the bicycle must have a foot brake. When 70 pounds of force is applied to the bicycle pedal, the foot brake must have a braking force of no less than 40 lbf. A rider weighing at least 150 pounds cycling at a speed of at least 15 mph must stop within 15 feet when the foot brake is applied. The foot brake must engage when the rider applies force in the opposite direction of the force that drives the bicycle forward. When a torque of 10 ft-lb is applied at each location on the crank where a rider can engage the brakes, the distance from that point to the location on the crank where the rider initiates forward pedaling must not exceed 60 degrees [34]. This test was not completed because the braking system was not modified.

3.3.4 Steering System

According to the Code of Federal Regulations, handlebar stems for sidewalk bicycles must be able to pass a series of three tests. First, they must be able to withstand a force of 225 lbf in a forward direction 45 degrees from the stem centerline. In addition, the handlebar assembly must be able to be twisted with a torque of 15 ft-lb without moving or showing signs of damage. During this test, the handlebars have to be secured in the clamp, so they do not turn. Lastly, the ends of the handlebars must be covered, and devices mounted on the ends must stay on while enduring a force of 15 lbf. Along with passing these tests, handlebars must be symmetrical, be no more than 16 inches above the seat in its largest difference, and there must be a permanent mark at the minimum depth the stem can be inserted into the fork. This mark must be at least 2.5 times the diameter of the stem from the bottom of the stem [34]. This test was not completed because the steering system was taken from a different commercial bicycle that already passed this safety testing.

3.3.5 Pedals

Pedals must have right and left-hand symmetry and treads on both sides if they do not have a definite user side. Also, sidewalk bicycles do not have to have reflectors [34].

3.3.6 Chain and Chain Guards

The drive chain of a bicycle must operate over the sprocket without catching or binding. Additionally, the tensile strength of the drive chain must be no less than 1400 lbf. There must be a chain guard over the top of the chain and at least 90% of the part where the drive chain contacts the sprockets. The chain guard must extend back towards the center of the rear axle. To prevent the chain from interfering with the wheel, the bicycle derailleurs must also be guarded [34]. This test was not completed because the chain and chain guard were not modified.

3.3.7 Tires, Wheels, Wheel Hub

Inflatable bicycle tires must have the manufacturer's recommended inflation pressure molded onto its sidewalls in letters at least an eighth of an inch high. Also, if the tire is inflated to 110% of the recommended pressure, it must stay on the rim even when tested under a side load of 450 lbf. All bicycle wheels must have spokes and be at least 1/16 inch away from any part of the frame as it turns. Sidewalk bicycles do not have to meet any wheel hub requirements [34]. This test was not completed because the tires, wheels, and wheel hub were not modified.

3.3.8 Seat

Nothing that is attached or a part of the seat can be more than five inches above the seat's surface. The clamp that adjusts the seat must be able to secure the seat to the post at any possible position and prevent the seat from moving during use. The seat and seat post must not move when a 75 lbf downward force or a 25 lbf horizontal force is applied [34]. This test was not completed because the seat was taken from a commercial bicycle that already passed this safety testing.

3.3.9 Reflectors

Bicycles must have reflectors to enhance visibility and make bicycle riders more noticeable to other road users. Reflectors must be on the front, rear, sides, and pedals of the bicycle to improve visibility from all angles [34].

3.3.10 Additional Requirements

Along with all other requirements, one more test must be performed to prove the bicycle is up to code. Bicycles must withstand being loaded with 30lb on the seat and 10lb on each handlebar and dropped onto a paved surface one foot above the ground three times in an upright position. Then, the weights are removed, and the bicycle must be dropped an additional three times in any orientation. After dropping the bicycle 6 times, the wheels, frame, seat, handlebars, and fork must not be broken. No part of the bicycle, excluding the tires, should touch the ground when the bicycle is tilted 25 degrees to either side with the pedals in the lowest position. This testing was not completed because alternative testing was performed on the bicycle.

Ethical standards must also be followed to deliver the best prototype and biking experience to the client, while making sure she is comfortable throughout the entire design process. The most important goal was to make sure the client always felt comfortable [34].

3.4 Ethical Standards

Creating a custom bicycle for an individual with achondroplasia would naturally require ethical standards to be upheld. The first standard that was incredibly important for this project group to follow was the Health Insurance Portability and Accountability Act or HIPAA. This act requires that no sensitive patient health information be disclosed throughout this paper without the patient's consent or knowledge [35].

On top of this, this project group followed standards laid out by the Institutional Review Board or IRB. When performing human subject research like this project, IRB approval of protocol, consent documents and other supporting documents, such as testing equipment descriptions, were needed. Before each meeting with the client, this group completed IRB approval forms. The IRB consent and approval forms (case #24-0042) for each meeting with the client are shown in Appendix A: 1-3. This was necessary because each meeting will be slightly different in protocol, and each change must be approved. The IRB assesses research to ensure the protection of human subjects, either requesting alterations or disapproving research altogether. Additionally, it scrutinizes privacy concerns and ensures informed consent is obtained [36].

Another ethical consideration when creating a bicycle for any child was the safety of the bicycle. Risk assessment of each modified part of the bicycle had to be performed to ensure there wasn’t any increased chance of injury. To implement this risk assessment into the bicycle design, the team followed multiple bicycle safety standards. These standards include the CPSIA standards for children’s bicycles, ASTM standards for all bicycles, and general FHSA regulations [37].

3.5 Final Client Statement

“The client, a 6-year-old girl with achondroplasia (the most common form of dwarfism) has never been able to ride a standard two-wheeled bicycle due to her body proportions being different than the average child. This presented an engineering challenge of designing, prototyping, and testing a custom bicycle that fits the physical and social needs of a child with achondroplasia. This device would be comfortable and adjustable for the user to accommodate the child’s growth.”

Chapter 4: Design Process

4.1 Needs Analysis

Riding a bicycle can be a core part of anyone’s childhood, from learning to ride for the first time to cycling around town with friends from school. It can promote exercise, reduce stress, and be a social outlet for children. This isn’t so easy for children born with a disability, specifically a disability like achondroplasia. Average bicycles will not work for these children because of different growth patterns and proportions. As mentioned in earlier sections, this can create social barriers for children with achondroplasia. Also, children with and without achondroplasia are still growing and need a bicycle that can get bigger with them. For most families, it is not financially feasible to invest in a custom bicycle that their child will not be able to ride in just a few years. The goal of this project is to design, prototype, and test a bicycle that meets the physical and social needs of these children. To reach this goal, the final bicycle design will be a modified 12” children’s bicycle from Walmart.

4.1.1 Needs Criteria

To better gauge the specific needs of this client, design criteria were created and ranked by the client's parents. Safety was a non-negotiable requirement for the bicycle, so it was not ranked along with the other criteria. Safety was top priority throughout the entire design process and was verified by performing simulations and mechanical testing using requirements from the Code of Federal Regulations, as discussed in Chapter 3.3. The other criteria and their descriptions are listed below.

The bicycle must be both comfortable and efficient. For the comfortability aspect, the bicycle must have intuitive and easy-to-access controls such as reachable pedals and handlebars. The client must be able to easily get on and off the bicycle without the risk of tipping/tripping, and it must have sufficient bicycle suspension for a comfortable ride. The client must also be able to propel forwards effectively and efficiently.

For transportation purposes, the bicycle must be lightweight and weigh about the same as an average children’s bicycle. The bicycle must also be transportable enough that the client is able to pick up the bicycle to turn it around. The material on the bicycle selected will play a large role in the weight of the bicycle. This material must also be durable and able to withstand weathering overtime.

The bicycle must be designed in such a way that it is able to be used for daily leisurely riding. Daily leisurely riding includes the ability to ride on flat, paved, and gravel surfaces without imposing any potential safety concern/hazards consistent with those of a standard bicycle. Along with operating like a standard bicycle, the bicycle should also visually resemble a standard two-wheel bicycle to allow the user to feel as socially comfortable as possible when riding.

Lastly, the components of the bicycle must be adjustable. The components should have the ability to adjust to a larger size to accommodate the physiological growth of a child with achondroplasia. This would allow the bicycle to be used throughout the client’s childhood.

4.1.2 Criteria Ratings

The criteria were ranked by the client's parents to give a greater understanding of what was most important for this project. The child was not asked to rank the criteria as they are only 6 years old. Below, in Table 3 and Table 4, are the parent's rankings:

Table 3. Father's criteria rankings.

	Comfortable and efficient	Lightweight and transportable	Durable	Daily leisurely riding	Visually resembles standard bicycle	Adjustable	Final Score
Comfortable and efficient		1	1	1	1	1	5
Lightweight and transportable	0		1	1	1	0	3
Durable	0	0		0	0	0	0
Daily leisurely riding	0	0	1		0	0	1
Visually resembles standard bicycle	0	0	1	1		0	2
Adjustable	0	1	1	1	1		4

Table 4. Mother's criteria rankings.

	Comfortable and efficient	Lightweight and transportable	Durable	Daily leisurely riding	Visually resembles standard bicycle	Adjustable	Final Score
Comfortable and efficient		1	1	1	1	1	5
Lightweight and transportable	0		1	1	0	0	2
Durable	0	0		0	0	0	0
Daily leisurely riding	0	0	1		0	0	1
Visually resembles standard bicycle	0	1	1	1		0	3
Adjustable	0	1	1	1	1		4

Based on the parents ranking the criteria were prioritized and are listed below in order of importance, starting with most important:

1. Comfortable and efficient
2. Adjustable
3. Lightweight and transportable & Visually resembles a standard bicycle
4. Durable
5. Used for daily leisurely riding

4.2 Part by Part Design of the Bicycle

As stated in section 4.1, the design approach was to modify a commercial 12" children's bicycle. To identify which modifications were to be made, the client was observed riding the bicycle purchased from Walmart [24]. Through observation and motion capture, the components that did not properly fit the client were identified. The design process was divided into four main components: the bicycle frame, bicycle pedals, bicycle handlebars, and bicycle seat. All four of these things needed to be modified for the client to ride the bicycle comfortably and safely. Through concept brainstorming and multiple design iterations, the final designs of each component were determined. This section walks through the design process for each of the four components.

4.2.1 Bicycle Frame

4.2.1.1 Concept Brainstorming

The bicycle frame's design is essential to the structural integrity and assembly of the bicycle. The main thing considered when designing the bicycle frame was the maximum height of the frame that the client must step over to mount and dismount on the bicycle. As discussed in Chapter 2.1, one characteristic of individuals with achondroplasia is that they often have hyper extensibility of joints. This means they are very flexible and can lift their leg up high. This ability easily allows the client to lift her leg over the top of the frame. However, the mounting and dismounting process requires stability and balance, which is something that needs to be considered. It was important to ensure that the client could safely get on and off the bicycle without the risk of falling over. Additionally, it was important that the client could comfortably stand over the frame when her feet are on the ground. This would allow the client to rest during riding without needing to get off the bicycle. The ability to stand during riding also ensures a safer riding experience as the client can stand when needed, which lessens the risk of injury.

4.2.1.2 Alternative Designs

Two frame designs were considered when determining the best bicycle frame for the client. The first frame design was a traditional diamond frame, also known as step-over frame. As the name explains, this type of frame requires the rider to lift their leg over the top tube when mounting and dismounting. This frame is the most common type for bicycles used for leisurely riding. Therefore, they are extremely accessible on the current bicycle market. In addition to daily leisurely street riding, this type of bicycle frame is utilized in bicycles that are made to be ridden on a wide variety of terrains. The geometrical design provides a strong and sturdy frame for the bicycle on different terrains. One concern of using this type of frame is that it requires mobility and flexibility for the rider to lift their leg over the top tube. Although individuals with achondroplasia have the flexibility to lift their leg, the mounting and dismounting process requires a lot of stability as the rider must balance on one foot while clearing the top tube. Another potential problem discussed is the client being unable to stand over the top bar when her feet are on the ground as her inseam length may not be taller than the height of the top bar. Therefore, she may not be able to comfortably rest on the bicycle when taking breaks from riding. The diamond frame may be a possible solution only if other modifications are made to bring the bicycle frame lower. For this design idea, the diamond frame would be taken from the smallest standard children's bicycle on the market. This idea is shown in Figure 17 below.

Figure 17. Diamond bicycle frame. [38]

The second frame design considered was a step through bicycle frame. Unlike the diamond frame, a step through frame does not have a top bar. This allows the rider to easily get on and off the bicycle as they do not have to swing their leg over the top bar. This increases the stability of the user during the mounting and dismounting process as they do not need to use as much of their balance. Additionally, the client would be able to comfortably stand with their feet on the ground during resting. There are a few concerns with using a step through frame. With the removal of the top bar, a step through frame is less stiff and sturdy. Because of this, the frame is made up of more durable materials which makes the bicycle heavier. A heavier bicycle may make it harder for the rider to balance while standing still or taking off on their ride. Step through bicycle frames are typically not included in standard children's bicycles and are more common in adult bicycles. Therefore, to have a step through frame on a children's bicycle it requires the purchase of a specialized bicycle. Because of this, the top bar would be removed from a standard diamond bicycle frame to replicate a step through frame. This idea is shown in Figure 18 below.


Figure 18. Step through bicycle. [39]

4.2.1.3 Final Design

The final design chosen for the bicycle frame was the step through frame. Since one of the traits of achondroplasia that the client displays is having shorter leg bones, having a step through frame will be advantageous to allow her to stand sturdily over the bicycle without interference. In an average commercial bicycle frame, the top bar of the bicycle is often almost equal to the height of the seat. However, because of the client's stature, this top bar would be too high for her inseam measurement. Removing it to create a step through frame will likely be the most comfortable and practical design for the bicycle frame.

4.2.2 Bicycle Pedals

4.2.2.1 Concept Brainstorming

The client's ability to reach the pedals is an important consideration in the bicycle design. Initial client screenings and tests revealed issues in comfortably reaching the full rotation of the pedals. The bottom of the pedal rotation was out of reach, while the top of the pedal rotation was a bit too high. This caused the client to begin unnecessary hip rotation to reach the top and bottom of the cycle, as shown in Figure 19. This can lead to lower back pain and a loss of power to the pedals. Hip rotation is associated with cranks being too long, bicycle saddle being too high, or the rider not being flexible enough. Some of the hip rotation could also be attributed to a bowleg deformity, however a shorter crank length would help this regardless.

Figure 19. Example of hip rotation in initial client observation.

Initial concept designs led to three concrete solutions. These solutions were adding pedal straps to the bicycle, shortening the pedal crank itself, and adding an attachment to the client's shoes to allow them to reach the bottom of the pedal cycle easier. After weighing the pros and cons of each solution and completing a Pugh concept selection matrix (Figure 20), the choice was simple. Adding pedal straps would keep the client's feet on the pedals, but it wouldn't help to reduce hip rotation and add an additional issue of preventing a quick dismount. Adding an attachment to the client's shoes would allow them to reach the bottom of the pedal cycle but make the peak of the cycle even higher. This could be solved by raising the seat, but this would add more issues such as a more difficult mounting or dismounting process. Also, having to constantly carry around a shoe attachment for the bicycle could impose a burden on the client. The most holistic, and what was decided as the optimal solution was shortening the pedal crank. Shortening the pedal crank solves the issue of the pedal cycle being too large, as well as maintaining the look and feel of the original bicycle.

Criteria	Weight	Baseline	Alternative Solutions		
		Frozen Bike	Shorter axle	Straps on pedals	Shoe attachment
Comfortable and efficient	6	0	1	1	0
Adjustable	5	0	0	0	1
Lightweight and transportable	4	0	0	0	0
Visually resembles standard bicycle	3	0	0	-1	-1
Daily leisurely riding	2	0	1	0	0
Durable	1	0	0	0	1
Sum of Positives		0	8	6	6
Sum of Neutrals		0	0	0	0
Sum of Negatives		0	0	-3	-3
Total		0	8	3	3

Figure 20. Pugh concept selection matrix of our pedal solutions.

It is important to note the control variable of the Pugh selection matrix above is written as 'Frozen Bike'. This is used to represent a commercial 12" bicycle from Walmart that the client's parents mentioned as the best fitting bicycle they could find.

4.2.2.2 Alternative Designs

After deciding that the pedal crank length needed to be shortened, three approaches were considered. The first approach considered was to use interchangeable cranks like those shown in Figure 21. This would allow for future adjustability as the client grows. However, the bicycle purchased did not have pedals which would interface with interchangeable cranks. Thus, to utilize this approach, a new pedal mechanism would need to be created.

Figure 21. Bicycle pedal crank arms. [40]

The second approach considered was to modify the original cranks on the purchased bicycle. The pedal cranks on the purchased bicycle consisted of two tubes held together by a screw, shown in Figure 22. The larger tube attaches to the pedals and the smaller rod attaches to the main bicycle frame. The first idea to make this adjustable was to extend the slot the screw sits in to allow for the cranks to shorten a range of distances. However, this idea presents the challenge of the crank not staying shortened to the desired length. Another idea discussed was to use a push button mechanism to lock the crank into different lengths. A final idea for creating adjustability within the existing crank was to create holes for the existing screw on the opposite side of the crank from the slot. Thus, would allow the screw to enter the existing threaded hole from the opposite side and lock the crank into different lengths.

Figure 22. Pedal cranks on purchased bicycle.

A final approach considered was to machine a new outer crank which would then attach to the existing inner crank and pedal. This approach would allow for additional adjustability and finer control over the final product. It would also minimize stress on the part caused by unnecessary cutouts.

4.2.2.3 Final Design

The final design choice was to modify the bicycle's existing cranks to shorten them. The idea was to create two new holes in the pedal crank that would allow for adjustability for the client as she grows. One of the holes would be placed to make the crank about the same length as it was originally, and the second hole's placement was calculated to yield an optimal length for the client. The calculations were done by taking 41% of the client's tibia length which resulted in a length of 2.24 inches [41]. There are a few ways to calculate for crank length, like hip or knee angle. Due to the client's hip rotation during initial observation, it was not possible to derive these measurements. It was more accurate to choose tibia length here. The new crank was calculated to be [42]. This is ~0.51 inches shorter than the current crank length of 2.75 inches.

4.2.3 Bicycle Handlebars

4.2.3.1 Concept Brainstorming

The client's parents expressed that most handlebars on current children's bicycles are hard for the client to reach, both in vertical and horizontal distance. Most handlebars cannot be lowered as far as the client would need when at the proper seat distance, and they are too far away from her. For comfortable riding, handlebars should be at a height that prevents the rider from bending too far forward and allows them to bike in an upright position. If the handlebars are not in the right position for her height, it could result in her riding without sitting with the right posture, which would result in back pain. Chronic back pain is already the most reported complaint of adults with achondroplasia [6]. Also, as further explained in section 2.1.2, the strength in dorsal extensors of the wrist is significantly lower than an average-sized child. If the client cannot properly reach the handlebars, she will not have a strong grip while steering.

4.2.3.2 Alternative Designs

To address these concerns, there were four possible solutions that could be implemented to position the handlebars at the most comfortable position for the rider. First, purchasing an adjustable handlebar stem, such as the one in Figure 23, would have allowed adjustability in the upwards and downwards directions or in the forwards and backwards directions.

Figure 23. Example of adjustable handlebar stem. [43]

Next, changing the shape of the handlebars could have been a solution. Instead of straight-across handlebars that are usually seen on standard children's bicycles, a form of curved handlebars, such as the ones in Figure 24, could have allowed the user to use different positions while holding the handles, to improve grip ability.

Figure 24. Example of handlebar with curved shape. [44]

After meeting with the client and observing her on the purchased bicycle, it was decided that the main issue that needed to be resolved was that the handlebar stem needed to be lowered. Although the child could reach the handlebars, her arms were at an upwards angle instead of an ideal downwards angle, as shown in Figure 25. In this figure, the handlebars were set at the shortest height that those specific handlebars could be lowered to. With this new information, it was decided that the current handlebars should either be modified or replaced with one from a different children's bicycle.

Figure 25. Client's handlebar placement on purchased bicycle.

4.2.3.3 Final Design

When considering whether it would be better to alter the current handlebars or completely replace them, observations were made about the mechanism involved in the current handlebar system. These handlebars locked into place using a mechanism like those used in crutches, where two buttons were pressed in to adjust the height and would lock in when they reached the two holes in the outer tubes. They could not be shortened past the current height because there was a horizontal bar and matching indents in the handlebar tubes that end at a certain point. These challenges led to the final design choice of replacing the original handlebars with those from another children's bicycle that are more adjustable.

4.2.4 Bicycle Seat

4.2.4.1 Concept Brainstorming

The design of the bicycle seat was also an important consideration in the bicycle design. The bicycle seat plays a key role in the client's ability to comfortably ride the bicycle. It needs to be positioned and designed so that the client can accomplish actions such as perform a complete rotation of the pedals, grasp onto the handlebars, and be seated for extended periods of time. The position of the seat impacts these factors, and thus can contribute to the comfort or discomfort of the user riding the bicycle. For the client specifically, as determined by the pairwise comparison chart, the ability for the bicycle to be comfortable and efficient was the main priority. The seat needed to be in a proper position for the client to reach both the handlebars and pedals at the same time, as well as to support them with a stable seat when moving.

4.2.4.2 Alternative Designs

Three seat modifications were considered when determining the best bicycle seat for the client. The first proposition was an adjustable seat that could move both horizontally and vertically. On most commercial bicycles, the bicycle seat can adjust up and down vertically. However, the addition of a horizontal adjustment mechanism would allow the seat to be more customizable to the client. This especially could be beneficial for an individual with achondroplasia, as the commercial seat and setup of the bicycle often do not fit the person comfortably. This mechanism was inspired by cycling bicycles and exercise bicycles, where the user is often able to move their seat laterally and longitudinally. This posed a few concerns, though, as changing the forward and backward location of the seat could alter the center of mass of the client and bicycle, thus introducing the possibility of the bicycle functioning differently in aspects such as accelerating, braking, and balance. This idea is shown in Figure 26 below.

Figure 1. The ability to adjust the seat vertically and horizontally on cycling bicycle. [45]

The second modification included interchanging the average foam bicycle seat for a gel seat. The gel seat would provide a softer and more malleable cushion than a traditional bicycle seat, theoretically allowing the client to be seated for longer periods of time without discomfort. Currently, on the market, there are various gel padded seat covers that consumers can purchase to fit over their bicycle seat. These range in size, color, and price, and are often purchased by recreational riders to use. However, although helpful in distributing one’s weight and providing longer lasting comfort, some consumers and companies, such as REI, state that gel seat cushioning often will get deformed and compacted more quickly than average bicycle seats, reducing the longevity of this solution [46].

Lastly, the third consideration for modifying the bicycle seat included adding a backrest on the back of the seat for support. As discussed in Chapter 2.1.2, a common trait of achondroplasia is hypotonia, or weak muscle tone. Introducing a backrest for the bicycle seat could help provide back and lumbar support as well as reduce the fatigue on the user's lumbar area muscles while riding. One of these commercial bicycle seat backrests is shown in Figure 27.

Figure 26. One of the current bicycle seat backrests available today. [47]

4.2.4.3 Final Design

Although there were other seat options that could increase comfortability, the changes made to the handlebars, pedal cranks, and frame made it, so the client felt comfortable on the original seat. To lower the seat to the shortest possible height, the seat reflector was removed off the seat stem and placed underneath. This allowed the seat to be pushed all the way down onto the frame, while keeping the reflector on for safety.

Chapter 5: Design Verification

5.1 Frame Verification

One of the major modifications the team hoped to make to the bicycle was removing the top bar of the bicycle frame to transform it into a step-through bicycle. To ensure this operation retained the safety of an average bicycle, finite element analysis (FEA) and mechanical testing were performed on the frame. The Huffy 12” bicycle purchased from Walmart [24] was used for this frame verification. This bicycle was used for frame verification because it was the same bicycle frame intended to be used on the final bicycle. Simulations run using FEA modeled the theoretical change in stress and strain that removing the top bar of the frame would cause. Mechanical testing using strain gauges was performed to validate these FEA simulation results.

5.1.1 Finite Element Analysis of Frame

To prove that the bicycle frame would be able to withstand loading without the top bar, finite element analysis was performed to compare the frame both with and without the top bar. To perform FEA, the bicycle frame was first modeled through computer aided design using SolidWorks. Dimensions of the frame were recorded using a tape measure, calipers, and Image J (an open-source image processing program). Two SolidWorks models were created of the bicycle frame: one of the original frame with the top bar, and the other of the frame without the top bar. Handlebars were also included in these models to apply loads caused by force on the handlebars during riding. The modeled frames are shown in Figures 28 and 29 below.

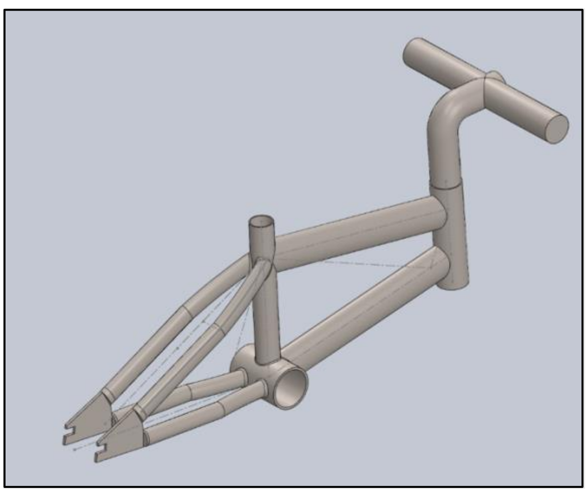


Figure 27. Huffy’s 12-inch bicycle frame and handlebars modeled in SolidWorks.

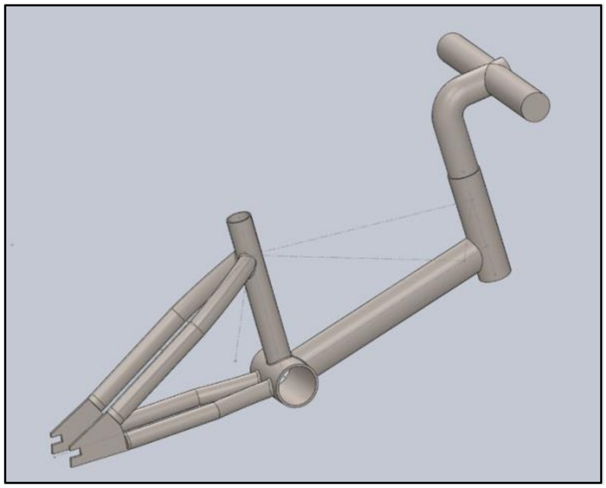


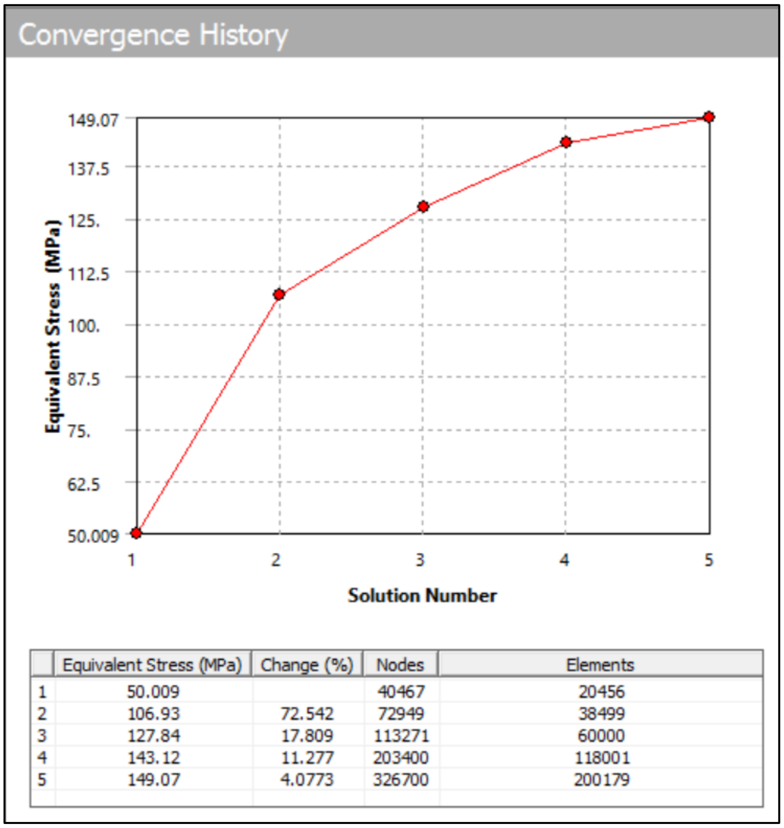
Figure 28. Huffy's 12-inch bicycle frame and handlebars modeled in SolidWorks, with the top bar of the frame removed.

The manufacturers of the 12" bicycle stated the material of the bicycle frame to be steel [24]. Thus, the material used for the bicycle frame model was steel AISI 4130, one of the common materials used for bicycle frames [5]. The specific mechanical properties for this material are detailed in Table 5. Their values were recorded from [48]. The isotropic elasticity of the mechanical properties was derived from the Young's modulus, the Poisson's ratio, the bulk modulus, and the shear modulus.

Table 5. Mechanical properties of Steel AISI 4130 [48]

Steel AISI 4130 Mechanical Properties	
Density	7850 kg/m^3
Young's Modulus	2.05e11 Pa
Poisson's Ratio	0.29
Bulk Modulus	1.627e11 Pa
Shear Modulus	7.9457e10 Pa
Tensile Yield Strength	4.6e8 Pa

The bicycle frames were then imported into Ansys Workbench 2023 as Static Structural simulations for FEA. To ensure that the element sizes used for FEA simulation were producing results that were accurate, mesh convergence was run using the built-in Ansys Workbench mesh convergence study function for both bicycle frame models. The converged equivalent stress for the bicycle frame without the top bar resulted in a value around 149 MPa as shown in Figure 30 below.



	Equivalent Stress (MPa)	Change (%)	Nodes	Elements
1	50.009		40467	20456
2	106.93	72.542	72949	38499
3	127.84	17.809	113271	60000
4	143.12	11.277	203400	118001
5	149.07	4.0773	326700	200179

Figure 29. Mesh convergence study run on the bicycle frame without the top bar in Ansys Workbench.

The loads applied to the frame were calculated based on research found in [49], where researchers experimentally determined the magnitude of force exerted on the handlebars, pedals, and bicycle seat during various steps of riding, in regard to body weight [49]. Two conditions were chosen from this article to be used for FEA simulation: starting bicycle riding while standing up, and riding on a flat surface while sitting down. These two conditions were applied to both the bicycle frame with the top bar and the bicycle frame without the top bar.

The first condition mimicked the rider starting riding while standing up [49]. Since the rider was standing up on the pedals in this condition, there were zero forces on the saddle. For the handlebars, the vertical push on one side of the handlebars was 0.44 times the body weight; on the other side of the handlebars, there was a vertical pull of 1.08 times the body weight. On the pedals, there was a vertical push of 2.19 times the body weight applied on the same side as the handlebar push force.

The second condition modeled a person sitting on the saddle, riding on a flat surface [49]. The forces on the saddle included both a vertical push and a horizontal drag force of 0.49 and 0.02 times the body weight, respectively. The handlebars had both a vertical push and pull force like the previous condition; however, the forces exerted in this condition were lower than the previous condition, at 0.16 and 0.11 times the body weight, respectively. On the same side of the handlebars as the vertical push, there was also a vertical push on the pedals of 0.47 times the body weight.

To constrain the bicycle in Ansys Workbench, two boundary conditions were applied to the frame based on previous studies on bicycle frame strength: one at the front of the bicycle at the bottom of the head tube and the other at the rear dropouts of the frame [50]. The rear dropout is the rear part of the frame that holds the back wheel in place. The first boundary condition is shown in Figure 31 below. For this boundary condition, motion is only allowed in the z-direction of the local coordinate system at the bottom of the head tube. This condition represents the normal motion of the bicycle as it is propelled forwards. For the second boundary condition, the back ends of the rear dropouts were constrained to have a fixed position. However, the frame was still able to rotate freely about the x-axis. This constraint was specified because in the actual model of the bicycle, the rear dropouts are secured to the rear wheel by a pin, allowing the frame to rotate about the wheel axis. This boundary condition is shown in Figure 32.

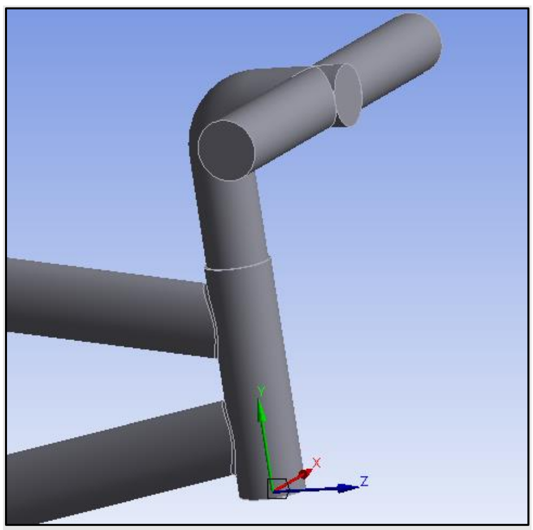


Figure 30. Boundary condition set at the bottom of the head tube. Motion is only free in the z-direction.

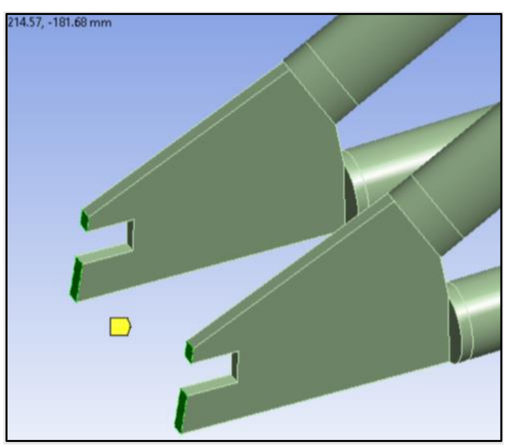


Figure 31. Boundary condition set at the rear dropouts. The position is fixed but can still rotate about the x-axis as defined in the image below.

These loading and boundary conditions were applied to each bicycle simulation. One example of the first condition, a bicycle with a top bar being ridden on a flat surface, is shown below in Figure 33. The pedal push forces were applied as a moment to the bottom bracket (where the pedal cranks are inserted) to minimize the number of exterior parts required to model the loading on the bicycle frame.

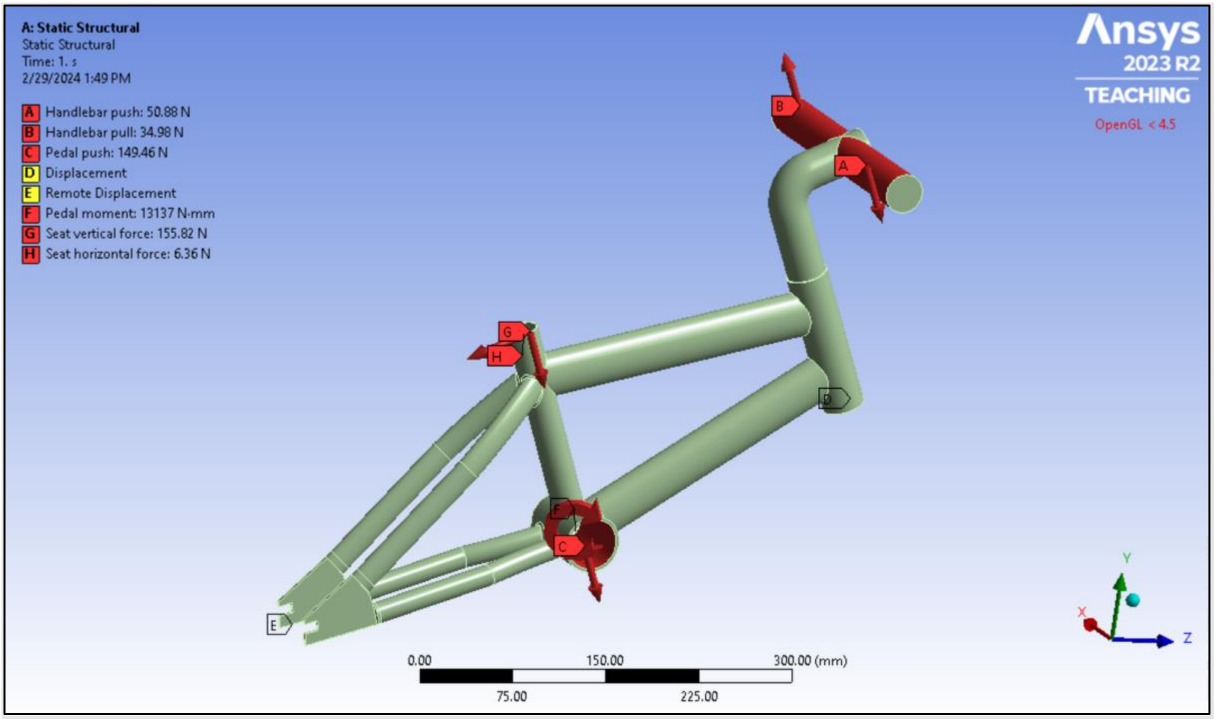


Figure 32. Loading and boundary conditions on the bicycle with the top bar, in the riding on a flat surface condition.

Once all loading and boundary conditions were applied, the Ansys simulations were run to obtain numerical results for the equivalent von-Mises stress and equivalent elastic strain. The results were analyzed to observe where locations of maximum stress were concentrated, and how the results changed between bicycle frames.

5.1.1.1 First FEA Condition: 12-Year-Old Female with Achondroplasia

The body weight chosen for analysis was determined from growth curves generated for females with achondroplasia [10]. Since the bicycle will be adjustable for the 6-year old client to be used throughout her childhood, the 50th percentile weight for an average 12-year old female with achondroplasia was used to estimate her weight in six years; this value was 32.5 kg, or about 318 N [10].

The first riding condition, riding on a flat surface while sitting down, was simulated. The values used for FEA simulation are shown below.

Saddle:

Vertical push = 0.49 X Body weight = 155.82

Horizontal = 0.02 X Body weight (drag force) = 6.36 N

Handlebars:

Vertical push = 0.16 X Body weight = 50.88 N

Vertical pull = 0.11 X Body weight = 34.98 N

Article states horizontal handlebar forces are equal when bicycle is flat

Pedals:

Vertical push = 0.47 X Body Weight = 149.46 N

The locations of maximum von-Mises stress of the bicycle frame with the top bar are shown in Figure 34 below. The leftmost screenshot of the frame shows the front bottom bar of the bicycle, having a stress of about 7 MPa. The middle photo displays a higher stress where the bottom bracket meets the front bottom tube, having a stress of about 30 MPa. The next photo displays the bottom of the seat post, having a stress of about 25MPa. Lastly, on the right, shows where the right side of the top back tube meets the seat post. This location has a stress around 10 MPa.

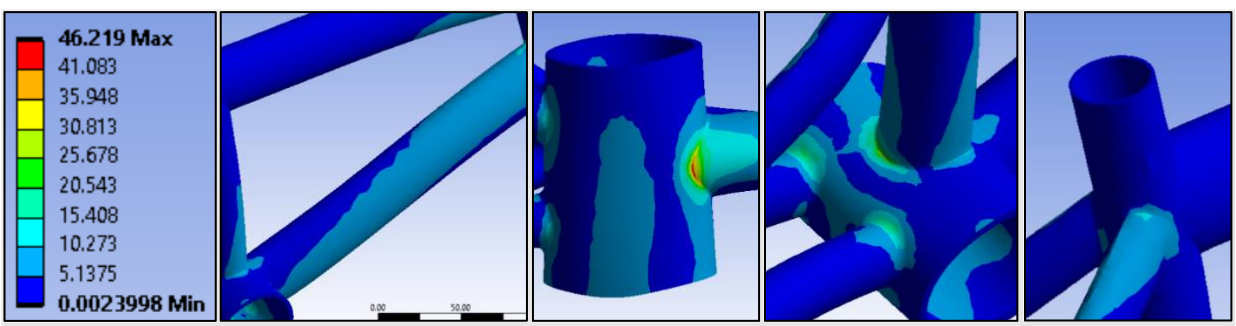


Figure 33. Locations of maximum stress for the bicycle frame with the top bar, in the riding on a flat surface condition.

The following images in Figure 35 show the locations of maximum stress for the bicycle without the top bar. Interestingly, the front bottom bar of the frame in this simulation has a similar stress when compared to the results of the frame with the top bar, a value of about 7 MPa (left image). However, under this simulation, the other areas of higher stress changed. In the middle photo, an area of high stress is shown to be under the back bottom tubes, where these tubes meet the bottom bracket. This location has an average stress of around 15 MPa. The two screenshots on the right shows where the front bottom tube meets the bottom bracket; these locations have von-Mises stresses of about 15 MPa and 10 MPa, respectively. The locations of the stress concentrations likely changed because of the structural difference between the bicycle frames. The loads on the seat, especially, seemed to cause the stress locations to change between models. Where the previous frame model was able to withstand the vertical and horizontal push better due to the support of the top bar, the second model was unable to do so with such strength. From the results of the stress analysis, it seems likely that without the top bar, more stress was distributed to where the bottom bracket met the bottom tubes of the bicycle frame. These loads were not very high, though they are still noteworthy to be aware of.

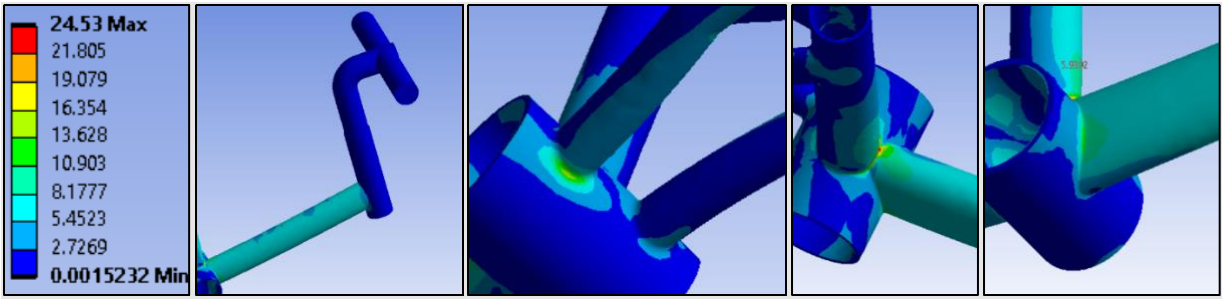


Figure 34. Locations of maximum stress for the bicycle frame without the top bar, in the riding on a flat surface condition.

To compare the strength of the bicycle frame to industry standards, the factor of safety was calculated through the following equation:

$$\textit{Factor of Safety} = \textit{(Yield Strength)/(von-Mises equivalent stress).}$$

The factor of safety is a value which represents the ratio of the yield strength of a material to the maximum stress under expected loading conditions. For example, a factor of safety of 2 would mean that a material would begin to yield (permanently deform) at twice the maximum expected loading of the structure.

The factor of safety was calculated for both the frame with and without the top bar. As seen in Table 6, the factors of safety were 9.95 and 18.75, respectively. This result makes sense as lower magnitude loads were placed on the frame. It is interesting though that the factor of safety for the frame without the top bar is greater than that of the frame with the top bar – this result could be due to a stress concentration in the Ansys simulation, or the changing of locations of higher stress. Additional simulation and analysis would allow a more precise answer to be concluded.

Table 6. Factor of safety calculations for riding on a flat surface condition.

Frame Type	Yield Strength (MPa)	von-Mises equivalent stress (MPa)	Factor of Safety
With Top Bar	460	46.219	9.95
Without Top Bar	460	24.53	18.75

Next, the second condition's results, starting riding while standing up, were analyzed. The loads calculated and applied to the model are shown below.

<u>*Saddle:*</u>

Vertical push = 0 N

<u>*Handlebars:*</u>

Vertical push = 0.44 X Body weight = 139.92 N

Vertical pull = 1.08 X Body weight = 343.44 N

Article states horizontal handlebar forces are equal when bicycle is flat

<u>*Pedals:*</u>

Vertical push = 2.19 X Body Weight = 696.42 N

For the frame with the top bar, much of the higher stress was concentrated at the bottom of the seat post and the bottom of the head tube, as seen in Figure 36. The leftmost image shows where the bottom bracket meets the front bottom tube; at this location, the stress is about 100MPa. The two middle images show the bottom of the seat post, where the stress was about 50MPa and 100MPa, respectively. The rightmost image captures where the bottom of the head tube connects to the front bottom tube; here, the equivalent von-Mises stress is about 25MPa.

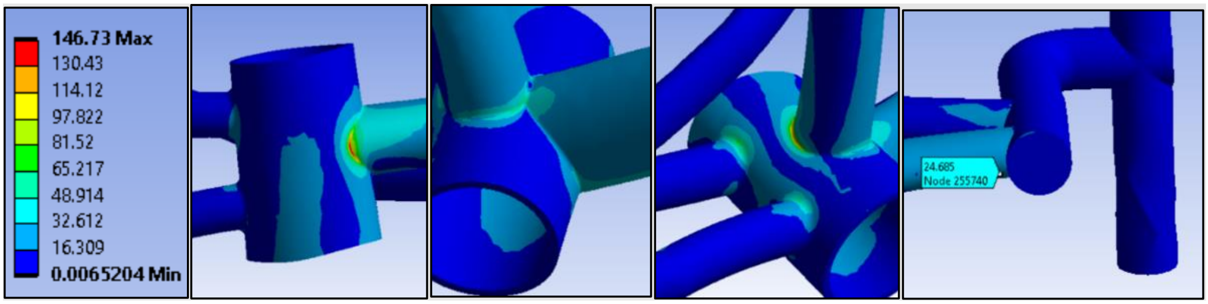


Figure 35. Locations of maximum stress for the bicycle frame with the top bar, in the starting riding while standing up condition.

For the bicycle frame without the top bar, the locations of maximum stress were similar to the frame with the top bar. However, the stresses at these locations were higher overall. The leftmost view in Figure 37 shows where the bottom bracket connects to the front bottom tube; at this location, the stress is around 200MPa, which is about double the stress for the frame with the top bar. The middle screenshot shows the bottom of the seat post. The equivalent stress here is about 100MPa. The rightmost photo shows where the bottom of the head tube meets the front bottom tube; here, the stress is about 100MPa. When compared to the frame with the top bar, overall, the stresses seem to double in this simulation. This result likely occurred because for the frame with the top bar, some of the stresses were placed on the top bar, but when this bar was removed, the stress became distributed and thus, concentrated, on the bottom bar.

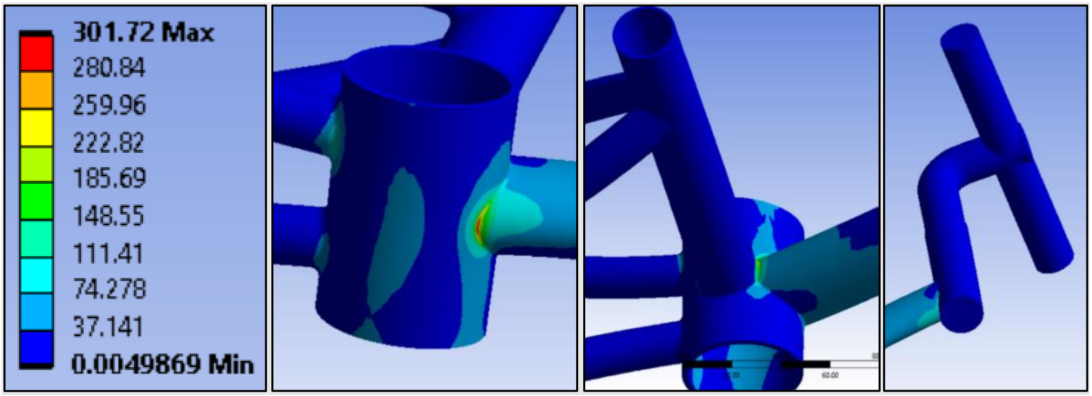


Figure 36. Locations of maximum stress for the bicycle frame without the top bar, in the starting riding while standing up condition.

Again, the factors of safety for the frames were calculated. The results of this calculation are shown in Table 7 below. As can be seen, the factor of safety for the frame with the top bar is about two times the factor of safety for the frame without the top bar: 3.14 and 1.52, respectively.

Table 7. Factor of safety calculations for the starting riding while standing up condition.

Frame Type	**Yield Strength (MPa)**	**von-Mises equivalent stress (MPa)**	**Factor of Safety**
With Top Bar	460	146.73	3.14
Without Top Bar	460	301.72	1.52

As the minimum industry standard factor of safety for bicycle frames is 1.67, this simulation of the bicycle frame without the top bar did not meet that requirement. However, the loads chosen for this simulation are conservative. First, the weight of the client six years down the line was used, 32.5 kg. The client currently weighs 14.8 kg, which is a value less than half the value chosen. Furthermore, this riding condition models the greatest amount of force that will likely be placed on the pedals. This condition assumes that the rider will be standing up and applying all of their weight on one pedal. Though, for riders who are just starting to learn to bicycle ride, this action is more unlikely to occur.

Nevertheless, the safety factor for this condition did not meet the requirements of industry standard. In the next section, when the maximum load weight specified by the manufacturer was modeled on the frames, the safety factors met the required value for bicycle frames. These values represented the load that the bicycle frame was designed to withstand. The safety factors calculated from this loading condition met the required safety factor for bicycle frames.

5.1.1.2 Second FEA Condition: Manufacturer's Standard

The second loading condition modeled was the manufacturing standard for the bicycle frame. According to [24], the maximum load weight for the frame used in the final design is 49 lbs., or 22.226 kg. This weight is 32% lower than the first condition tested using the client's projected weight at 12-years old. The loads on the bicycle were calculated through the same equations as before but using the manufacturer standard. For this loading condition, only the starting riding loads were applied, as the starting riding model causes the greatest amount of stress on the frame between the two riding conditions, as seen in the previous section. If the bicycle frame is able to withstand this condition, it will be able to withstand the normal riding condition, which has lower and more distributed loads. The calculations are shown below for the starting riding condition.

<u>*Saddle:*</u>

Vertical push = 0 N

<u>*Handlebars:*</u>

Vertical push = 0.44 X Body weight = 95.8 N

Vertical pull = 1.08 X Body weight = 234.36 N

Article states horizontal handlebar forces are equal when bicycle is flat

<u>*Pedals:*</u>

Vertical push = 2.19 X Body Weight = 475.23 N

The results of these conditions for the frame with and without the top bar were compared after FEA was performed. The equivalent von-Mises stress results are shown in Figures 38 and 39 below. In Figure 38, the bicycle frame with the top bar, it can be seen that under the manufacturer's maximum loading conditions, the bicycle frame with the top bar experiences a maximum stress of 82.781 MPa, while the bicycle frame without the top bar experiences a maximum stress of 205.34 MPa.

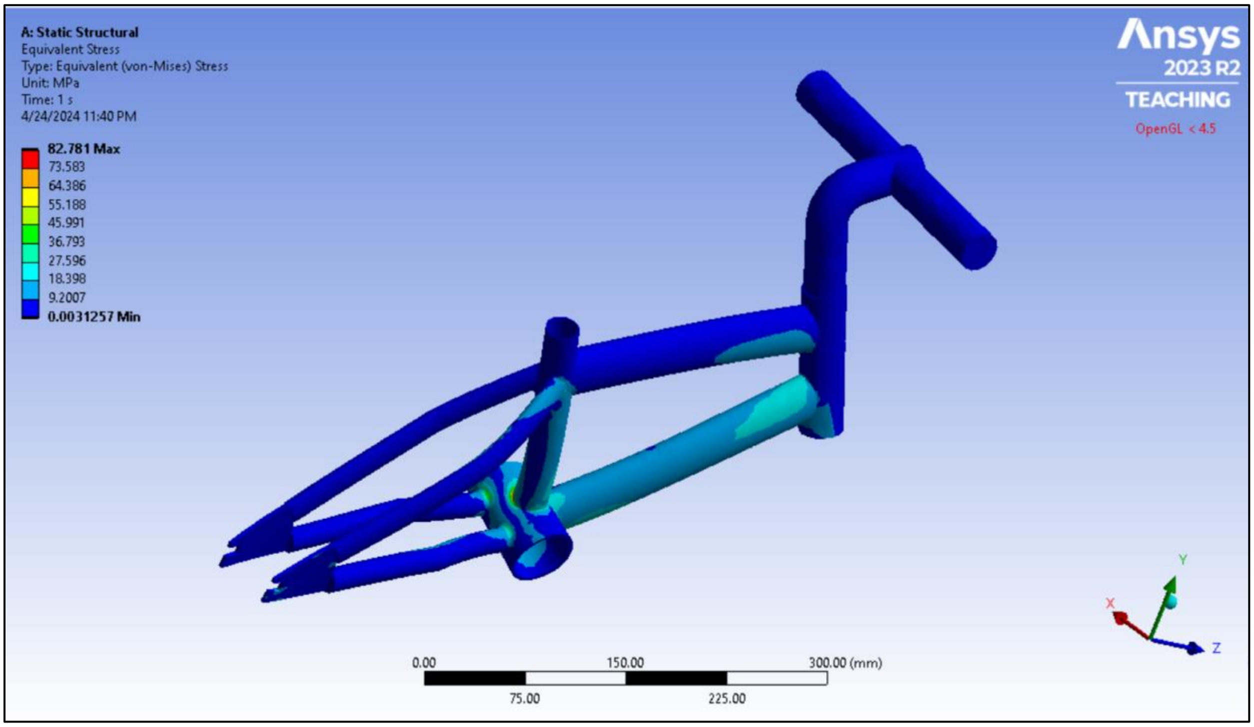


Figure 37. Bicycle frame with the top bar modeled with the manufacturer's maximum load weight.

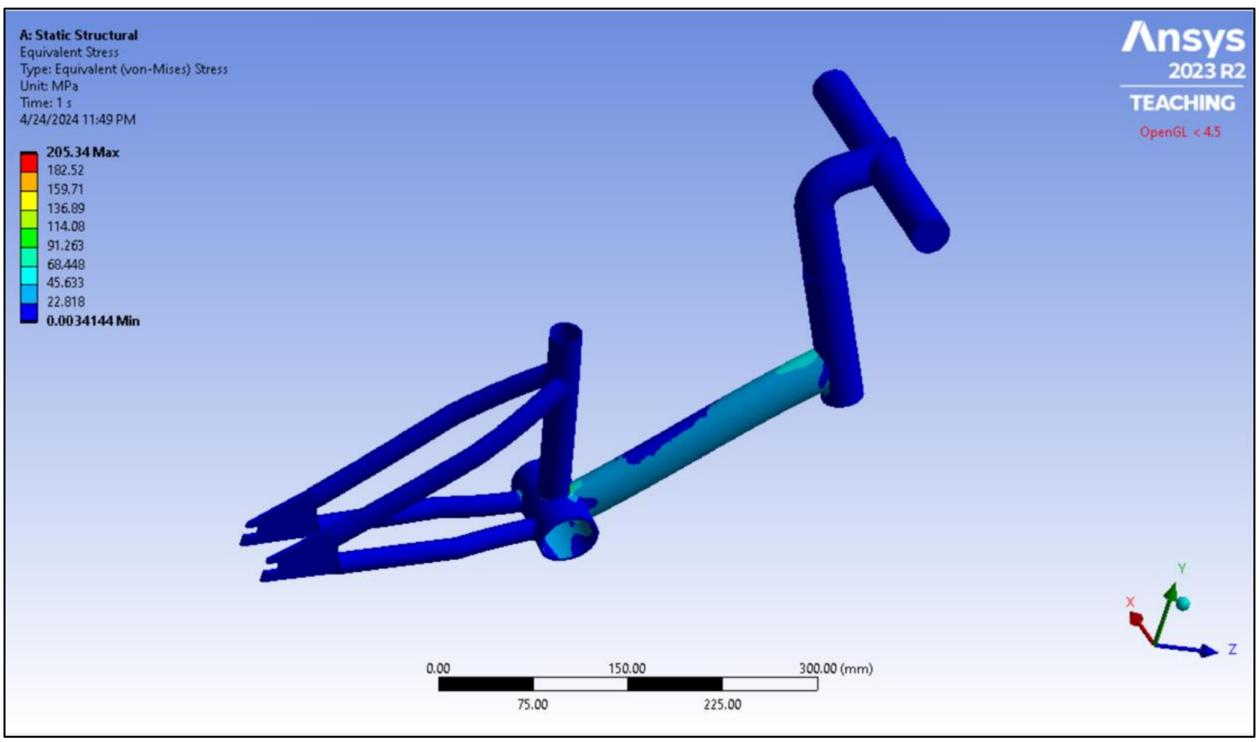


Figure 38. Bicycle frame without the top bar modeled with the manufacturer's maximum load weight.

The factor of safety of these maximum stresses were calculated in order to compare the values against the industry standard safety factor; these values are shown in Table 8 below. As can be seen, per the manufacturer's maximum load of 49 lbs., the safety factor for both the frame with and without the top bar (5.557 and 2.24, respectively) are above the standard of 1.67 [5]. This shows that for the load that the bicycle is designed to withstand, the top bar can be removed without compromising the safety of the bicycle and the client. These results gave the team confidence that removing the top bar of the frame was a safe modification to make, since this FEA simulation is a study on the maximum load that the bicycle is designed to hold.

Table 8. Factor of safety calculations for the bicycle frame during starting riding, with the manufacturer's maximum load weight.

Frame Type	Yield Strength (MPa)	Von-Mises equivalent stress (MPa)	Factor of Safety
With Top Bar	460	82.781	5.557
Without Top Bar	460	205.34	2.24

5.1.2 Mechanical Testing of Frame

As discussed in the previous section, the FEA performed on the bicycle frame model indicates that the top bar can be safely removed. However, there are many factors which could cause the simulation to differ from reality. Mechanical testing was performed to validate the simulation results and thereby prove that the bicycle will be safe without the top bar under expected riding conditions. To perform this testing, strain gauges were carefully placed in three locations that experienced maximum, consistent strain on each of two bicycle frames (one with the top bar and one without).

The three locations were determined by mimicking our mechanical testing loading setup in the Ansys simulation. The loading setup was started by placing the bicycle in a homemade wooden bicycle trainer, and then loading it with weight. The bicycle was loaded by placing two 45-pound weight plates on the seat and a 25-pound weight plate on each handlebar (Figure 40).

Figure 39. Loading setup of bicycle for mechanical testing.

To simulate this mechanical testing loading condition in Ansys, a similar procedure was followed as described in Section 5.1.1, but with modified boundary and loading conditions. First, since the bicycle would be secured at the back wheel to the bicycle trainer, the rear dropouts (where the frame connects to the back wheel) was fixed in Ansys. This condition restricts translational motion of the rear dropouts. However, because the bicycle could still rotate about the bicycle trainer at the rear dropouts, rotational motion was set to be free around the corresponding axis. In Ansys, shown in Figure 41 below, this was the x-axis. Next, boundary conditions were applied to the bottom of the front tube. For mechanical testing, the fork of the bicycle would support the front tube. The wheel would also be attached to the fork, allowing the bicycle to move forward and backward, if applicable. To model this condition in Ansys, a displacement boundary condition was set to only allow translational motion in this direction of motion.

Next, to accurately represent the loading of the weight plates on the handlebars and seat, forces were applied to the model at both locations. The handlebars were sliced into a top and bottom portion in Ansys Design Modeler to apply a force on just the top section. This way, the forces would follow the direction of gravity. The magnitude of the handlebar force on each side was 111 N, or about 25lb. The load on the seat also was set to be in the direction of gravity – in this model, that was the negative y-direction. The magnitude of this load was 401 N, or about 90lb. These loading and boundary conditions were repeated for the bicycle frame without the top bar as well.

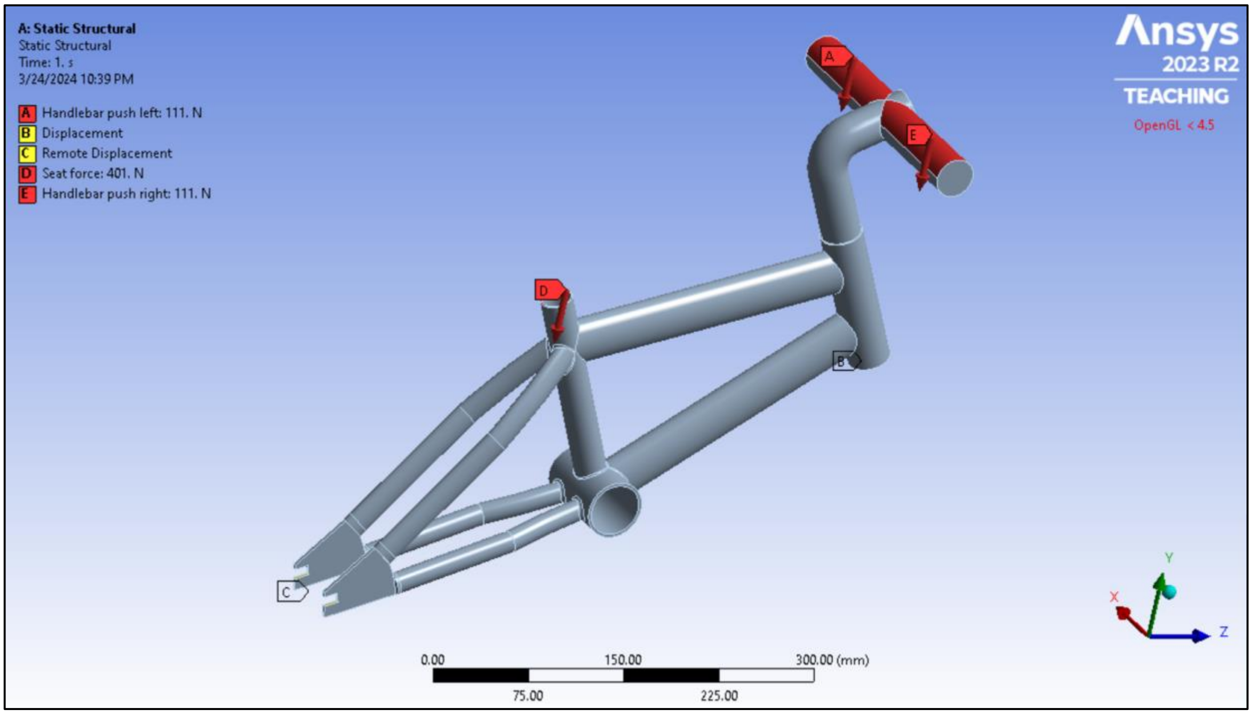


Figure 40. Loading and boundary conditions on the frame with the top bar, following the setup for mechanical testing.

The resultant elastic strain of the models was observed to pinpoint locations where strain remained relatively constant in a defined area. These locations were sought out to determine where to place the strain gages. The results showed that the strain gauges should be placed in the locations shown in Figures 42 through 47 below.

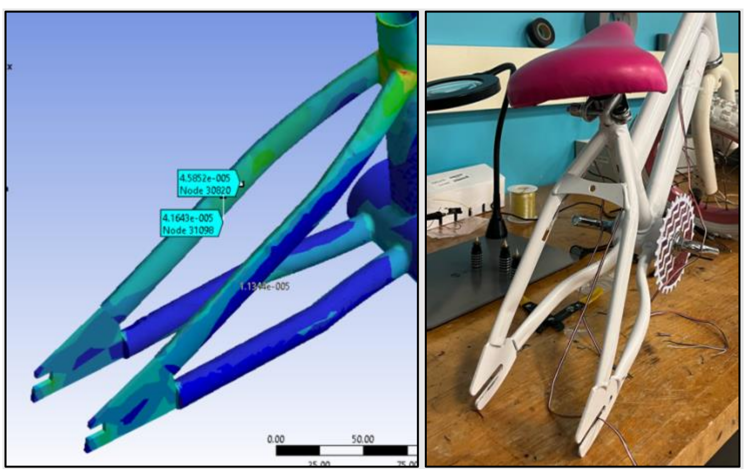


Figure 41. Strain gauge location 1 (with top bar).

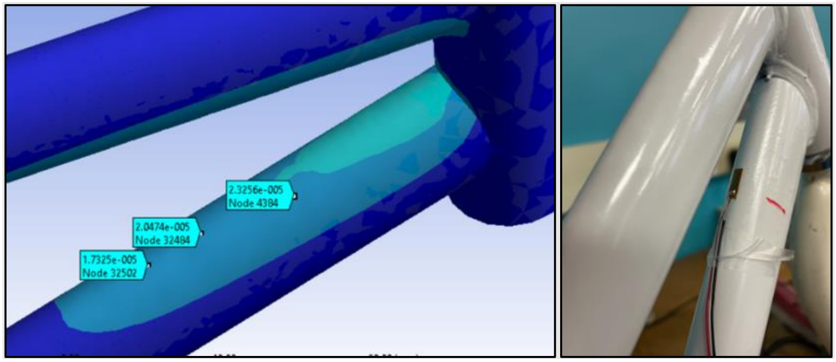


Figure 42. Strain gauge location 2 (with top bar).

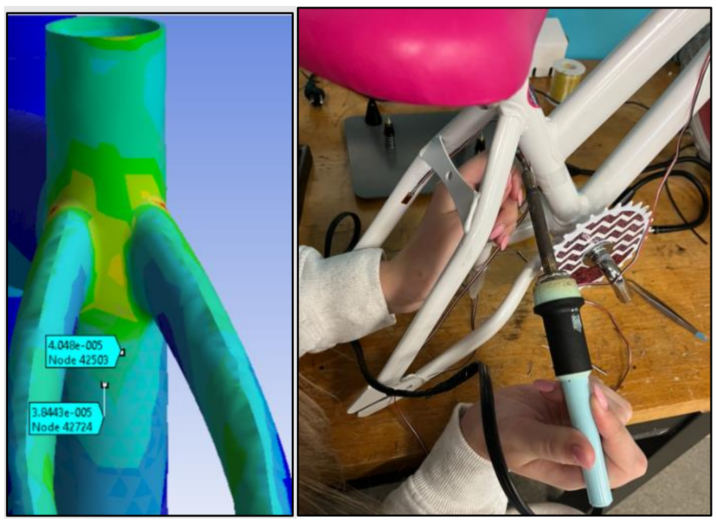


Figure 43. Strain gauge location 3 (with top bar).

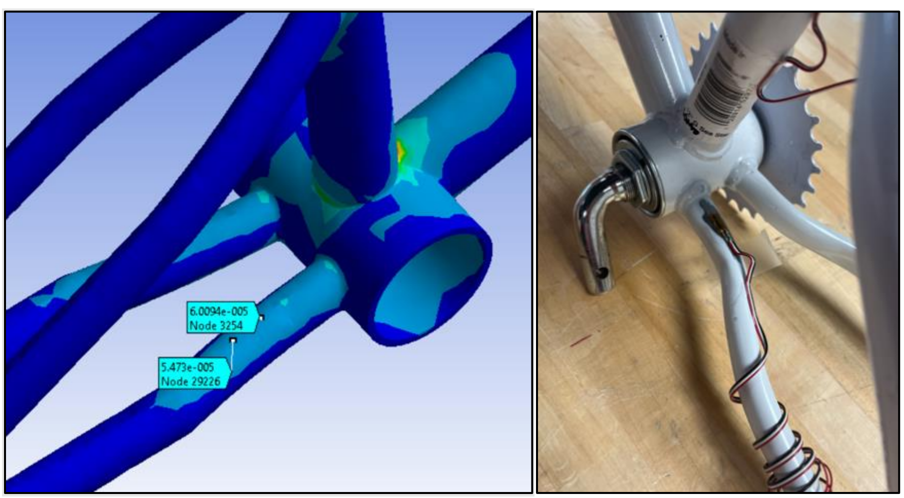


Figure 44. Strain gauge location 3 (without top bar).

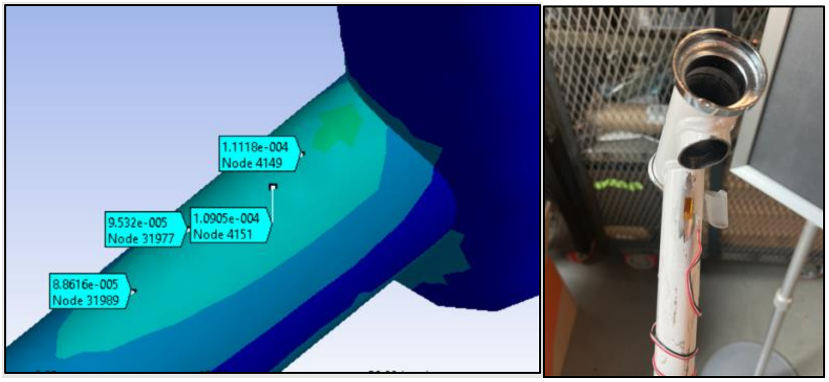


Figure 45. Strain gauge location 5 (without top bar).

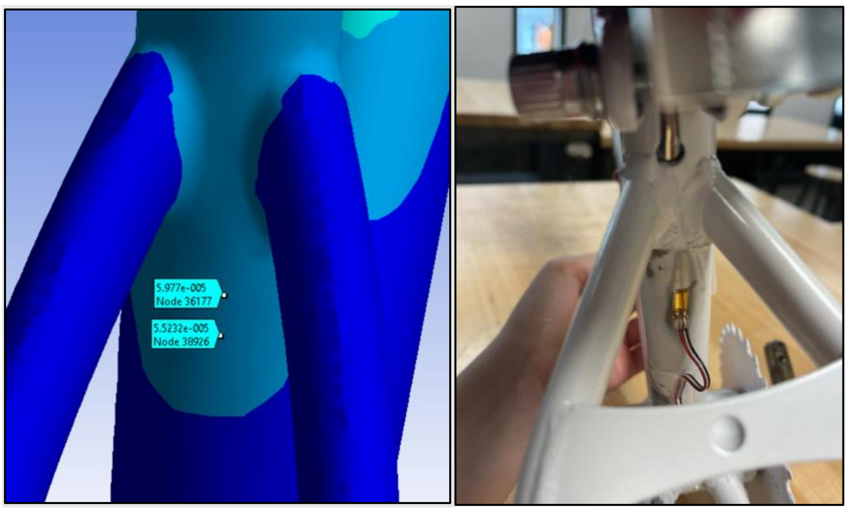


Figure 46. Strain gauge location 6 (without top bar).

To verify that the strain gauges and Arduino being used could read a strain as small as the Ansys simulation was measuring, equations 1-3 were used to calculate the minimum strain they could measure.

(1) $\Delta V\ (mV) = V_F - V_i$

(2) $\frac{E_0}{E_i} = \frac{\Delta V}{Source}$

(3) $\in = \frac{4\frac{E_0}{E_i}}{GF(1-2\frac{E_0}{E_i})}$

The calculations shown below resulted in a minimum possible strain measurement of **2.9762*10^-6**.

$$\in = \frac{4 * \frac{7.8125\ mV}{5000000\ \mu V}}{2.1 * \left(1 - 2\left(\frac{7.8125\ mV}{5000000\ \mu V}\right)\right)} = 2.9762 * 10^{-6}$$

Next, an electrical circuit consisting of an Arduino Uno, Wheatstone bridge, and DAQ unit for the experimental setup. Figure 48 shows the Wheatstone bridge connection diagram that was referenced.

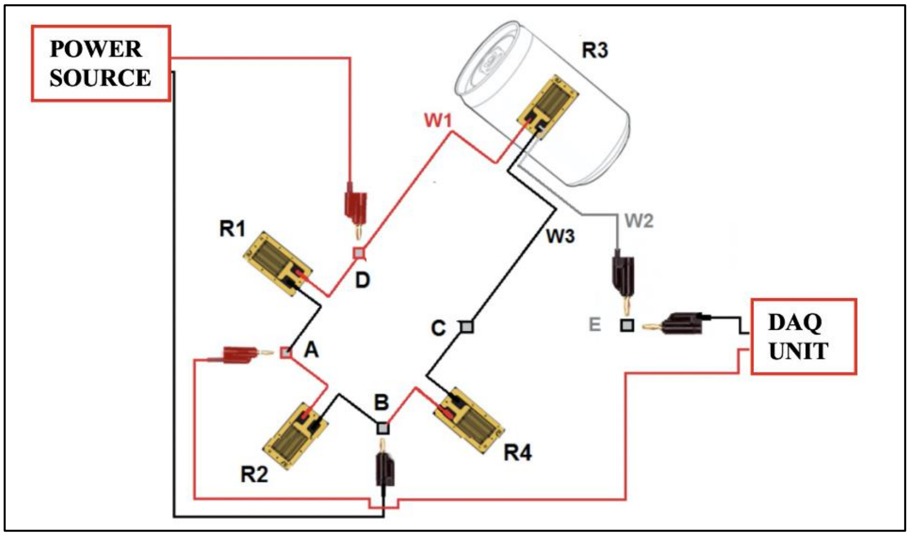


Figure 47. Wheatstone bridge connection reference diagram. [51]

The code created to record data from Arduino IDE, along with more information about the procedure, is shown in Appendix B: Mechanical Testing Procedure. The Arduino code measured voltage differences between the loaded and unloaded states. These measurements were then used to calculate strain using equation (3). Finally, these values were compared to simulation values with equivalent loading conditions. It is important to note that before running the tests, the strain gauge setup was calibrated.

The testing setup was calibrated by attaching the setup to a strain gauge fixed to an aluminum cantilevered beam. The Wheatstone bridge was adjusted so the initial output voltage measured was close to zero. Two 100-gram masses were then placed on the end of the cantilevered beam. The Arduino code recorded the measured voltages, and those measurements were used to calculate the measured strain using equation (3). This value was compared with the theoretical strain in a cantilevered beam which was calculated using equation 4 [52]. The theoretical value was calculated to be about 46.2 micro-strain and the measured value was calculated to be about 57.4 micro-strain. This means there was about a 20% difference between the theoretical and measured value.

$$(4)\ \epsilon = \frac{6WL}{Ebh^2}$$

Table 9 shows the simulation values versus the mechanical testing values. Since the strain gauges can only measure strain in one direction, the strain along the direction of the members where the strain gauges were placed was found in the model and used for comparison. The first attempt at testing the bicycle with the top bar yielded suspiciously large results in locations 1 and 2, likely a result in a problem with the set up. Location 3 did not yield any useable data. Because of this, the experiment was repeated on a different day, however, the gauge for location 2 got disconnected from the wires in storage. The strain measured at location 1 was lower than the first test, but still much larger than the value the model predicted. Due to limited time, it was determined that the best course of action would be to move on to the bicycle without the top bar as validating the finite element analysis results for that modification was more important than continuing to troubleshoot the setup for the unmodified bicycle.

Table 9. Results from mechanical testing.

Location	Delta V Measured (mV)	Strain from Simulation	Experimental Strain	Percent Error
1	244.202	0.000012	0.000093	675.321
2	228.299	0.000026	0.0000869	234.531
3	N/A	0.000043	N/A	N/A
4	275.589	0.000065	0.000104	59.581
5	110.516	0.000111	0.0000421	-62.129
6	115.676	0.000057	0.0000440	-23.355

Based on malfunctioning strain gauges in an initial trial of the bicycle without the top bar, it was likely that the strain gauges were attached incorrectly. To minimize this source of error, new strain gauges were attached to the bicycle after removing the paint in the attachment locations. Extra care was taken to attach and wire the new strain gauges correctly. New testing yielded results much closer to the strain given in the model. Location 4 had an experimental value of about 104 micro strain and a theoretical value of about 66 micro strain, this represents a percent error of about 60%. Location 5 had an experimental value of about 42 micro strain and a theoretical value of 111 micro strain, which is a percent error of about -62%. However, the data for this gauge was noisy to the point that this number was almost meaningless. Location 6 had an experimental value of 44 micro strain and a theoretical value of 57.5 micro strain, which represents a percent error of about -23%. While this value on its own could validate the Ansys model based on the calibration experiment, when paired with the results from the other two strain gauges, the result is conflicting data which cannot be relied upon.

Because of the inconsistent data and lack of additional time to troubleshoot, the strain gauge testing was unable to validate the results from the Ansys model. However, the mechanical testing still confirmed that the bicycle without the top bar would be safe for the client. The bicycle was loaded with a total of 140 pounds repeatedly over the course of several days, a weight well over the 49lb weight limit set by the manufacturer [24]. Throughout this testing there was no visible damage or deformation caused by the loading. This demonstrates that the bicycle will support the weight of the client without failing. Additionally, multiple team members rode the bicycle with no adverse effects.

5.2 Pedal Verification

Another major modification made to the bicycle was the addition of two holes in each of the pedal cranks, allowing the client to either shorten or lengthen the pedal cranks depending on what fits them best. This design allows the pedals to be adjustable to accommodate the client's growth overtime. To ensure that the incorporation of extra holes did not threaten the structural integrity of the bicycle pedals, finite element analysis (FEA) was performed on a computer aided design of the pedals. The FEA simulation was used to model the theoretical change in stress and strain.

5.2.1 Finite Element Analysis of Pedal Crank

To perform the FEA, the bicycle pedal was modeled through CAD using SolidWorks. Using a tape measure and a caliper, the dimensions of the pedals on the 12" Huffy bicycle were recorded. Using these dimensions, a SolidWorks model was created of the original pedal (Figure 49).

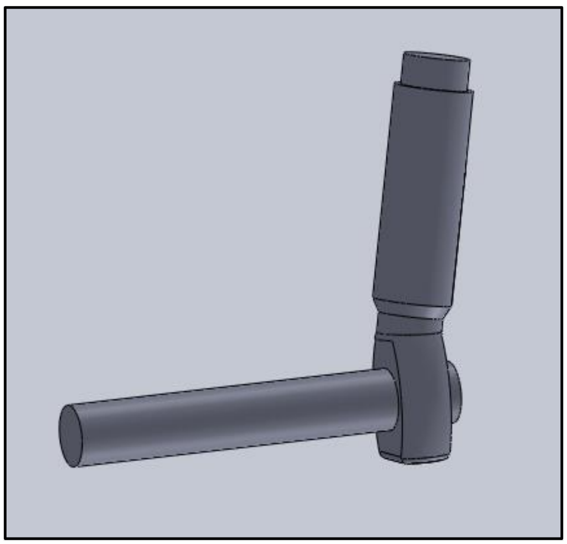


Figure 48. CAD model of the regular bicycle pedal.

A second CAD model was created that included the planned modifications: two 0.2-inch diameter holes on the pedal crank that would allow the pedal crank length to be adjusted. In addition to the holes, a pin was added to the bottom hole to mimic the screw that would be holding the pedal crank to the bottom of the bicycle frame. A third model was created that switched the pin to the top hole. It was important to model the pin in both holes to ensure that either of the length options could be used on the modified pedal. The modified pedal model is shown in Figure 50.

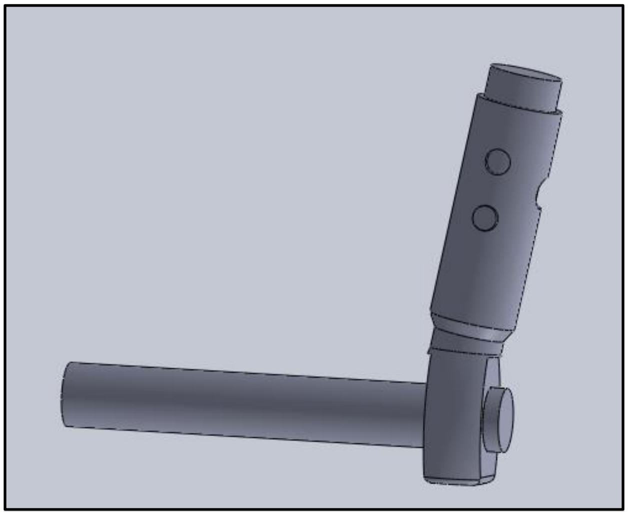


Figure 49. CAD model of the bicycle pedal with holes.

The material specified for the bicycle pedals was the same material used for the bicycle frame modeling, steel AISI 4130. The pedal models were then imported into Ansys Workbench 2023 as Static Structural simulations for finite element analysis. To ensure that the mesh element sizes used for FEA simulation were calculating both accurate and consistent results, mesh convergence was run on each of the models. The results of the mesh convergence are shown in the graphs below (Figure 51 and Figure 52).

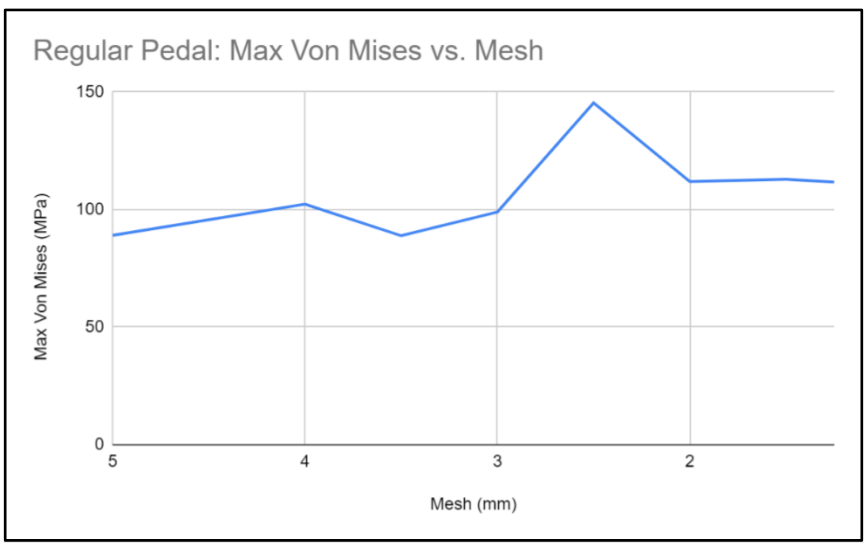


Figure 50. Mesh convergence of the regular pedal Ansys.

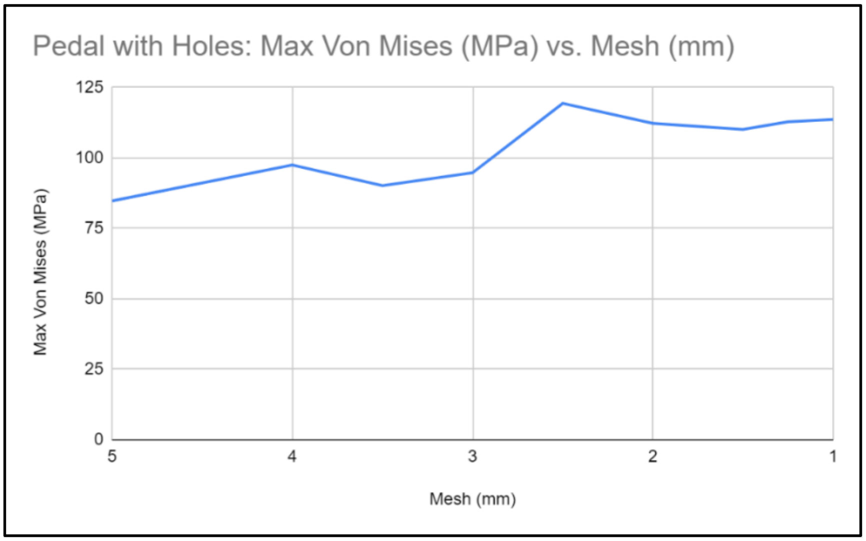


Figure 51. Mesh convergence of the pedal with holes Ansys.

As seen on the graphs, the models converged at a mesh element size of 2.0 mm. Therefore, the models were meshed using an element size of 2.0 mm before moving forward with the simulations.

Boundary conditions and loads were applied to all models. The top face of the rod inside the pedal crank was fixed in Ansys, which is seen in purple in Figure 53. This face was fixed because it was the part of the pedal assembly that was attached to the bicycle frame. Like the bicycle frame FEA loads, the load applied to the pedals was calculated based on research found in [49]. However, the pedal FEA was modeled using only one of the conditions mentioned in the article, which was starting bicycle riding while standing up. When standing up on a bicycle, most of the rider's force is exerted on the pedals. Therefore, only this condition was modeled as it represented the greatest magnitude of force that the pedals will likely experience during riding. If the pedals can withstand the force of the rider standing, they will be able to withstand the force of the rider during normal riding conditions.

The body weight chosen for pedal analysis was 49 pounds. This weight was chosen as the maximum allowable weight on the bicycle is 49 pounds according to the manufacturer [24]. In the starting bicycle riding while standing up condition, the pedals experience a vertical push of 2.19 times the body weight. The calculation for this force is shown below.

$$Vertical\ push = 2.19\ X\ Body\ Weight = 477.34\ N$$

Therefore, a downward force of 477 Newtons was applied to the pedal axle in each model. The application of this force is shown highlighted in red in Figure 53.

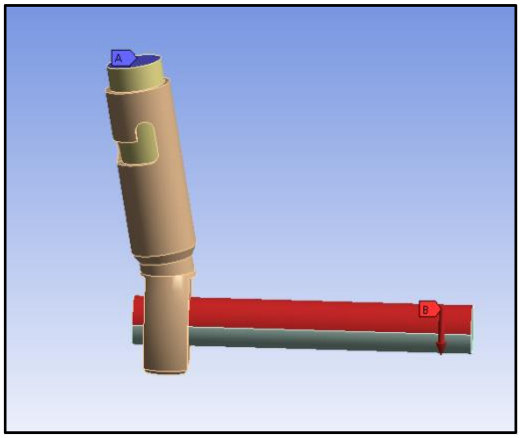


Figure 52. Loads and boundary conditions applied to Ansys model.

Once all loads and boundary conditions were applied, the simulations were run and data was collected on the maximum von-Mises stress in each of the models. In all models, the location of maximum stress was found to be on the inside of the pedal. This location is shown in Figure 54 and Figure 55 below, with the specific area of maximum stress colored in red.

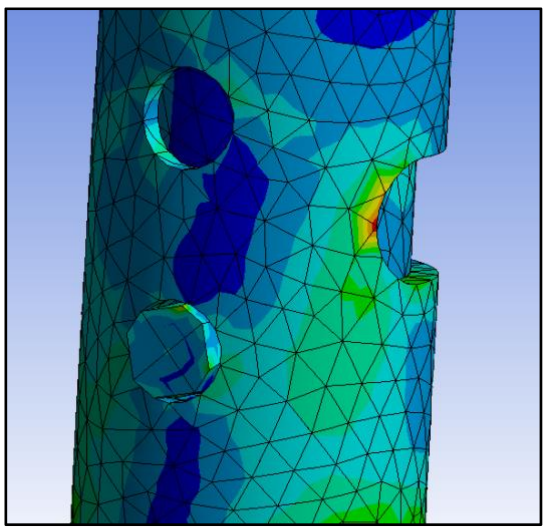


Figure 53. Area of maximum stress on the pedal with holes Ansys simulation.

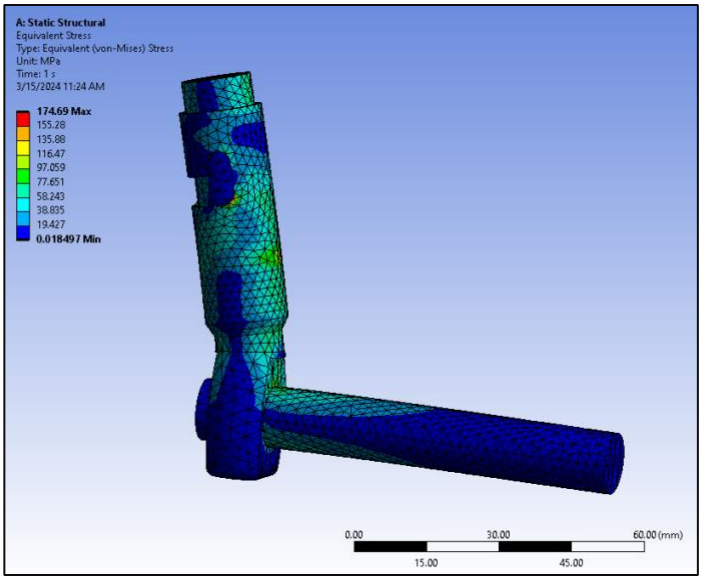


Figure 54. Von-Mises stress results for the pedal with holes.

From the boundary condition of the pedal axle (horizontal rod in Figure 53) attaching to the pedal crank, the downward force on the axle induces a great amount of stress on the crank. The downward force acts as a pulling motion on the axle. Since the axle runs through the pedal crank, the downward force also pulls down on the lower part of the crank. As the axle is pulled down from the pedal crank, there is some bending behavior just above the connection between the two components. The bending behavior causes the left side of the pedal crank to be in compression, and the right side to be in tension. Therefore, the slot on the tension side experiences the most stress because it undergoes deformation due to tension forces, causing the area to have higher stress concentrations. By dividing the material's yield strength (460 MPa) by the maximum von-Mises stress value for each of the models, the factors of safety were calculated. These values are shown in Table 10 below:

Table 10. Factor of safety calculations for the pedal crank.

Model	**Maximum von-Mises (MPa)**	**Factor of Safety**
Regular Pedal	111.19	4.14
Pedal with Holes (Pin in Bottom Hole)	174.69	2.63
Pedal with Holes (Pin in Top Hole)	141.33	3.25

As shown in the table above, the factor of safety of the modified pedal models did not decrease drastically in comparison to the factor of safety of the regular pedal model. Additionally, the factor of safety of the modified pedal models remained above 2.63. Based on prior research articles, a safety factor of above 1.67 for a bicycle is deemed safe to use [49]. Therefore, adding the two additional holes to the bicycle pedal cranks does not threaten the structural integrity of the bicycle pedals and is a safe modification to make.

5.2.2 Verification of Pedal Structure

To ensure the pedals' structural integrity was not compromised by adding two new holes to the pedal crank, additional physical testing was conducted. To do this, two holes were drilled into a set of pedal cranks purchased for testing purposes. Once the holes were added, the pedal cranks were secured to the bicycle frame using a set of screws. The pedals were rotated over 100 revolutions by hand to ensure that the screws properly anchored the pedal crank to the rest of the pedal. After it was confirmed that they were properly secured, a young adult rode the test bicycle. The pedals were observed both before and after riding, ensuring no physical changes to the pedals occurred during riding. After seeing that the pedals with holes could withstand the force of a 120-pound adult, the change to the pedal structure could be physically verified.

Chapter 6: Final Design and Validation

Once it was ensured that all the desired modifications were safe, the final prototype could be created. This involved making changes to the frame, pedals, handlebars, and seat plus some cosmetic changes to make the bicycle more appealing to a 6-year-old child. These modifications were made to a 12-inch Huffy children's bicycle. Specific procedures were taken to make each of these changes, as discussed below.

6.1 Frame

After performing the finite element analysis and mechanical testing from Chapter 5, the top bar was removed. This procedure was performed in the manufacturing lab using a vice to hold the frame in place and a standard handheld hack saw. All other elements of the bicycle were detached prior to removing the top bar to prevent any damage to the components. The original frame is shown in Figure 56 and the frame after the top bar was detached is shown in Figure 57.

Figure 55. Commercial bicycle frame with the top bar.

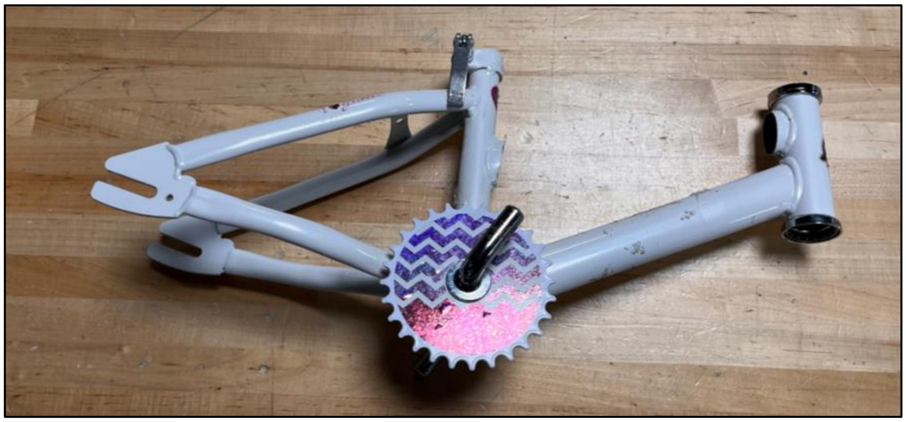


Figure 56. Bicycle frame after the top bar was removed.

The first removal of the top bar using the hand saw resulted in a few sharp edges at either end of the cut. To create a smooth surface free of sharps and protrusions, an angle grinder was used to flatten these edges down. Once the surface was even, a file was used for further precision in making the surface smooth. These surfaces were tested for sharp projectiles by running a finger around the edge and using a sweatshirt string to determine if anything could get caught. Grinding and polishing continued until the surface became completely free of protrusions and jagged edges.

6.2 Pedals

To create the adjustable pedals, there were two new holes drilled into the pedal attachment of the 12-inch Huffy bicycle. The two new adjustable crank lengths were 2.24 inches and 2.75 inches. The shorter length allowed the crank to be 0.51 inches less than the original crank length. The safety for this procedure was proved through the extensive finite element analysis shown earlier.

The pedal holes were drilled through a simple machining process using an automatic floor drill press, as shown in Figure 58. There were three different drill bits used to ensure a more consistent result. The drill bits used were a TSS spot drill bit, a size 33 drill bit, and finally a size 5 drill bit. The size for the final drill bit was chosen because it was the closest to the size of the threaded hole already on the pedal crank. After the pedal was set up to be drilled, the spot drill bit was used to mark the pedal and ensure it was in the correct spot. Second, the size 33 drill bit was used to drill a small hole on the spot marked previously. The smaller hole helped maintain the cut's precision and reduce friction and heat. Finally, the size 5 drill bit was used to drill the final hole. This process was then repeated for the second hole on each pedal.

Figure 57. Setup for drilling pedal crank holes.

After the holes were completed, a screw and 5-millimeter washer were used to secure the pedals in place. To change settings and make the pedals longer again, a screwdriver is required to unscrew and shift the pedal forwards.

6.3 Handlebars

The bicycle handlebars were replaced with those of a different commercial children's bicycle. To locate ones that would fit and interact correctly with the new bicycle, different bicycle handlebars were observed and tested. The final handlebars were shorter than the original ones by two inches. To cosmetically fix the old handlebars up, new handlebar grips were ordered, along with the entire mechanism being deep cleaned with soap and rust remover. A picture of the handlebars before cosmetic changes is shown below in Figure 59.

Figure 58. Final handlebars.

The new handlebars interfaced with the bicycle frame through a new fork, handlebars, fastener, a screw and a clamp. The first step to attach the new handlebars was to insert the bicycle fork into the front of the frame. The fork was attached to the frame by screwing in the fastener on the top of the bicycle frame.

After the fork was secure, the handlebars were inserted inside of the fork. The mechanism that secured the two together was a screw and clamp combination. A clamp was inserted inside of the fork and handlebars through the bottom, and the screw was inserted into the top. As the screw was tightened the clamp moved further up the inside of the handlebar shaft. The tension that was created kept the handlebars in place.

6.4 Seat

The bicycle seat was lowered to let the user easily reach the pedals while sitting. To accomplish this task, the reflector located beneath the seat was detached by utilizing a screwdriver to remove the screw fastening the reflector to the seat stem. This was done because the reflector was prohibiting the seat from being lowered completely. The reflector that was removed is shown in Figure 60. This reflector was moved to below the seat clamp.

Figure 59. Original seat height with the reflector attached.

Once removed, the seat could be pushed down all the way to its lowest point. As a result, the seat was effectively decreased in height by 0.5 inches. This new seat height better accommodated the client's shorter inseam. The final seat height is shown in Figure 61, which is currently 17.5 inches from the ground.

Figure 60. Final seat height after reflector was moved.

6.5 Cosmetic Changes

The manufacturing process caused the bicycle to have chipped paint and exposed metal. To remedy this, as well as make the bicycle more appealing to the client, the bicycle was sanded down in some areas and repainted different colors per the client's request. Additionally, brand new handlebar grips were purchased to replace the old and dirty ones. These modifications resulted in a more attractive and cleaner-looking bicycle to present to the client. The final bicycle with all modifications made is shown in Figure 62.

Figure 61. Final bicycle design after cosmetic changes.

6.6 Economics

The results of this project would mainly help the economic situation of families of young children with achondroplasia. The methods of this project could be used to create multiple inexpensive achondroplasia-friendly bicycles. This could be in the form of the families modifying a bicycle themselves, or a company recreating these methods. Either way, it would provide a much cheaper option for families to obtain a bicycle like this rather than paying for a completely custom one. If large companies were to create these bicycles, it could lead to the creation of other inclusive bicycle models, opening the bicycle market to a whole new demographic.

6.7 Environmental Impact

By using a bicycle, less carbon intensive modes of transportation need to be used. Bicycles do not have a carbon footprint like cars do, so the creation of this bicycle may have a positive impact on the environment if it can be used as an alternative mode of transportation. Realistically, the client will not be using this bicycle as a substitute for transportation, but rather as a tool for recreation. However, if this sort of project was done for adults with achondroplasia or other forms of dwarfism, transportation would be a real environmental benefit. On the other hand, this project resulted in a waste of material. Multiple bicycles were purchased for manufacturing and testing purposes, resulting in unused leftover material. If this material is not recycled, it may have a negative impact on the environment. However, spare parts that are still intact can be donated to local bicycle shops to prevent harm to the environment. If this bicycle were to be replicated in the future, measures should be taken to limit the amount of waste produced during the manufacturing process.

6.8 Societal Influence

While this project's product will mainly help families of children with achondroplasia, its underlying principles could greatly impact society. Intentionally creating products with adjustability built in allows a wider range of people to use any given product. Additionally, intentional design helps further the normalization and acceptance of disability and of people with Achondroplasia and other forms of dwarfism.

6.9 Political Ramifications

There are no foreseen political ramifications from the procedures and results of this project.

6.10 Social Ethics

This project promotes a good and satisfying life by allowing children with achondroplasia to ride a bicycle without feeling different. Feeling included is an important part of being human and for people with disabilities it is so easy to feel like the odd one out. Having a bicycle that works with their body that looks visually similar to commercial options is an important tool for facilitating inclusion. The result of this project will allow the client to ride a bicycle with her family and friends.

6.11 Health and Safety Issues

The adaptive bicycle produced for this project promotes both physical and mental health. First, the bicycle can be used as a form of exercise in a fun and leisurely way. Cycling helps to improve things like balance, coordination, and strength all while having fun riding. As for mental health, the adaptive bicycle provides a feeling of inclusivity for the rider. Specifically, it allows children with achondroplasia to join their friends in cycling, granting opportunities previously unavailable.

Safety was prioritized at every stage of the bicycle's production. Mechanical testing and FEA were performed on some of the component modifications to ensure their safety. Additionally, the bicycle adjustments allowed the client to reach both the pedals and handlebars, making it safer for them to ride. Lastly, the removal of the top bar allowed the client to easily disembark from the bicycle if needed. All these things promote the personal safety of the rider.

6.12 Manufacturability

The manufacturing process undergone to create this bicycle can be reproduced with the correct tools. The top bar of the frame was removed using a simple handsaw and the remaining material was removed with an angle grinder. The grinding process could also be reproduced with a file and sometimes, meaning the barrier for entry on this modification is very low. The additional holes on the pedals were done using a drill press and are once again easily reproduced for an experienced user. On a larger manufacturing scale this bicycle would cost either the same or even less to manufacture than a standard children's bicycle. The frame uses less material, the handlebars are less complicated, and the pedal cranks have the same amount of machining steps.

6.13 Sustainability

This project supports UN Sustainable Development Goals 3, 10, and 12 (Figure 63), which are good health and well-being, reduced inequalities, and responsible consumption and production, respectively [53]. The design and creation of a bicycle for children with physical disabilities such as achondroplasia ties into the good health and well-being and reduced inequalities goal. With the final prototype of the project, the client, a child with dwarfism, can ride a bicycle comfortably, which is something that they were not able to do before due to the lack of accessible devices. Bicycle riding and exercise in general has proven to have many mental health benefits, both socially and physically. Additionally, by producing a bicycle that can grow with the child for an estimation of at least six more years, she will not have to purchase a new bicycle until many years down the line. This contributes to the responsible consumption and production goal, as the materials and methods used in creating this bicycle will likely be durable and of use for years to come.

Figure 62. Goals 3, 10, and 12 of the UN Sustainable Development Goals. [53]

Chapter 7: Discussion

The overall objective of this project was to design, test, and deliver a custom bicycle to the client. Understanding the physical and social needs of the client throughout the design process was of the utmost importance. This involved working with the client and her family to narrow in on the different design requirements that would fulfill the client's needs. Through conversations with the client's family and research on achondroplasia and the current bicycle market, a list of design requirements could be established and utilized to guide the design process. These requirements formed the basis of the final bicycle design.

Design improvements that could be made to the current children's bicycle were established. By making modifications to a current children's bicycle, the final product visually resembles a standard two-wheel bicycle to allow the client to feel as socially comfortable as possible when riding. Resembling a standard bicycle was one of the most important requirements for the client and was achieved in the final design.

Once all modifications were determined for the bicycle, a final product was created that could be used for daily leisurely riding. Before these modifications were made, however, testing was conducted to ensure the safety of the bicycle design. All potential changes were verified before moving forward with them. Therefore, the design achieved safety standards set forth for commercial bicycles, something that was prioritized on the design requirements list.

The final design was presented to the client and their riding was observed. Originally when she tried the commercial children's bicycle, it didn't match her physique, making it difficult for her to reach the pedals and handlebars because of her short inseam and arms. When she rode the final bicycle design, she could comfortably reach the handlebars and pedals and successfully ride the bicycle with ease. The bicycle being physically comfortable for the client to ride was another design requirement that was achieved. Riding a standard two-wheel bicycle was something that the client did not have the opportunity to do before and now could easily do with this adaptive bicycle.

In the context of the current market, bicycles that cater to those with achondroplasia do exist, as discussed in section 2.4. However, these bicycles can cost up to $900. This is not feasible for most families as most children will eventually outgrow their bicycle as they grow during childhood. There are no bicycles on the current market for children with achondroplasia that are easily obtainable for the average family. The bicycle created for the client cost around $100 to make, which is much less than custom bicycles on the market currently cost. This proves that it is possible to have a custom bicycle that both fits the needs of a child with achondroplasia and is low cost.

The finished product has an adjustable seat, handlebars, and pedals. This allows the client to adjust the bicycle throughout her childhood so that it can cater to her proportions as she grows. This bicycle's adjustability was important as she could use it longer than a typical commercial bicycle. Allowing components to be changed to accommodate her growth patterns makes this custom bicycle more adaptable than the current custom bicycles on the market.

Throughout the design process, several assumptions were made. These assumptions consisted of the client's growth patterns following achondroplasia growth curves. The design of the adjustable components of the bicycle caters to the average height and weight of children with achondroplasia throughout their childhood. There is a chance the client will not follow the growth curve referenced and that the components may not all work throughout her entire childhood. Also, it was assumed that the client may use this bicycle until 12. Therefore, the components were designed in a way to accommodate the child's projected height and weight at 12 years old. Lastly, it was assumed that the child would be able to ride this bicycle for 6 years. However, there is a chance that the client will outgrow the style of the bicycle before then.

Chapter 8: Conclusions and Recommendations

The client was delivered a bicycle that successfully fit her physical and societal needs. She can properly reach all components of the bicycle, as well as get on and off safely. Based on achondroplasia growth curves and the bicycle's adjustability, this bicycle is projected to fit her needs until at least age 12. The style and colors of the bicycle may even be outgrown before the actual measurements are. When the bicycle was originally tested, the client was overjoyed to finally be able to ride a standard bicycle. She had only ever been able to ride tricycles and scooters until the day where she received a bicycle of her own.

There are three adjustable components of the final bicycle: the pedal crank lengths, the handlebar height, and the seat height. By altering these components on a standard 12-inch children's bicycle sold at Walmart, a more accessible bicycle was created, but it is one that can be reverted to its original proportions. This proves that all bicycles can be made more accessible for children with disabilities such as achondroplasia. By making all children's bicycles adjustable by component, companies can sell bicycles to the average child, while still designing them to fit the physical needs of children with disabilities. By designing bicycles with this need in mind, all children will be able to participate in bicycle riding, which will lead to psychological and physical benefits.

Due to lack of time, a way to embark onto the bicycle without the training wheels on was not addressed. The client can only barely reach the ground while on the bicycle. For an easier embarkation, she steps on the pedals to mount the seat. In the future, our client will most likely learn to ride the bicycle without the training wheels on. Without the training wheels on, there will be no way for the bicycle to balance while she gets on. To fix this incoming issue, we recommend the development of a kickstand which is robust enough to support the client's weight and stows back into position as she starts pedaling.

Along with this, there was not enough time to research possible manufacturing avenues to potentially streamline the product and its mission in the future. If this bicycle were to be manufactured, full bicycles could be made and sold, but it could also be sold as a kit of components. For example, a kit with the adjustable handlebars and pedal cranks could be manufactured and sold with instructions on how to attach them to a commercial children's bicycle to make it more adjustable for children with physical disabilities. No cost analyses have currently been performed, but it is assumed that since no new pieces were added to the bicycle and one of the bars were removed, it would be even cheaper to manufacture than the original bicycle, which was sold for around $60 at Walmart. It is important to compare this price to the custom bicycles that were previously researched that could cost up to $900.

Overall, it was extremely rewarding and exciting to deliver the client a working bicycle that she feels comfortable riding. She will hopefully be able to utilize this bicycle throughout the entirety of her childhood growth. A quote from the client's father describes the success of this project, "[She] is beyond excited to ride the bike. She's been talking about it since Sunday and even wrote a bike centric journal entry at school."

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Appendices

Appendix A: IRB Consent and Approval Forms

Before meeting with the client, IRB consent forms were approved. Below are the consent and approval forms for each meeting we had with the client.

1. First Meeting with Client

Informed Consent Agreement for Participation in a Research Study
Investigators: Avinash Bissoondial, Eliza Dion, Kacie Miller, Kelsey Reno, Sequoia Truong
Contact Information: [redacted]
Title of Research Study: Bicycle for Child with Achondroplasia

Sponsor: Worcester Polytechnic Institute

Introduction: You are being asked to provide assent for your child to be part of a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about

Purpose of the study: Design, prototype, and test a custom bicycle that fits the physical and social needs of a child with achondroplasia. This bicycle will be comfortable and adjustable for the user to accommodate the child's growth.

Procedures to be followed: For the MINOR: We will ask you to bring your child to King's Kingdom Playground in Lunenburg, Massachusetts biweekly on Sundays from October 8th to April 21st for 1-2 hours. You as parents should be present with your child/minor at all times during the research study. Your child will be asked to ride bicycles for observation and test purposes. We will ask your child some questions during the study to address design concepts, comforts, aesthetics, biomechanics, and safety. We will record your child to understand the bike mechanics and how your child uses the bike.

For the Parents: We will ask you questions pertaining to your child/minor at each of the study visits. These questions will relate to activities they like and measurements of your child.

Risks to study participants: There may be safety concerns/hazards consistent with those of a standard bicycle throughout the course of the study. The area where testing takes place will be clear of obstacles and at least three researchers will be present to attend to the space. The child will be required to be wearing a helmet at all times. The bicycle will fulfill all safety requirements set in place by the United States Consumer Product Safety Commission.

Benefits to research participants and others: A possible benefit to the subject and others is the creation of a solution to the lack of working bicycles for children with

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Achondroplasia. The subject will receive a custom bicycle that is fit specifically for their needs. The child will keep this bike after the conclusion of the project.

Record keeping and confidentiality: Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or its designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you. The minor's name and identifying features will be kept confidential. Any pictures or videos of the minor will be edited so their face is blurred out and unidentifiable. These will be used to demonstrate biomechanics and design concept validation. The child's physical measurements will be used in our research to determine the proper design for the bicycle. These numbers will be included in our report. After the conclusion of our study, the original pictures and videos will be stored in our research team's private google drive folder.

Compensation or treatment in the event of injury: The bicycle provided will limit any potential safety concern/hazards as consistent with those of a standard bicycle. Thus, there will be no compensation in the event of injury. In the event of injury, medical treatment can be found at any urgent care, hospital, or primary care provider. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact:

Avinash Bissoondial, Tel. [redacted] Email: [redacted]

Eliza Dion, Tel. [redacted] Email: [redacted]

Kacie Miller, Tel. [redacted] Email: [redacted]

Kelsey Reno, Tel. [redacted] Email: [redacted]

Sequoia Truong, Tel. [redacted] Email: [redacted]

MQP Team Email: [redacted]

IRB Manager Ruth McKeogh, Tel. 508 831 6699, Email: irb@wpi.edu

Human Protection Administrator Gabriel Johnson, Tel. 508 831 4989, Email: gjohnson@wpi.edu

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Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

____
Parent of Minor's Name (Please print)

____
Parent of Minor Signature

Date: ____________________

____
Signatures of People who explained this study

Date: ____________________

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10/25/23 to 10/24/24

WORCESTER POLYTECHNIC INSTITUTE

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

Institutional Review Board

FWA #00030698 - HHS #00007374

Notification of IRB Approval

Date :	25-Oct-2023
PI:	Sarah Jane Wodin-Schwartz
Protocol Number:	IRB-24-0042
Protocol Title:	Bicycle for Child with Achondroplasia
Approved Study Personnel:	Reno, Kelsey P~Dion, Eliza B~Truong, Sequoia L~Bissoondial, Avinash S~Miller, Katharine C~Wodin-Schwartz, Sarah Jane~Reidinger, Amanda Z~
Start Date:	25-Oct-2023
Expiration Date:	24-Oct-2024
Review Type:	
Review Method:	Expedited Review
Risk Level:	Minimal Risk
Sponsor*:	

The WPI Institutional Review Board (IRB) approves the above-referenced research activity, having conducted a review according to the Code of Federal Regulations (45 CFR 46).

This approval is valid through 24-Oct-2024 unless terminated sooner (in writing) by yourself or the WPI IRB. Research activities involving human subjects may not continue past the expiration date listed above, unless you have applied for and received a renewal from this IRB.

We remind you to only use the stamped, approved consent form, and to give a copy of the signed consent form to each of your subjects. You are also required to store the signed consent forms in a secure location and retain them for a period of at least three years following the conclusion of your study. You are encouraged to use the InfoEd system for the storage of your consent forms.

Amendments or changes to the research must be submitted to the WPI IRB for review and approval before such changes are put into practice.

Investigators must immediately report to the IRB any adverse events or unanticipated problems involving risk to human participants.

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

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

2. Second Meeting with Client

Informed Consent Agreement for Participation in a Research Study

Investigators: Avinash Bissoondial, Eliza Dion, Kacie Miller, Kelsey Reno, Sequoia Truong

Contact Information: [redacted]

Title of Research Study: Bicycle for Child with Achondroplasia

Sponsor: Worcester Polytechnic Institute

Introduction: You are being asked to provide assent for your child to be part of a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about

Purpose of the study: Design, prototype, and test a custom bicycle that fits the physical and social needs of a child with achondroplasia. This bicycle will be comfortable and adjustable for the user to accommodate the child's growth.

Procedures to be followed: For the MINOR: We will ask you to bring your child to Worcester Polytechnic Institute on Wednesday November 22nd for an hour. You as parents should be present with your child/minor at all times during the research study. Your child will be asked to ride a bicycle we purchased from Walmart for observation and test purposes. The bicycle is an average 12 inch wheel children's bicycle. We made one modification to the bicycle – we removed a reflective piece located under the seat in order to bring the seat to its lowest position. Besides that, the bicycle has not been modified at this time. We will ask your child some questions during the study to address design concepts, comforts, aesthetics, biomechanics, and safety. We will video record your child on the bicycle to also understand the bike mechanics and how your child uses the bike so that the necessary modifications can be made to the bicycle in the future. For instance, we will record how the handlebars fit your child, and measure what distance and orientation they need to be. We will also analyze if your child is able to reach the pedals, and if not, we plan to measure the distance between her foot and the pedal height in order to identify what modifications need to be made.

We also will ask your child to lay down on a plank of wood in one of our Biomedical Engineering Labs (Goddard Hall 207) in order to find her center of mass. This value is important to our bicycle design. We will also ask you to trace your child's outline onto a large piece of cardboard, which will allow our team to get an idea of your child's dimensions when we are designing the bicycle. We intend to do this so that when we do have working prototypes for your child to test out, we have already made sure they will likely fit your child and be comfortable for her.

For the Parents: We will ask you to remain in the area throughout the visit and observe your child to ensure they are completely comfortable throughout the testing process. If your child is not comfortable at any moment, we will stop the testing.

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Risks to study participants: There may be safety concerns/hazards consistent with those of a standard bicycle throughout the course of the study. The area where testing takes place will be a paved surface and clear of obstacles. At least three researchers will be present to attend to the space. The child will be required to be wearing a helmet at all times. The bicycle will fulfill all safety requirements set in place by the United States Consumer Product Safety Commission. If modifications are made to a bicycle component, it will need to pass the tests listed in the ASTM testing procedures for different bicycle components prior to the child using the bicycle.

Additionally, there are safety concerns/hazards in the Biomedical Engineering Laboratory area. All laboratory rules will be followed when in the laboratory space. If necessary, personal protective equipment will be provided and worn. At least three researchers will be present to monitor the space and child.

Benefits to research participants and others: A possible benefit to the subject and others is the identification of bicycle components that do not work properly for the child. This will help to make the necessary modifications that are needed to create a bicycle that is a solution to the lack of working bicycles for children with Achondroplasia. The subject will receive a custom bicycle that is fit specifically for their needs. The child will keep this bike after the conclusion of the project.

Record keeping and confidentiality: Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or its designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you. The minor's name and identifying features will be kept confidential. Any pictures or videos of the minor will be edited so their face is blurred out and unidentifiable. These will be used to demonstrate biomechanics and design concept validation. The child's physical measurements will be used in our research to determine the proper design for the bicycle. These numbers will be included in our report. After the conclusion of our study, the original pictures and videos will be stored in our research team's private google drive folder.

Compensation or treatment in the event of injury: The bicycle provided will limit any potential safety concern/hazards as consistent with those of a standard bicycle. Thus, there will be no compensation in the event of injury. In the event of injury, medical treatment can be found at any urgent care, hospital, or primary care provider. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact:

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11/21/23 to 11/20/24

Avinash Bissoondial, Tel. [redacted] Email: [redacted]

Eliza Dion, Tel. [redacted] Email: [redacted]

Kacie Miller, Tel. [redacted] Email: [redacted]

Kelsey Reno, Tel. [redacted] Email: [redacted]

Sequoia Truong, Tel. [redacted] Email: [redacted]

MQP Team Email: [redacted]

IRB Manager Ruth McKeogh, Tel. 508 831 6699, Email: irb@wpi.edu

Human Protection Administrator Gabriel Johnson, Tel. 508 831 4989, Email: gjohnson@wpi.edu

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

____

Parent of Minor's Name (Please print)

____

Parent of Minor Signature

Date: ___________________

____

Signatures of People who explained this study

APPROVED BY
WPI IRB-1
11/21/23 to 11/20/24

WORCESTER POLYTECHNIC INSTITUTE

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

Institutional Review Board

FWA #00030698 - HHS #00007374

Notification of IRB Approval

Date: 21-Nov-2023

PI: Sarah Jane Wodin-Schwartz
Protocol Number: IRB-24-0042
Protocol Title: Bicycle for Child with Achondroplasia

Sponsor*:

The WPI Institutional Review Board (IRB) approves the modification submitted on to the above-referenced protocol.

This modification does not extend the expiration date of your approval. The previous approval remains in effect from 21-Nov-2023 until 20-Nov-2024 unless terminated sooner (in writing) by yourself or the WPI IRB. If the research is to continue past 20-Nov-2024, you must submit a Study Renewal form to the IRB via InfoEd, at least 30 days prior to expiration.

Modification-Participant testing on bike

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

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

3. Third Meeting with Client

Informed Consent Agreement for Participation in a Research Study

Investigators: Avinash Bissoondial, Eliza Dion, Kacie Miller, Kelsey Reno, Sequoia Truong

Contact Information: [redacted]

Title of Research Study: Bicycle for Child with Achondroplasia

Sponsor: Worcester Polytechnic Institute

Introduction: You are being asked to provide assent for your child to be part of a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about

Purpose of the study: Design, prototype, and test a custom bicycle that fits the physical and social needs of a child with achondroplasia. This bicycle will be comfortable and adjustable for the user to accommodate the child's growth.

Procedures to be followed: For the MINOR: We will ask you to bring your child to Worcester Polytechnic Institute on Wednesday April 3rd for an hour. You as parents should be present with your child/minor at all times during the research study. Your child will be asked to ride the bicycle prototype for observation and test purposes. The bicycle is an average 12 inch wheel children's bicycle from Walmart with some modifications made. We made four modifications to the bicycle. For the seat height, we removed a reflective piece located under the seat in order to bring the seat to its lowest position. To make the handlebar height shorter, we replaced the handlebars with a set of handlebars from a different bicycle. To make the pedals adjustable, we added holes to the pedal crank to allow the crank length to be changed. This change was verified through finite element analysis to ensure that the additional holes would not threaten the structural integrity of the pedals. Lastly, the top bar of the bicycle was removed to make it easier for your child to get on and off the bicycle. This change was verified through finite element analysis to ensure that the removal of the top bar would not threaten the structural integrity of the frame. Additional mechanical testing was run on the frame using strain gauges to verify the results of our finite element analysis. We will ask your child some questions during the study to address comfort and safety. We will video record your child on the bicycle to also understand how the child rides the modified bicycle. For instance, we will record how the handlebars fit your child, if your child is able to comfortably get on and off the bicycle, and analyze if your child is able to reach the pedals.

For the Parents: We will ask you to remain in the area throughout the visit and observe your child to ensure they are completely comfortable throughout the testing process. If your child is not comfortable at any moment, we will stop the testing.

Risks to study participants: There may be safety concerns/hazards consistent with those of a standard bicycle throughout the course of the study. The area where testing takes place will be a

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paved surface and clear of obstacles. At least three researchers will be present to attend to the space. The child will be required to be wearing a helmet at all times. The bicycle will fulfill all safety requirements set in place by the United States Consumer Product Safety Commission. All modifications made to the bicycle components passed simulation and/or experimental tests. These included running simulations in a finite element software and performing mechanical testing on the different components.

Benefits to research participants and others: A possible benefit to the subject and others is the creation of an adaptable bicycle that fits specifically to the child's needs. The necessary modifications were made to create a bicycle that is a solution to the lack of working bicycles for children with Achondroplasia. The subject will receive a custom bicycle and will keep this bike after the conclusion of the project.

Record keeping and confidentiality: Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or its designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you. The minor's name and identifying features will be kept confidential. Any pictures or videos of the minor will be edited so their face is blurred out and unidentifiable. These will be used to demonstrate biomechanics and design concept validation. The child's physical measurements will be used in our research to determine the proper design for the bicycle. These numbers will be included in our report. After the conclusion of our study, the original pictures and videos will be stored in our research team's private google drive folder.

Compensation or treatment in the event of injury: The bicycle provided will limit any potential safety concern/hazards as consistent with those of a standard bicycle. Thus, there will be no compensation in the event of injury. In the event of injury, medical treatment can be found at any urgent care, hospital, or primary care provider. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact:

Avinash Bissoondial, Tel. [redacted], Email: [redacted]

Eliza Dion, Tel. [redacted], Email: [redacted]

Kacie Miller, Tel. [redacted], Email: [redacted]

Kelsey Reno, Tel. [redacted] Email: [redacted]

Sequoia Truong, Tel. [redacted] Email: [redacted]

APPROVED BY
WPI IRB-1
4/2/2024 to 11/20/2024

MQP Team Email: [redacted]

IRB Manager Ruth McKeogh, Tel. 508 831 6699, Email: irb@wpi.edu

Human Protection Administrator Gabriel Johnson, Tel. 508 831 4989, Email: gjohnson@wpi.edu

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

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Parent of Minor Signature

Date: ____________________

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Signatures of People who explained this study

Date: ____________________

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WPI IRB-1
4/2/2024 to 11/20/2024

WORCESTER POLYTECHNIC INSTITUTE

100 INSTITUTE ROAD, WORCESTER MA 01609 USA

Institutional Review Board

FWA #00030698 - HHS #00007374

Notification of IRB Approval

Date: 02-Apr-2024

PI: Sarah Jane Wodin-Schwartz
Protocol Number: IRB-24-0042
Protocol Title: Bicycle for Child with Achondroplasia

Sponsor*:

The WPI Institutional Review Board (IRB) approves the modification submitted on 02-Apr-2024 to the above-referenced protocol.

This modification does not extend the expiration date of your approval. The previous approval remains in effect from 02-Apr-2024 until 20-Nov-2024 unless terminated sooner (in writing) by yourself or the WPI IRB. If the research is to continue past 20-Nov-2024, you must submit a Study Renewal form to the IRB via InfoEd, at least 30 days prior to expiration.

Modification: Test site for final prototype testing. Revised consent form.

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

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

Appendix B: Mechanical Testing Procedure

This procedure was used to guide the mechanical testing described in section 5.1.2.

Mechanical Testing of Bike

Goal: Verify that our Ansys simulation results are correct using strain gauge testing.

Two iterations of the bike will be tested under two different conditions:

1. Bike with top bar under loading condition 1
2. Bike without top bar under loading condition 2

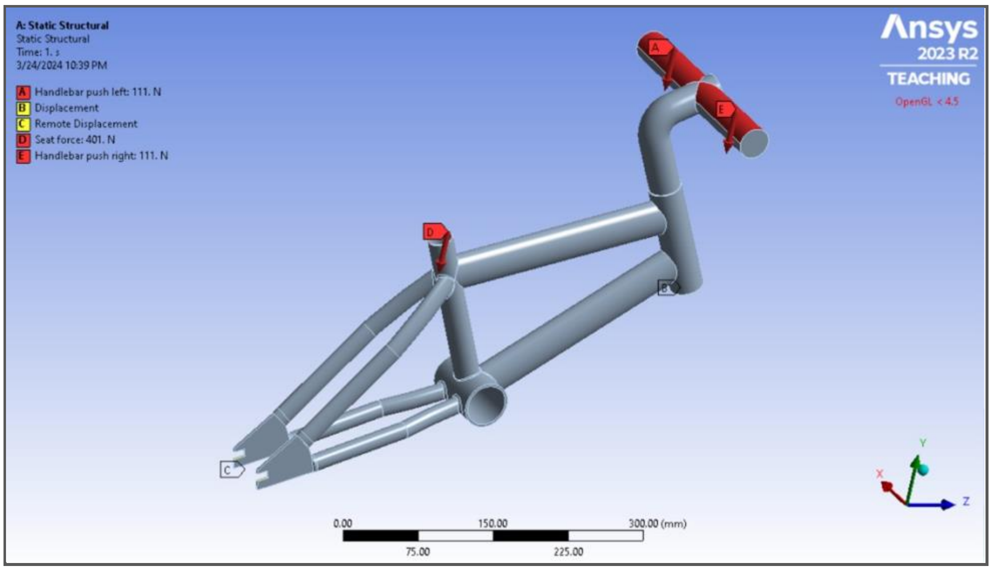

Figure 1: Loading condition 1

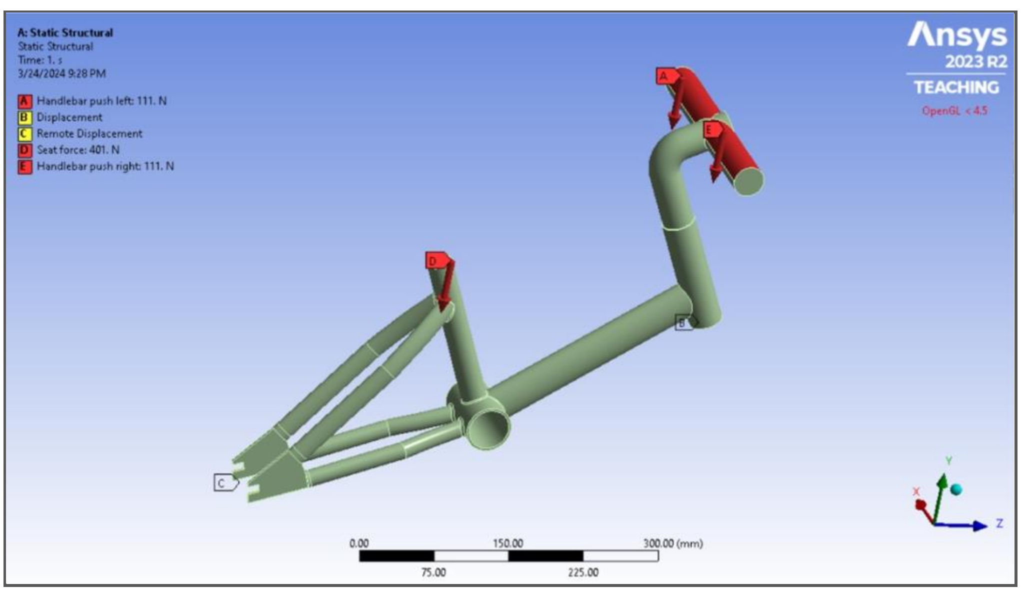

Figure 2: Loading condition 2

The material properties are shown below:

Steel AISI 4130

Density	7850	kg/m^3
Structural		
Isotropic Elasticity		
Derive from	Young's Modulus and Poisson's Ratio	
Young's Modulus	2.05e+11	Pa
Poisson's Ratio	0.29	
Bulk Modulus	1.627e+11	Pa
Shear Modulus	7.9457e+10	Pa
Tensile Yield Strength	4.6e+08	Pa

Figure 3: Steel AISI 4130 Material Properties

Setting up Arduino:

1. Set up wiring

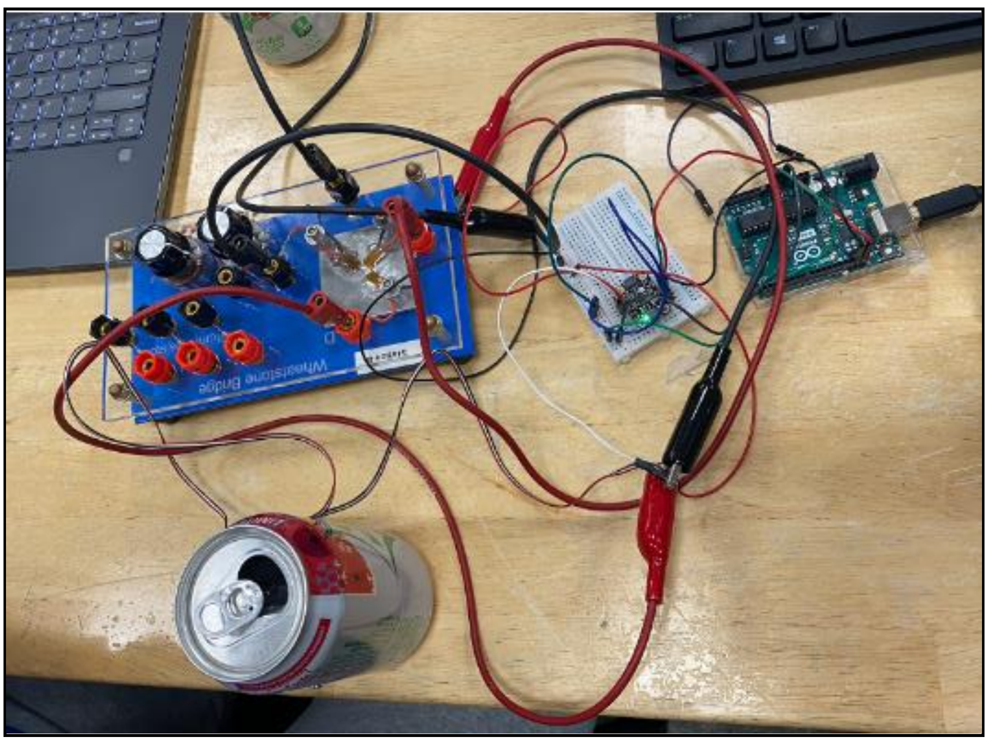

Figure 4: Experimental setup example from past lab

2. Insert code shown below into Arduino [51]

```
//  by John Sullivan and Ahmet Can Sabuncu, ME3902 Summer 2021
//
#include <Adafruit_ADS1X15.h>  // same library for both the ads1015 and ads1115
Adafruit_ADS1115 ads1115;  // Declare an instance of the ADS1115 at address slot 0x48
int16_t rawADCvalue;  // The is where we store the value we receive from the ADS1115
                    //  int16_t is a 16 bit signed integer range = -32768 to +32767
                    // scalefactor = max Voltage /(  (2^15)-1 = max Voltage/(32767) for 16 bit with
most
                    //   significant bit reserved for sign (+ or -)

float volts = 0.0;        // The result of applying the scale factor to the raw value
float bit_res = 0.0078125;    //  This is the bit resolution in [mV] will change with the gain,
please refer to the table below
float uV = 0.0;          //  This is just volts times a million [uV]
float a0 = 0, a1 = 2.5928e-2, a2 = -7.602961e-7, a3 = 4.637791e-11;  //  These are the NIST
coefficients for converting voltage readings to temperature
float a4 = -2.165394e-15, a5 = 6.048144e-20, a6 = -7.293422e-25;    //  These are the NIST
coefficients for converting voltage readings to temperature

// PLEASE LOOK UP THE NIST COEFFICIENTS FOR YOUR THERMOCOUPLE


float TempDegC=0;
unsigned long StartTime = 0;
//                              //  Gain      Max Volt     ads1015          ads1115
// ads1115.setGain(GAIN_TWOTHIRDS);// 2/3x gain +/- 6.144V  1 bit = 3mV (default)  1 bit
= 187.5 micro-V
// ads1015.setGain(GAIN_ONE);      // 1x gain   +/- 4.096V  1 bit = 2mV        1 bit = 125.
micro-V
// ads1015.setGain(GAIN_TWO);      // 2x gain   +/- 2.048V  1 bit = 1mV        1 bit =  62.5
micro-V
// ads1015.setGain(GAIN_FOUR);     // 4x gain   +/- 1.024V  1 bit = 0.5mV       1 bit =  31.25
micro-V
// ads1015.setGain(GAIN_EIGHT);    // 8x gain   +/- 0.512V  1 bit = 0.25mV      1 bit
=  15.625 micro-V
// ads1015.setGain(GAIN_SIXTEEN);  // 16x gain  +/- 0.256V  1 bit = 0.125mV     1 bit
=  7.8125 micro-V
//
void setup(void)
{
  Serial.begin(9600);
  ads1115.setGain(GAIN_SIXTEEN);  // Set gain to 16x
  ads1115.begin(0x48);
  //  start a timer
  StartTime = millis();
```

```
}

void loop(void)
{
  rawADCvalue = ads1115.readADC_Differential_0_1(); // Differential voltage measurement
between A0 and A1 on the ADC chip
  volts = rawADCvalue * bit_res; // Convert rawADC number to voltage in [mV]
  uV = volts*1e3; // Express the voltage in microVolts

  unsigned long CurrentTime = millis();
  float ElapsedTime = (CurrentTime-StartTime)/1000.0;
  Serial.print("Time (sec) ");
  Serial.print(ElapsedTime,3);
  Serial.print(",   microVolts Measured = ");
  Serial.print(uV,2);
  //Serial.println();
  delay(500);
}
```

Setting up 120 ohm strain gauge:

1. Clean the location on the bicycle frame where the strain gauge will be placed using 70% isopropyl alcohol.
2. Using tweezers, remove the strain gauge from its plastic covering/packaging.
3. Attach the strain gauge to a piece of scotch tape and stick the tape onto the frame. Ensure the strain gauge is facing the proper orientation with the solder pads facing outward.
4. Carefully peel back the tape and apply Loctite 4471 under the strain gauge.
5. Press the tape back down and allow Loctite to dry for at least 10 minutes. Once the glue has set, remove the scotch tape at a sharp angle.
6. Tin the wires with solder.
7. Solder the lead wires to the strain gauge.
    a) Red wire to left side
    b) Black & white wire to right side
8. Connect the strain gauge to a Wheatstone bridge
    a) The power is the 5V output from the Arduino
    b) Connection B of Figure 5 returns to ground
    c) The A0 and A1 for the positive and negative connections on the ADS1115 analog to digital converter are channels A and C in Figure 3, respectively
    d) Ideally, the voltage read across channels or Pins A and C should read zero. Use the potentiometers to have zero volts output.

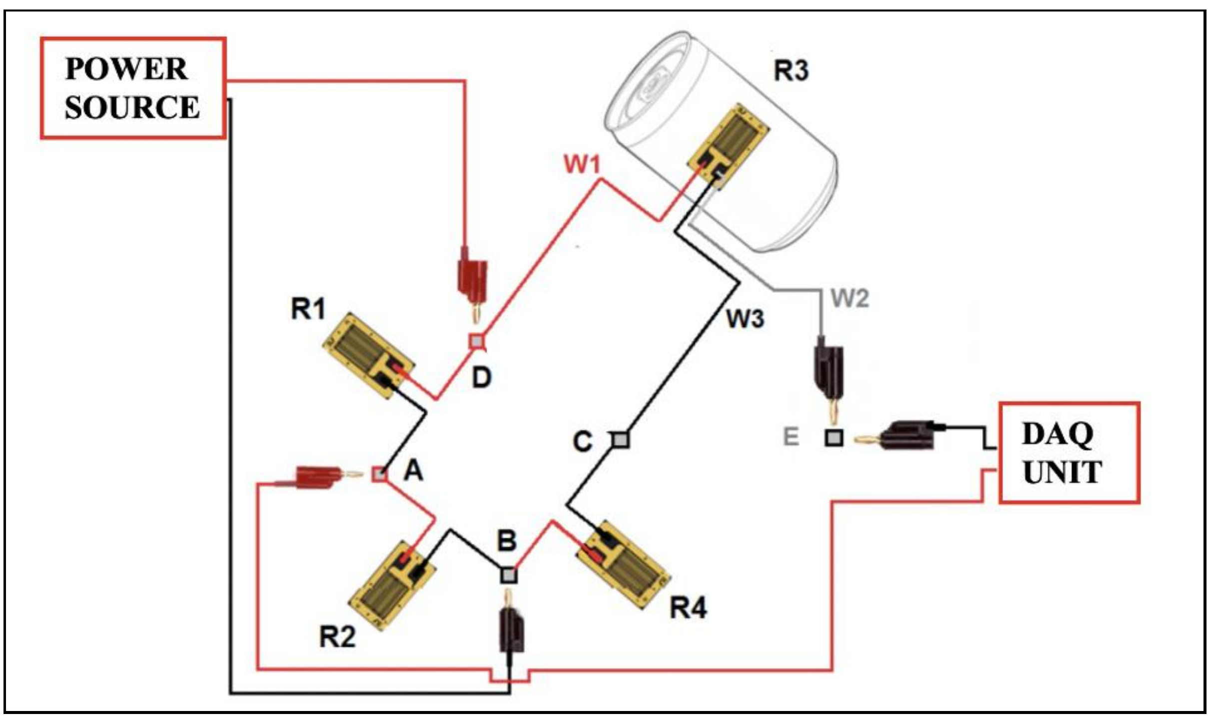

Figure 5: Wheatstone Bridge Connection Reference Diagram [51]

9. We will place strain gauges in three spots on each bicycle (with and without top bar). These strain gauges will be located on three spots with large amounts of strain that have consistent strains across an area. These spots are shown below in Figure 7.

Bicycle Experimental Setup

1. Construct bicycle stand that acts as a bike trainer (Figure 6), holding the back wheel above the floor, to secure the bike into position during tests

Figure 6: Bicycle Trainer

2. Place bicycle in stand
3. Place two 45lb plates onto the bicycle seat, secure with paracord if necessary
4. Place one 25lb plate on each side of the handlebars. Do this by hanging them off each side of the handlebars

Performing Test

1. Once the strain gauge is set up, the gain on the digital converter chip should be set to full gain (16)
2. We will transfer the strain gauges to our bicycle loading area, where the bicycle frame will be secured and ready for weight to be applied.
3. Once the bicycle is secure we will run our setup without load to zero out the Wheatstone bridge so the measured voltage across the bridge is all due to the change in resistance of the strain gauge as the bicycle is loaded
4. For each bicycle configuration (i.e. with and without the top bar) we will load the bicycle as laid out in the bicycle experimental setup section above. A new test will be run for each strain gauge location.
5. We will place our strain gauges in the three locations shown below. These are locations of higher strain where the strain is similar over an area large enough for the strain gauge to measure accurately

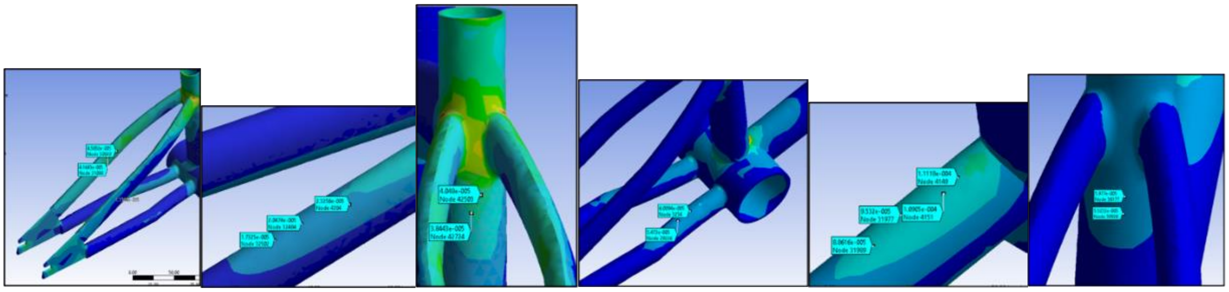

Figure 7: Strain Gauge Locations

6. We will run the code until the strain stabilizes for at least 10 seconds

Calculations:

1. Top bar is about 3/32 of an inch thick
2. We calculated the absolute minimum strain that the strain gauges and Arduino we are using can measure using Equations (1-3) as shown in the table below. These calculations are shown in Figure XX. Our results show that the minimum strain our setup can measure is **2.9762*10^-6**

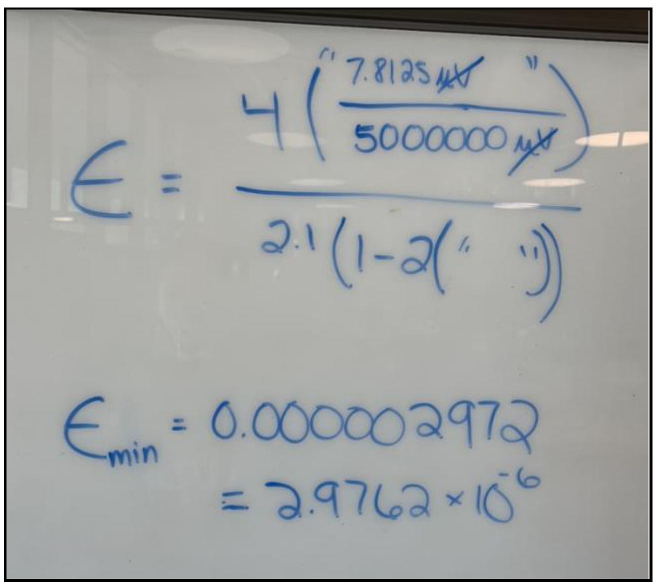

Figure 8: Minimum Strain Calculations

3. Using this, we found the locations of our strain gauges, which all show a higher strain value than the previously calculated minimum value. These three locations can be seen in Figure 7
4. In order to know what voltage value we are looking for to verify these results during the tests, we used the strain equation (3) to calculate the voltages for each spot.

Equations:

(1) Delta V (mV)	Vf-Vis

(2) E0/Ei	Delta V/Source
(3) Strain	$$\epsilon = \frac{4\frac{E_o}{E_i}}{GF(1-2\frac{E_o}{E_i})}$$

Success/Failure Conditions:
If the calculated strain values from our tests are on the same order of magnitude or less than the Ansys strain values, then our tests are a success. If they are on the same order of magnitude, then our SolidWorks model is accurate to our actual bicycle. If the actual values are less than the Ansys values, we know our model is conservative and that cutting the top bar off the model is safe.